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Civil Excavations and Tunnelling

A practical guide

Second edition

Ratan Tatiya

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To my mother ‘Rami-Shree’, and father ‘Jalam-Shree’.

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Preface

Excavation means dislodging the rock or ground from its place in situ and disposing of it from there, thereby creating an opening. When exposed to the sun and atmosphere this opening is known as an *open cut* or *surface opening*, and when the opening is created beneath the ground and not exposed to the atmosphere it is known as an *underground* or *subsurface opening*. Civil excavations mean those excavations that are usually under the purview of Civil and Construction Engineering disciplines, in terms of their planning, design, execution, construction and maintenance.

Excavation activities were first undertaken by ancient civilisations. Naturally, humans would have used primitive tools to make excavations for their shelters. Civil excavations gained momentum around the world in the 19th and 20th centuries, and they are now very widely used.

The relationship between mining and excavation technology as applicable to civil and construction engineering is very close and very old. This is due to the fact that most of the methods, techniques and equipment used in the two cases are the same, and the approaches taken to drive through various ground conditions, such as soft and unstable ground, watery strata and hard rocks, are to a great extent similar. However, an important distinction between mining and civil excavations is that the lifetime of a mine is limited to the time until the mineral deposit has been depleted, whereas the lifetime of a civil excavation is the time until its purpose has been served, and this can be almost unlimited. In addition, civil excavations are costly, and once built and created they should prove trouble free.

Surface excavations include benching, trenching, channelling, pitting, demolition, road construction and constructions related to civil and other construction projects. Muck is the material that is produced as a result of these operations. Removing this muck from its place of generation is known as *mucking*, or *loading*. The equipment used for this purpose is known as a *mucker*, *loader* or *excavator*. These types of equipment are known collectively as *earth-moving machinery*. Such equipment is used for mucking, scarping, digging, casting, pushing, shifting, ripping, dozing, levelling and dragging the earth material, and it has multiple uses as it meets the requirement of many industries and public utilities. The equipment is versatile and can perform multiple tasks;

for example, a dipper shovel can be used as dragline, crane, backhoe, clamshell, etc., as detailed in Chapter 3.

Today, tunnels can be driven at any location to meet the development needs for infrastructure such as *railways*, *roads*, *metros*, *hydropower projects*, *pipeline networks* and *utilities* (water and sewerage). Projections up to the years 2030–2035 indicate that each of these areas will show tremendous growth. The trends in the increase in *road traffic* in the Big Five countries (Brazil, India, Russia, China and Indonesia) will presumably mean that these countries are likely to increase their investment in roads by 700% by 2030 (Chapter 1).

New rail links are being built to extend and connect national and international networks. Today's technology ensures fast, precise and safe rail links; for example, transport interchange hubs such as airports, tram and bus terminals, metros and even car-parking facilities can be reached easily and quickly. The mechanised tunnelling methods (Chapters 5 and 6) used today are highly productive (0.5 man-hours/m^3) compared with current conventional tunnelling today (2–4 man-hours/m^3), and greatly exceeds the productivity that could be achieved with manual methods in the 1800s (70 man-hours/m^3).

In order to increase personal mobility and economic growth, metro systems are being built and extended in cities around the world. For example, due to the scarcity of land, to optimise its land use Singapore has planned to double the length of its existing metro line by 2030.

The use of underground space in urban areas is becoming increasingly important due to scarcity of land in these densely populated areas and environmental concerns. During the last 50–60 years, the advances made in rock mechanics for the evaluation of ground conditions, together with developments in ground consolidation and support techniques, have made it possible to create large underground excavations. Methods, techniques and equipment are now available to efficiently excavate large volumes of rock from beneath the surface. This has meant large excavations (Chapter 9), which are known as *caverns*, are now created for many purposes, such as civil works, storage facilities, defence installations, hydroelectric power plants, recreation facilities, etc. The majority of hydropower plants, which have an installed capacity of 480 GW, are located in the OECD (Organisation for Economic Co-operation and Development) countries, but in the future most will be located in Asian countries, such as India and China, and in Brazil and Africa.

The excavation activities undertaken by the civil and construction industries are vital. However, they generate billions of cubic metres of earth material daily, in addition to the material generated by mining activities the world over. The modern equipment for handling earth material on a mass scale has enormous capacity and is among the largest man-made equipment in the world. Such equipment includes: bucket wheel excavators, which weigh 14 000 ton and are capable of excavating ground at a rate of 10 000 m^3/h; draglines, which weigh 12 000 ton and have a bucket capacity of 170 m^3; hydraulic excavators, which have a bucket capacity of 45 m^3 of rock in a single scoop; and off-highway trucks that weigh 360 ton.

The present book provides comprehensive coverage of *civil excavations at both surface and subsurface locales, including tunnels*. It covers excavations created with or without the aid of explosives, the latest methods, equipment and techniques, with considerations with regard to health, safety and the environment. The text is separated into ten chapters.

- The introductory chapter (Chapter 1) begins with a review of the growth in and development of civil excavations, from their inception to the present day. This is followed by the details of site-investigation tasks, such as prospecting, exploration and seismic surveys, for establishing the geological and geotechnical parameters at a site. Theories and relationships that have been proposed for the identification of the rock-mass and ground characterisation are covered, and projections of the future development of different infrastructure types are given.
- The text covers 'unit operations' such as: drilling and blasting (Chapter 2); cutting and boring (Chapters 5 and 6); sinking and raising (Chapter 9); mucking/loading, earth-moving, dozing, scraping, hauling (transportation) and supporting (Chapters 3 and 4). Descriptions are given of the equipment used to carry out these operations, including rock drills, multi-boom jumbos, excavators, loaders, earth movers, trucks, locomotives, conveyors, tunnel borers, raise borers, shields, roadheaders and few others.
- The use of explosives, blasting accessories and controlled blasting is covered in Chapters 2–4.

Coyote blasting (a non-nuclear mass blasting technique, in which bulk quantities of explosive are used to blast huge rock masses without drilling) is covered in detail in Chapter 2, which includes two case studies. The chipping hammers and pneumatic breakers used in the construction industry are also described in this chapter.

- The use of fully automated and semi-automated multi-boom drilling jumbos to undertake longer rounds, up to 7–8 m in length, has become economically viable. This is described in Chapter 4, which also covers the trails of this method and gives case studies of the use of the technique at Swedish mines and tunnels. Explosives are still the cheapest way of achieving rock fragmentation, provided proper drilling patterns are applied and precision in the drilling and charging operations is ensured. If applied inaccurately or incorrectly, the use of explosives can result in a waste of resources and damage to the surroundings, the latter potentially leading to ground stability problems, overbreak, reduced productivity and higher costs. This is demonstrated in Chapter 4 through two case studies.
- The criteria used to select equipment are demonstrated in Chapter 3 through a case study. Chapter 3 also covers environmental, safety, ergonomic, economic and technical factors related to the selection of equipment. Guidelines for selecting suitably matched sets of equipment, explosives, blasting accessories, service appliances and devices, etc., to undertake any excavation are given in Chapter 9.
- *Mechanised tunnelling* is the result of a number of innovations that have been made over the last 150–200 years. Today there is hardly any location, formation or set of conditions where mechanised tunnelling for diameters in the range 1.5–19 m, cannot be used. *Partial face-heading machines* (PFM) and *full-face tunnel-boring machines* (TBMs) are the two categories of tunnelling machine. TBMs without shields are of two types: *open-beam machines* (Robbins Company, Solon, OH, USA); and *single- or double-gripper machines* (Herrenknecht AG, Schwanau, Germany), which are suitable for hard rocks. A comprehensive description of modern partial-face borers, full-face tunnel borers, multi-tool miner (MTM) attachments and impact/hydraulic hammers is given in Chapter 5. The same chapter also covers parent–child shield machines, which can

drive a tunnel with two different section diameters, and rectangular shield machines, which can excavate a rectangular tunnel by means of a rotating cutter (just like a normal TBMs).

- Robbins' *crossover TBMs* and Herrenknecht's *multi-mode TBMs* (Chapters 5 and 6) are recent innovations that produce time-saving and efficient tunnelling in ground with mixed geology (ground containing a little bit of everything: hard rock, soft rock, boulders, soil, weathered rock). These TBMs are designed to cross between ground conditions that would otherwise require the use of a number of different machines. They are also known as 'hybrid' or 'dual-mode' machines in the tunnelling industry. A classic example of the use of a Herrenknecht multi-mode TBM is the use of such a machine (slurry and open mode) at Lake Mead, Nevada, USA, which achieved the world record for mechanised tunnelling under high pressure. This example is described in a case study in Chapter 6.
- Herrenknecht has also developed the *variable density TBM*, which applies a totally unique tunnelling technology. Without major mechanical modifications, the geological and hydrogeological changes along the alignment (tunnel route) can be managed with extreme flexibility, as detailed by the case study in Chapter 6 of the Kuala Lumpur metro. Chapter 6 also covers *earth-pressure-balance* (EPB) and *mix-shield TBMs*, the use of which is illustrated by the case study of Crossrail, London, UK (Europe's largest infrastructure project, with 42 km of tunnels). *Shield TBMs* (Hitachi Zosen Corporation, Osaka, Japan), which are designed to cope with any type of ground, particularly beneath sea and river beds, are covered extensively in the same chapter.
- The success of any tunnelling technique lies in keeping the disturbance to the natural ground setting to a minimum, to reduce costs and minimise problems. Chapter 7 details such techniques, and includes those not covered in Chapters 4–6: cut and cover, the new Austrian tunnelling method (NATM; also known as the sequential excavation method), Lee's tunnelling method, the pre-vault method (mechanical pre-cutting tunnelling method), immersed tunnels and box jacking. It is claimed that for tunnel lengths less than 3–4 km these techniques are much cheaper than using a TBM to drive the

tunnel. For these reasons, such techniques are the obvious choice for the majority of urban tunnelling projects.

- The principles of the NATM are fundamental to modern-day tunnelling, and the use of this method in the USA is increasing, particularly for shallow tunnels in soft ground. Chapter 7 details the other designations of the NATM and illustrates its use through case studies of the Heathrow Express rail link, London, UK, and the Beacon Hill Station, Seattle, WA, USA.
- Chapter 7 also deals with ground consolidation techniques, which are illustrated by the case-study of the use of grouting techniques on the Xiang'an tunnel, China, which was driven in a highly weathered rock under the seabed.
- More than 150 immersed tunnels (Chapter 7) have been constructed worldwide, as they are a suitable alternative to bored tunnels where a waterway needs to be crossed. Immersed tunnels can be placed immediately beneath the floor of a water body, even in earthquake-prone areas.
- Box jacking (Chapter 7) is similar to pipe jacking, but it takes less time to complete and there is no disruption to traffic. For these reasons it continues to be the most popular method of installing underground infrastructure for any purpose.
- For quality-of-life, environmental and economic reasons an urban area needs efficient infrastructure for supply and disposal services. Trenchless technology (micro-tunnelling) (Chapter 8) has proven to be clean, quick and economical for the installation of pipelines (including for oil and gas), cables and sewerage lines. The technology can be applied in ground of any geology, from soft and heterogeneous to rocks, to create boreholes with diameters of 0.1–4.2 m. Therefore, this technology has huge potential.
- The network of vertical, inclined and horizontal openings (excavations) required for the construction of caverns for different purposes (e.g. repositories, oil storage, power generation and recreational facilities for the general public) is described in Chapter 9. The same chapter covers shaft construction using Herrenknecht's VSM technology, which is suitable for use in ground with difficult geology, beneath groundwater level and where space is constrained. This technology has been also used for inclined shafts. The application of various techniques and unit

operations is demonstrated through a case study of an underground hydropower station.

- When creating excavation of any kind at any location, damage to the environment (pollution) and accidents are unavoidable. Both of these are detrimental to health of the direct (workers) and the indirect stakeholders and, while they cannot be eliminated, efforts can be made to minimise them. Moreover, the successful completion of any project lies in the optimum use of the input resources (natural and man-made), which can be achieved by minimising the losses of various kinds. Chapter 10 covers both the prevention of resource loss and health, safety and environmental guidelines.

As the foregoing discussion reveals, the subject areas chosen for this book are many, and all of them are vital. It was my more than 40 years of experience of working in excavation-related disciplines, initially in the field and then as a university professor and an industrial consultant, that inspired me to write the first edition of this book in 2005, which was followed by student and e-book editions in 2010.

Excavation is a multi-disciplinary activity involving civil, construction and mining engineers, Earth scientists and geologists, and hence this book is likely to be used by students, academics and professionals in these fields. This book is intended to serve as a textbook for undergraduate-level and first-year-graduate level students at schools or institutes that teach any of the above-mentioned subjects.

This book covers best practice and the latest trends and practices, illustrated by case studies. It advocates the prevention of losses of all kinds, which is a virtuous way of working, as it results in the achievement of the targets set, with maximum productivity, least cost and maximum safety. Each chapter ends with concluding remarks that indicate the way forward, and a list of questions to help readers test their understanding of the subject matter. Instructors and teachers could design quizzes using these questions and other supplementary material.

In the end this book is the result of the appreciation I have been shown by students and colleagues, and the support of my family members: my wife Shashi, my sons Anand and Gaurav, and my daughter Sapna. The book has been enriched by the cooperation of the professional societies, companies and organisations listed in the

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Ratan Tatiya

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About the author

Ratan Tatiya is a mining graduate from Jodhpur University, India, and he was awarded a PhD and Diploma by Imperial College, London University, in 1987, as a Commonwealth Scholar. He has developed a methodology for the design and economic evaluation of underground mining methods. His applied research into bench-blasting models carried out during 1998–2000 has resulted in substantial savings to users worldwide.

During the initial decade of his career at Hindustan Copper Ltd. (1970–1979), Ratan planned and executed work on low-grade copper deposits, using the latest technology, including the execution of a mass blasting underground – a first in Indian mines.

His academic career began in the 1980s, when Jodhpur University recognised his outstanding work on mines and appointed him to the senior position of Reader.

Among the honours Ratan has been awarded are a Gold Medal from the University of Jodhpur, three awards for best publication from the Institution of Engineers (India) and recognition as being one of the best professors at MBM Engineering College, Jodhpur, India as well as one of the top-ten professors at Sultan Qaboos University, Oman (1992–2004).

His publications include 70 papers, and within the last decade he has published five books on surface and underground excavations, civil excavations and tunnelling, occupational health, safety and the environment, and loss prevention.

Ratan has worked with multinational companies in more than 40 countries and in multi-cultural environments. His career has covered field assignments, teaching and research, consultancy and publications:

- in industry (2006–2009): first-line supervisor, planner and executor to the chief technical officer
- academic posts at universities (1979–2004): senior professor and researcher, and director
- consultant (1988–present): member of the Engineering Management Expert Panel of the leading construction company Hindustan Construction Company Ltd.

Ratan Tatiya is among the very few in the world who have a background that covers senior positions in industry, posts as an academic and researcher at universities and work as a consultant, in addition to being a published author – a rare combination.

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Erratum

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Please make note of the following amendments:

Chapter 5
The caption for Figure 5.25 should read (a) Enlarging TBM; (b) dual shaped TBM; (c) oval shaped TBM.

Chapter 10
The caption for Box 10.1 should read Box 10.1 The six letters of the word 'SAFETY' define a well-balanced safety program, campaign or strategy that should be followed through to promote its safety campaign.

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Chapter 1
Introduction and site investigations

Site investigation is the foundation on which a future structure is built, and a shaky foundation is always dangerous. Trouble can start when floating tenders, negotiating bids, awarding tenders or during execution of a project, and can become the cause of a dispute between the contractor and project owner. Cost overrun, delays and abnormal incidents can all be a result of improper and inadequate site investigation.

1.1. Introduction

Excavation is the dislodging of rock or other ground and disposing of it, thereby creating an opening. When the opening created is exposed to the sun and atmosphere it is known as an open cut or surface opening, and when the opening is beneath the ground and thus not exposed to the atmosphere it is known as an underground or subsurface opening. Civil excavations are those excavations that are usually under the purview of civil and construction engineers in terms of their planning, design, execution and construction. The content of this book is confined to civil excavations, and does not cover excavations required for the exploitation of mineral deposits (mining). There are many ways to classify civil excavations (e.g. based on locale – either surface or underground). The classification based on utility and functions is shown in Figure 1.1.

1.2. Brief history of civil excavations

The first human excavation activities were undoubtedly excavations made for shelter, using primitive tools (Shepherd, 1993). Tunnels, mainly for mining out minerals, dating to the period 3000 BC to AD 500, have been found in Egypt, Malta, Austria and a few other places. During the period AD 50–1500, in addition to tunnels for mining, tunnels were also driven for water supply (there is a water tunnel in Greece dating from this period that is 1.5 km long). Around AD 600, tunnels were driven for road, military and burial purposes. The making of civil excavations gained momentum around the world during the 19th and 20th centuries.

In modern times, many major highway, rail, building, hydroelectric and tunnelling projects have been undertaken, and many others have been proposed for the next 15–20 years (see Section 1.11). These projects have been made possible by the advances achieved in the techniques, methods and equipment required. Today, civil excavations are no longer an art but one of the basic tasks of engineering, and civil excavations play an important role in the development of infrastructure in any country (Whittaker and Frith, 1990).

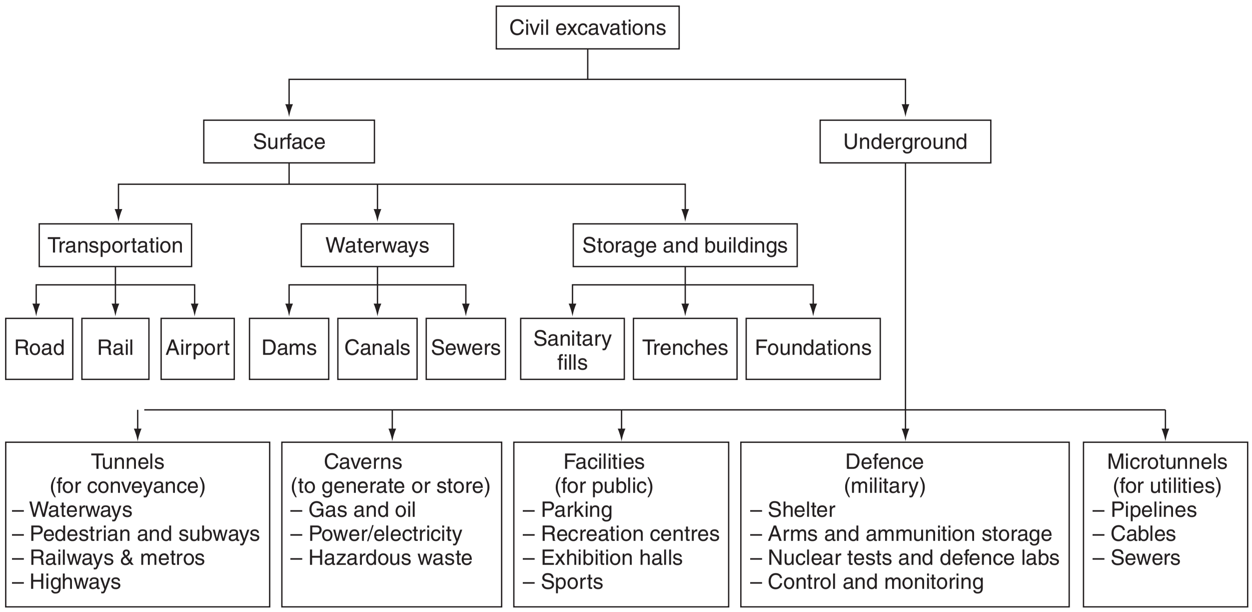


Figure 1.1 Classification of civil excavations

The relationship between mining and excavation technology as applicable to civil and construction engineering is very close and very old. This is due to the fact that most of the methods, techniques and equipment used in them are common, and the approaches taken to drive through different ground conditions, such as soft and unstable ground, watery strata and hard rocks, are to a great extent similar. However, an important distinction between them is that the lifetime of a mine is limited to the time until the mineral deposit has been depleted, whereas the lifetime of a civil excavation is until its purpose has been served, which can be almost unlimited. Civil constructions are costly, but once built and created should prove trouble free. There are some unique features of civil constructions that must be considered, and these are described in Table 1.1.

1.3. Site investigations – ground and rock characterisation

1.3.1 Prospecting and exploration

As stated above, civil constructions are costly, and so they should be made in ground, or an area, where there will be the least potential problems, both during construction and during the operational life of the construction. Thus a thorough investigation should be made of the site proposed for a civil project. ‘Prospecting’ and ‘exploration’ are the terms used for the procedures and techniques used to search for a mineral deposit, and they can also applied to investigations into the ground (insofar as is possible within the given constraints) before undertaking any tunnelling or excavation project. The aim is to examine the suitability of the ground or site for a particular civil construction or excavation project, including tunnels (Nilsen and Ozdemir, 1999; Railing, 1983; Whiteley, 2001; Whittaker and Frith, 1990).

Today, geologists use a variety of tools and instruments to help them locate mineral resources. They use aeroplanes and helicopters fitted with photographic equipment, and magnetism- and gravity-detecting equipment, which gives information about the Earth’s subsurface. They sometimes use pictures taken from satellites in their search for hidden mineral resources. Thus, a variety of methods, techniques and equipment are available to accomplish the task at hand, and these are selected and deployed according to the available resources (i.e. the money available to deploy workers, machines and equipment) and the requirements of the project in terms of the time for completion and the accuracy required.

Prospecting and exploration techniques are used to establish the presence of solid, liquid and gaseous regimes within the area of search. For solid regimes the survey includes geological details of lithostratigraphic units (rock types and their sequence) and the type of ground and soils (if any), and for liquid regimes it includes the position of the water-table and the type of water and any other liquid, if present. The presence of gases (quality and quantity) is also determined during the survey. The survey thus provides data for characterising the rock and ground and making estimates of geomechanical properties, and information about the soil, ground and rock. The main considerations and steps that need to be taken in a survey are summarised in Table 1.2.

Table 1.1 Features of civil engineering structures, including tunnels of different types (Monsees and Hansmire, 1992; Sinha, 1989))

	Rail transit	Highways	Water supply	Waste water	Caverns, etc.
Alignment	Perfect horizontal alignment essential	Perfect horizontal alignment essential	Less critical than for rail transit and highways	Horizontal alignment less critical than for rail transit and highways, but perfect vertical alignment required to avoid low spots	Perfect alignment in all directions essential
Operational life	Permanent structure with a practically unlimited life	Permanent structure with a practically unlimited life	Permanent structure with a practically unlimited life	Permanent structure with a practically unlimited life	Permanent structure with a practically unlimited life
Ventilation and illumination during operational phase	Should be considered	Should be considered	–	–	Should be considered
Infiltration of water, gases or ground contaminants	Should be tightly controlled	Should be tightly controlled	Should be tightly controlled	Exfiltration may be important	Should be tightly controlled
Lining	May require multiple embedment of utilities. Should be strong and aesthetically appealing	May require multiple embedment of utilities. Should be strong and aesthetically appealing	Smoothness will affect flow capabilities; embedment usually not required	Embedment usually not required	May require multiple embedment of utilities; should be strong
Provision of cross-passages and emergency exits	Required	Required	–	–	Required
Noise and vibration impacts on nearby inhabitants and structures	Requires isolation and special mounting pads	Requires isolation and special mounting pads	–	–	Requires abatement within the structure
Special attention	Should not be located in earthquake-prone areas Cathodic protection essential where direct current (DC) is used to power trains	Should not be located in earthquake-prone areas	Should not be located in earthquake-prone areas Special design for interior pressure may be required	Special design often required for inlet-drop structures Corrosion-resistant lining may be required where effluent is acidic, for long-term benefits	Should not be located in earthquake-prone areas Special design for interior pressure may be required for hydroelectric structures

Table 1.2 Summary of investigations to be carried out when undertaking civil constructions, including tunnelling projects (Whittaker and Frith, 1990)

Principal consideration/ step	Details and comments
Literature review	Should include published/unpublished information about the area, its history, and details of any construction or mining activities undertaken.
Aerial photography	Provides an overview of the project site and enables identification of important features such as topography, drainage pattern, vegetation, land use and sources of potential construction material. Also provides information on landslides, major faults, and folds and dome structures.
Study of local geology	Includes local geological history, tectonic movements and appraisal of geological evidence.
Geophysical surveys	Although the precision of these surveys (see Table 1.4) is low, the information obtained, particularly in the case of large tunnel projects, can be used to locate anomalies that require further more detailed investigation.
Exploratory drilling	One of the most important elements in a site investigation. The number of boreholes drilled, their location, interval, size, depth and other relevant parameters are the matter of judgement and depend on the specific need. Boreholes provide information about the geology (rock types, structures; groundwater), the position, quality and quantity of water, the type of overburden (thickness of each soil, ground or rock layer), etc. The data obtained can be used to determine the physical properties of rocks, the fracture pattern in the main rock types, the permeability and porosity, the in situ stress levels and the rock strengths. Ultimately, the data obtained assist in evaluating support requirements, arrangements to be made to deal with water, and possible problems during the construction of the tunnels.
Status of water regime	Includes information on the presence of water and the study of any nearby water wells. In some situations, packer tests for hydraulic conductivity and installation of piezometers to study the groundwater regime and monitor water pressures are essential.
Test pits and drifts	Sometimes exploratory pits, trenches and drifts are dug to obtain detailed information so that a full-scale evaluation can be made, a first-hand impression of the site obtained and the tunnelling conditions anticipated.
Areas of uncertainty	The uncertainty with regard to the geological structures must be recognised and considered.
Laboratory work	Sampling, testing, analysis and recording of results is carried out simultaneously with the site survey. This work includes determination of rock strength, elastic constants, creep behaviour, rock joint strength, permeability, porosity, density, rock hardness, abrasiveness and other physical properties.

1.3.2 Data on rock behaviour

Studies, literature surveys, field investigations and other means (see Table 1.2) provide data on the rock behaviour. Some factors that are essential in a site investigation are described in Table 1.3.

1.4. Core drilling

Core drilling is among the routine methods used for subsurface exploration (Nilsen and Ozdemir, 1999). Holes of different diameters can be drilled but an NX-size core (hole diameter 76 mm, core diameter 54 mm) is common. Figure 1.2 illustrates the types of information that can be obtained from a borehole. Core drilling fulfils a number of purposes, prominent among which are to:

- verify a geological interpretation that has been arrived at using other techniques and means
- obtain more information on rock-type boundaries and the degree of weathering, and more detail about the overburden and soil covers, and formations
- obtain supplementary information on the orientation and character of weakness zones and discontinuities (fault, folds, joints, etc.) of various types
- obtain samples for laboratory tests and analyses

Figure 1.2 The different types of information (seismic refraction, rock quality designation and Lugeon values) obtained from core drilling along an exploratory borehole (Nilsen and Ozdemir, 1999)

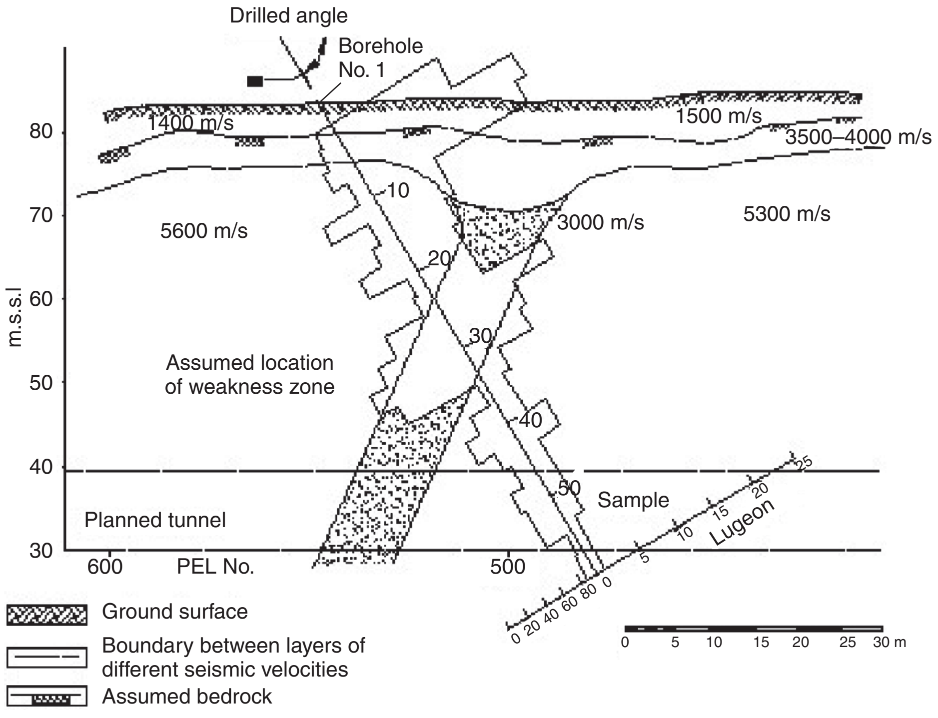


Table 1.3 Factors governing the behaviour of rock (US National Committee on Rock Mechanics, 1981)

Material parameters	Mass material parameters	External parameters	Stress–strain state
■ Lithology and stratigraphy (rock type, occurrence, grain size, colour, minerals) ■ Anisotropy ■ Porosity ■ Cracks and weaknesses ■ Specimen geometry (shape and size) ■ Physical and mechanical properties (density, strength, moduli, failure mode) ■ Chemical properties	■ Structure (stratification, lamination, dip, strike, size, shape) ■ Discontinuities (type, orientation, spatial configuration, condition) ■ Porosity ■ Permeability ■ Physical and mechanical properties (strengths, moduli, friction angle) ■ Creep	■ Environment ■ Pressure ■ Temperature ■ Hydrological (moisture content, groundwater flow, pore pressure) ■ Presence of chemicals	■ In situ stresses (magnitude, direction, distribution) ■ External load (type, magnitude, direction, distribution and configuration, nature, rate) ■ Non-mechanical stress (thermal, electrical, magnetic)

- obtain data on water regimes (hydrological details) and/or geophysical testing and logs
- determine the presence of formation fluid and gas, if any
- obtain graphical data or log tapes (density, resistivity, induction, source pulse, gamma rays, neutrons, etc.).

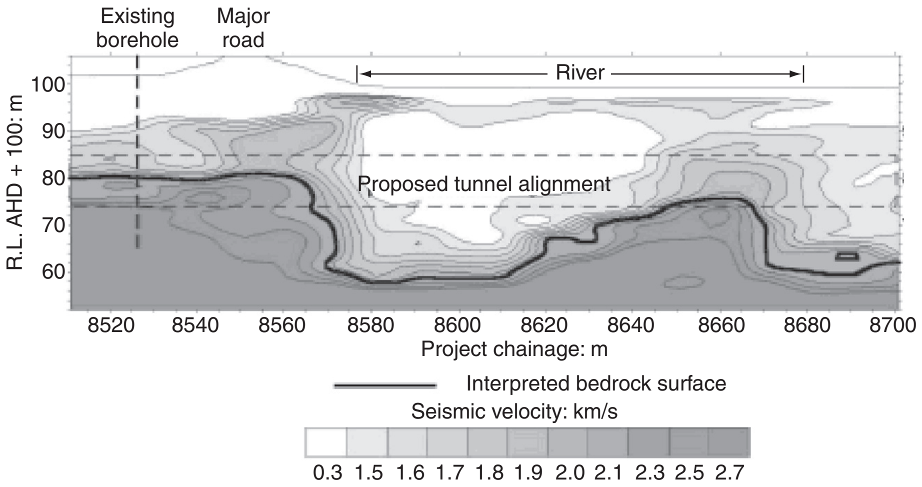
1.5. Tomography

This technique, also known as ‘seismic imaging’, has seen significant developments. Most commonly, the tomographic method applied between drill holes is known as *cross-hole tomography*. Horizontal as well as vertical tomographs can be obtained, and these help identify: whether the rock is weak/weathered or competent; the presence of water-bearing rocks and fault and shear zones; and the location of the interface between different rock types. The use of this technique in the Sydney area of Australia is shown in Figure 1.3.

1.6. Lugeon test

The water injection test, commonly referred to as the Lugeon test, is a method for predicting water inflow in a tunnelling project (Nilsen and Ozdemir, 1999). The test involves the injection of water at a pressure of 1 MPa between two packers 3 m apart in a borehole, and recording the flow rate when constant flow is achieved. The unit 1 Lugeon (1 L) is equivalent to a water loss of 1 l/min per metre of drill hole. The results obtained from Lugeon testing, such as those obtained from the borehole shown in Figure 1.2, show that it is a good technique for predicting water inflow in a proposed tunnel. However, local features, such as the presence of joints, can markedly influence the results, and therefore in some cases the results obtained may be misleading.

Figure 1.3 Seismic tomographic image showing an irregular bedrock profile beneath Alexandra Canal to the west of Sydney Airport, Australia (Whiteley, 2001)



1.7. Laboratory testing

Careful sampling is a key factor in all site-characterisation programmes and in predicting the performance of a tunnel-boring machine (TBM). If the test samples are not representative of the actual field conditions the predicted performance of the TBM will, of course, not be very reliable. The principal tests used in TBM projects include those for (Nilsen and Ozdemir, 1999)

- mechanical strength (uniaxial (or unconfined) compressive strength, brittleness value, triaxial strength, Brazilian and point-load strength tests)
- surface hardness (Vickers hardness)
- abrasiveness of the rock (Cerchar and abrasion value (AV) tests)
- excavatability of the rock, i.e. the energy needed for efficient chipping (punch penetration tests)
- rock cutting (linear and rotary)
- Siever's J-value (miniature drill tests)
- fracture toughness
- petrographic analysis (thin-section analysis and X-ray diffraction analysis).

The various tests are standardised according to the performance prediction models developed by various organisations and institutions around the world.

However, some factors, if not properly investigated, or if underestimated, are still the basis of claims made in TBM projects:

- Groundwater – in cases of excessive inflow this can cause great problems and considerable extra cost.
- Rock stresses – in the worst-case scenario, rock stress may cause the TBM to become stuck, particularly in squeezing ground.
- Adverse ground conditions (e.g. running or swelling ground).
- Geological features (e.g. joints, fractures, bedding/foliation) – these can have a significant impact on the performance of a TBM.
- Microscopic features of the rock (e.g. grain suturing/interlocking) – these can increase the difficulty of excavation (Franklin and Dusseault, 1989). The texture or fabric of a rock is dictated by the size, shape and arrangement of its constituent materials. All igneous and most metamorphic rocks are crystalline, whereas sedimentary rocks are made up of grains or fragments (and are known as *fragmental*). Crystalline rocks consist of interlocking mosaic crystals, whereas fragmental (detrital or clastic) rocks are made up of grains that are usually not in such close contact. Due to these features, crystalline rocks are stronger, less porous and less deformable than fragmental rocks of a similar mineral composition. Quartz–feldspar granite is much stronger than quartz–feldspar sandstone. These features play an important role in the selection of drills and TBMs, and they have a considerable bearing on the overall cost of a project.

Particular attention should be paid to these factors on new projects, although other factors are also important and should not be ignored. The accuracy of interpretation

Table 1.4 Summary of relevant geophysical methods (Nilsen and Ozdemir, 1999)

Method	Main information	Main limitations	Applications
Seismic refraction	Thickness of soil cover Location of groundwater table Location of rock surface Quality of rock mass	'Blind zones' (if non-increasing velocity with depth) Side reflection	Extensive
Seismic reflection	Location of different layers (soil, rock, sea bottom, etc.) Soil/rock structure	'Blind zones' Side reflection Interpretation of results for great depths	Limited (mainly subsea tunnels)
Cross-hole tomography	Rock-mass quality Karst caverns, etc.	Interpretation	Increasing
Geo-electric	Location of groundwater table Soil structure Openings	Interpretation Stray current/ buried metals	General
Electromagnetic	Structural geology	Restricted to soft ground	Limited
Magnetic	Structural geology	Interpretation	Minimal
Gravitational	Structural geology	Interpretation	Minimal

of results obtained from investigations and the accuracy of the description of the rock and geological conditions will often be improved considerably if several investigation methods are combined. The basic principle is always to tailor the investigation methods and analyses to match closely the character and complexity of the geological conditions and the scope and specific requirements of the particular project.

A summary of geophysical methods used for site investigation is given in Table 1.4, and the main methods used to assess ground conditions are summarised in Table 1.5.

1.8. Rock composition and ground types

Rocks. The Earth's crust consists of different types of rock, which are composed of one or, more frequently, more than one mineral element or chemical compound. The common rock-forming minerals are quartz, calcite, feldspar, hornblende, mica and chlorite. Based on the concept of rock mechanics, a rock can be said to be composed of three phases: solid minerals, water and air. The solid phase is composed of minerals of different types and properties, while the water and air fill the pore space.

Minerals. A mineral is a naturally occurring inorganic (sometimes organic, e.g. coal) substance, and a mineral deposit is a natural body in the Earth's crust. A mineral has three physical states: solid, liquid and gas. The solid minerals can be divided further into metals, non-metals and fuels. The physical characteristics of minerals include properties such as

Table 1.5 Applicability of main investigating methods to assess ground conditions (Nilsen and Ozdemir, 1999)

Factor to be investigated	Investigation method						
	Desk study	Field mapping	Core drilling	Geo-physics	Exploratory headings	Field testing	Lab. testing
Rock types	✓	✓	✓	(✓)	✓	–	✓
Mechanical properties	(✓)	(✓)	(✓)	(✓)	✓	✓	✓
Weathering	(✓)	(✓)	✓	✓	✓	–	–
Soil cover	✓	✓	✓	✓	✓	–	–
Jointing	(✓)	✓	(✓)	–	✓	(✓)	(✓)
Fault/weakness zones	✓	✓	✓	✓	✓	–	(✓)
Rock stresses	(✓)	–	–	–	(✓)	✓	–
Groundwater conditions	(✓)	(✓)	(✓)	✓	✓	✓	–

✓, Method is well suited; (✓), method is partly (sometimes) suited; –, method is not suited.

colour, lustre, form, fracture, cleavage, hardness, tenacity and specific gravity. Other characteristics include fusibility, fluorescence, magnetism and electrical conductivity.

The six common rock-forming mineral assemblages that control the mechanical properties of most rocks encountered in engineering projects are detailed in Table 1.6, and the classification of the types of ground encountered in projects is given in Table 1.7. Table 1.8 details the geological and geotechnical parameters that influence the cost and construction duration (i.e. advance per unit time) for a tunnel project.

Table 1.6 Common rock-forming mineral assemblages and their usual properties and features (Franklin and Dusseault, 1989; Whittaker and Frith, 1990)

Rock-forming mineral assemblage	Usual properties and features
Acid igneous: quartz and arkose, sandstones, gneisses and granulities	Strong and brittle
Lithic/basic: basic igneous rocks (basalts and gabbros), lithic and greywacke sandstone, amphibolites	Strong and brittle
Micaceous: schists and gneisses containing more than 50% platy minerals, and gneisses containing more than 20% mica	Often fissile and weak
Carbonate: Limestone, marble, and dolomites Viscous and plastic only at high temperatures and pressures Usually weak and plastic; sometimes viscous when deep seated; soluble over engineering time span.	Weaker than category 2 and 3; and soluble over geological time spans. Normally brittle
Pelitic (clay bearing): Mudstone, shales, and phyllites	Often viscous, plastic, and weak

Table 1.7 Ground classification for tunnelling (Leonard, 1987; Whittaker and Frith, 1990)

Classification	Behaviour	Typical soil types
Firm	The heading (tunnel face) can advance without initial support, and the final lining can be constructed before the ground starts to move	Loess above water-table; hard clay, marl, cemented sand and gravel when not highly overstressed
Ravelling: – slow ravelling – fast ravelling	Chunks or flakes of material begin to drop out of the arch or walls, sometimes after the ground has been exposed, due to loosening or to overstress and 'brittle fracture' (the ground separates or breaks along distinct surfaces, as opposed to squeezing ground). In fast-ravelling ground, the process starts within a few minutes, otherwise the ground is slow ravelling	Residual soils or sand with small amounts of binder may be fast ravelling below the water-table and slow ravelling above. Stiff fissured clays may be slow or fast ravelling depending on the degree of overstress
Squeezing	The ground squeezes or extrudes plastically into the tunnel without visible fracturing or loss of continuity, and with no perceptible increase in water content. Ductile, plastic yield and flow due to overstress	Ground with low frictional strength. The rate of squeezing depends on the degree of overstress. Occurs at shallow to medium depth in clay of very soft to medium consistency. Stiff to hard clay under high cover may move in a combination of ravelling at the excavation surface and squeezing at depth behind the face
Running – cohesive running	Granular materials without cohesion are unstable at a slope greater than their angle of repose (±30–35°). When exposed at steeper slopes they run like granulated sugar or dune sand until the slope flattens to the angle of repose	Clean, dry granular materials. Apparent cohesion in moist sand, or weak cementation in any granular soil, may allow the material to stand for a brief period of ravelling before it breaks down and runs. Such behaviour is called 'cohesive running'
Flowing	A mixture of soil and water flows into the tunnel like a viscous fluid. The material can enter the tunnel from the invert as well as from the face, crown and wall, and can flow for great distances, completely filling the tunnel in some cases	Below the water-table in silt, sand or gravel without enough clay content to give significant cohesion and plasticity. May also occur in highly sensitive clay when such material is disturbed
Swelling	The ground absorbs water, increases in volume and expands slowly into the tunnel	Highly preconsolidated clay with a plasticity index in excess of about 30, generally containing a significant percentage of montmorillonite

Table 1.8 Geological and geotechnical parameters that influence the cost of tunnelling and the duration of tunnel construction (i.e. advance per unit time) (Einstein and Vick, 1974)

Parameter	Detailing of parameter	Major construction consequences and remarks
Rock type	1. Shale 2. Sandstone 3. Limestone/dolomite 4. Schist 5. Granite (basalt, diabase, intrusive, gneiss, quartzite) (see Figure 1.4(b))	Wear of cutters or drill bits: 1–3, sedimentary; 4, metamorphic; 5, igneous
Jointing; rock-quality designation	High, medium, low	Support requirements, rate of advance, overbreak problems
Major structural defects	Faults or shear zone Clay seams	Support requirements, rate of advance, overbreak problems
Foliation	Highly foliated, non-foliated	Support requirements, overbreaks, boring rate
Gas	Existence, absence	Delay, ventilation requirements
Water inflow	High inflow, low inflow	Remedial measures, including grouting, may be necessary
Compressive strength	Very high, high, medium, low	Boring/drilling rates, support requirements

1.9. Rock-mass classification

Many theories and relationships have been proposed for the identification of rock-mass type and the characterisation of ground. These are commonly known as *rock mass classification systems* and the most commonly used of these are detailed in Table 1.9.

The concept of rock-mass classification enables the designer to gain a better understanding of the influence of geological and other parameters (see Tables 1.9 and 4.6). This leads to better engineering judgement and communication and, ultimately, to cost savings and better execution of the project. The application of these theories is described briefly in Section 4.10, which describes a selection of tunnel supports.

1.10. Construction of a geological model

A model that incorporates geological parameters relevant to construction allows for a quantification of the site geology that can be correlated directly with the implications for construction (Einstein and Vick, 1974; Railing, 1983). In addition, a geological submodel allows for a more direct and precise input by the geologist, thus eliminating mistakes in information transmission due to difficulties of communication between the geologist and the estimator. The geological submodel satisfies the requirements of the

Table 1.9 Ranking of the geological and geotechnical factors that influence key tunnelling issues (Bieniawski, 1992)

Geological/ geotechnical factor	Phases and key issues													
	Planning				Design			Construction						
	Routing	Alignment	Portal siting	Tunnel size	Excavation stability	Tunnel shape	Lining	Tunnelling method	Rate of advance	Material handling	Water inflow	Water pressure	Lining	Blasting
Stratigraphic/structural														
Stratigraphic sequence	2	2	2	3	1	1	1	1	1	2	2	3	3	1
Lithology	2	1	2	3	1	1	1	1	1	1	1	1	1	1
Folding	2	2	2	3	2	3	3	1	2	3	2	3	3	2
Faulting	1	2	1	2	1	2	1	1	1	2	1	1	1	1
Tectonic														
Seismicity	3	3	3	3	2	3	3	3	3	3	3	3	3	3
Crustal instability	3	3	3	3	2	3	3	3	3	3	3	3	3	3
Capable faulting	1	1	1	3	1	3	1	1	2	3	3	3	3	3
In situ stresses	3	3	3	1	1	1	1	1	1	3	3	1	1	2
Volcanic activity	2	2	2	3	2	3	3	3	3	3	3	3	3	3
Mechanical														
Rock-mass strength	3	3	3	1	1	1	1	1	1	1	3	3	1	1
Deformation modulus	3	3	3	2	1	1	1	3	3	3	3	3	1	2
Discontinuities	3	3	3	2	1	1	1	2	2	2	1	1	1	1
Hydrological														
Groundwater regime	2	2	2	3	2	3	2	1	1	2	1	1	1	2
Miscellaneous														
Mass wasting	1	1	1	3	2	3	3	3	3	3	3	3	3	3
Avalanches	1	1	1	3	2	3	3	3	3	3	3	3	3	3
Karstification	1	1	2	3	1	3	3	3	3	3	1	1	2	3
Gas	1	1	2	3	3	3	3	3	3	3	3	3	3	3

1, Critical influence; 2, major influence; 3, minor influence.

tunnel cost model, as it provides a geological description that can be correlated with potential consequences for construction and a quantitative assessment of the risks in terms of time and cost associated with geological uncertainties. The set of seven construction-oriented geological parameters listed in Table 1.8 can be correlated with major consequences for construction. Further refinements to the model can be achieved by replacing or adding parameters.

Due to the complexity of geological conditions, it is necessary to organise the geological parameters and their associated probabilities of occurrence using a decision-tree and the segmentation of the geology along the tunnel (Figure 1.4). This technique allows parameter probabilities to be assessed individually, while accounting for the interdependence of parameters and their associated probabilities in a systematic way. The structuring procedure thus consists of two parts:

1. the structuring of parameters and their associated uncertainties, which is accomplished by the use of decision trees
2. the geometric structuring of combinations and associated uncertainties along a tunnel alignment, which is accomplished through segmentation.

The major limitation of using a geological model is the time required to construct the model, which is normally longer than the time required for the traditional approach. However, this limitation is outweighed by the more thorough assessment achieved of geological risks.

Once a model has been completed, the design process can proceed. Table 1.9 shows the ranking of geological and geotechnical factors that influence key tunnelling issues. Factors having a critical or major influence should be given due importance.

Undertaking an analysis of the ground using the major engineering rock-mass classification systems (Table 1.10) will further reduce the risks associated with tunnelling operations.

1.10.1 Ground-type categories used by some TBM manufacturers

Some manufacturers have a clear understanding of ground types based on their years of experience and expertise. For example, Herrenknecht AG (Schwanau, Germany) uses the following classification to distinguish between soft ground, heterogeneous ground and rocks.

- **Soft ground** – cohesive soils, such as clay, silt or loam with low water permeability and a relatively small range of grain sizes.

  Properties. A mixture of minerals and/or fractions of rock and/or organic material without mineral cohesion. The ground is usually unstable, and formed of cohesive loose soils with a high silt or clay content and a pulpy consistency.

  Tunnelling method. Typically earth-pressure support tunnelling (Herrenknecht's earth-pressure-balance (EPB) shield tunnelling method) is used.

Figure 1.4 Procedure for assessing, predicting and characterising the ground along a tunnel route (Einstein and Vick, 1974). (a) Geological cross-section: the tunnel route is divided into segments according to rock types. (b) The lithostratigraphic units within the tunnel route are identified. (c) Decision trees (usually one for each of the lithostratigraphic units identified in (b)) are used to assess the amount of risk associated with each of the segments identified in (a). RQD, rock-quality designation

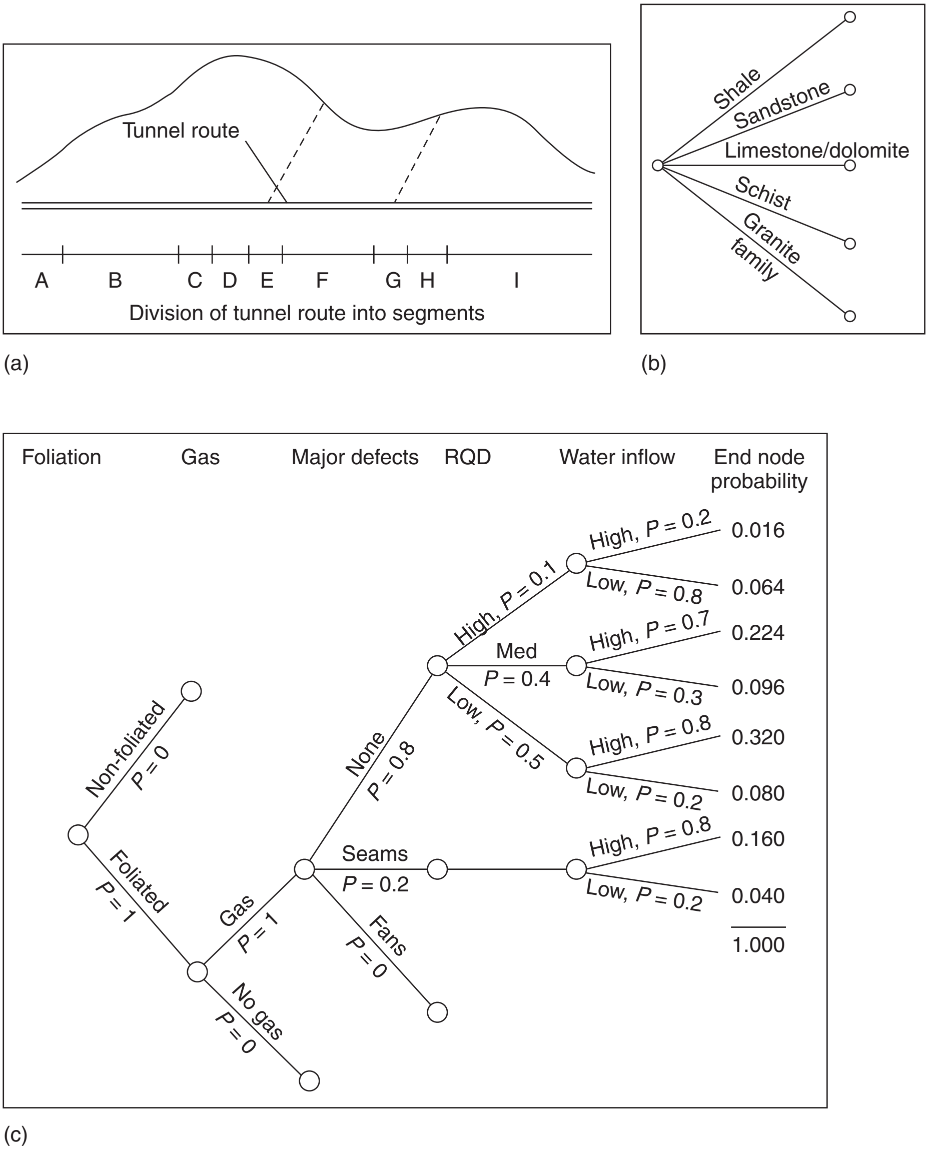


Table 1.10 Summary of major engineering rock-mass classification systems (Railing, 1983)

Classification system	Originator	Work done/remarks	Application
Rock loads	Terzaghi classified rocks into six groups	Stratified, intact, moderately jointed, blocky, crushed, squeezing and swelling rocks	Tunnelling with steel supports
Rock quality designation (RQD) index	Deere proposed a relationship for calculating the RQD	The RQD is calculated from cores recovered during drilling from a drill hole RQD (%) Classification 90–100 Excellent 75–90 Good 50–75 Fair 25–50 Poor <25 Very poor	Core logging, tunnelling
Rock structure rating (RSR) concept	Wickham *et al.* considered geological and construction parameters	Geological parameters: rock mass, joint pattern, dip and strike, discontinuities, faults, shears and folds, groundwater, rock material properties, weathering or alteration Construction parameters: direction of drive, size of tunnel, method of excavation	Tunnelling
Rock mass rating (RMR) concept	Bieniawski divided rock mass into six groups and applied ratings as shown in the next column (method modified by many others)	Parameters (range values): 1. uniaxial compressive strength (0–15) 2. rock quality designation (3–20) 3. spacing of discontinuities (5–20) 4. condition of discontinuities (0–30) 5. groundwater condition (0–15) 6. orientation of discontinuities (0–60)	Mining and tunnelling
Rock mass quality system	Barton *et al.* designated a rock-mass quality as shown in the next column	Rock mass quality, Q Behaviour of rock mass in tunnelling 1000 ← 400 Exceptionally good 400 ← 100 Extremely good 100 ← 40 Very good 40 ← 10 Good 10 ← 4 Fair 4 ← 1 Poor 1 ← 0.1 Very poor 0.1 ← 0.01 Extremely poor 0.01 ← 0.001 Exceptionally poor	Tunnels, chambers

- **Heterogeneous ground** – non-cohesive soils such as sand, gravel or stones with high water permeability, or mixed geologies of solid and loose rock.

  Properties. Alternate layers of loose soils and solid rock, or alternate layers and interlocking of cohesive and non-cohesive loose soils. Often in combination with geological deposits such as, for example, boulders when crossing beneath the body of water.

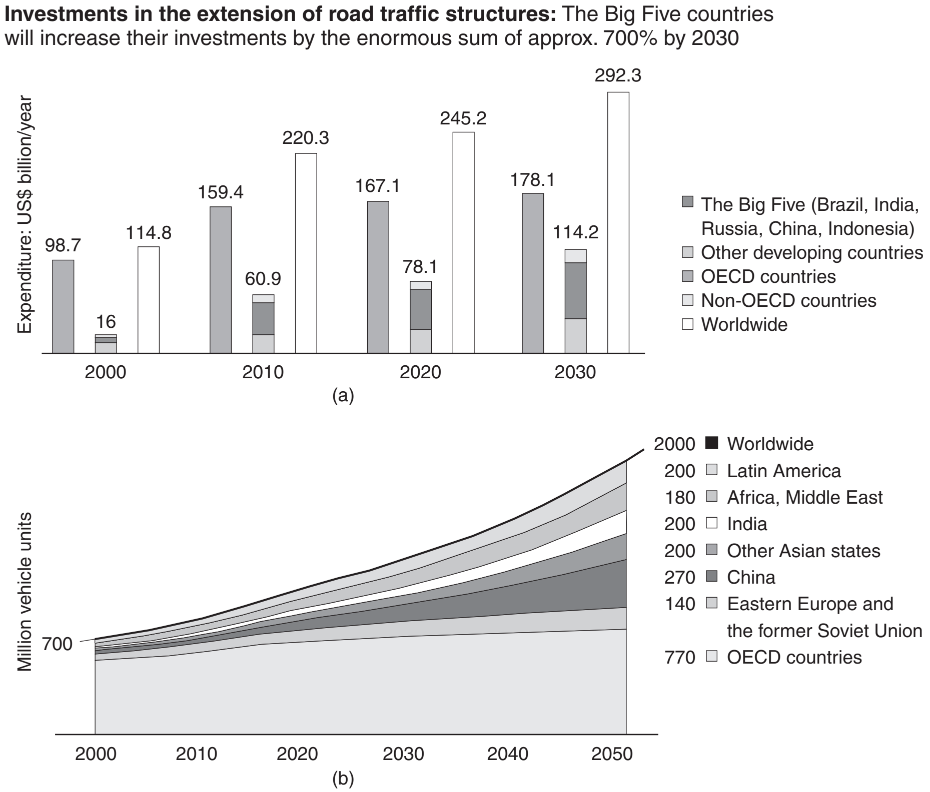
  Tunnelling method. Typically slurry-supported tunnelling methods are used.

- **Rock** – rocks such as sandstone, limestone, basalt or granite with high compressive strength in some parts. The main feature is that the components mostly come into contact or are jointed.

  Properties: A mixture of minerals and/or fractions of rock with mineral cohesion. The term 'rock' includes a wide variety of rock types ranging from soft formations to gneiss or granite which have rock strengths up to 400 MPa.

  Tunnelling method. Typically hard rock TBMs are used.

Figure 1.5 Trends in roads and road infrastructure construction: (a) investment in the extension of road traffic structures; (b) the number of passenger cars (courtesy of OECD and World Business Council for Sustainable Development)



Investments in the extension of road traffic structures: The Big Five countries will increase their investments by the enormous sum of approx. 700% by 2030

1.11. Role of tunnelling in infrastructure development – future projections

Today, tunnels can be driven at any location to meet the need for infrastructure developments such as railways, roads, metros, hydropower projects, pipeline networks and utilities (water and sewerage). The projected trends in infrastructure development for each of these areas are shown in Figures 1.5–1.10, respectively. It can be seen that tremendous growth is predicted in each area.

- *Roads* (see Figure 1.5). The Big Five countries are expected to increase their investment in the extension of road traffic structures by 700% by 2030 (OECD, 2007). Worldwide, the number of passenger cars is rising. This is particularly true in the Asian states, which will account for 35% of all cars driven by the year 2050. To improve traffic flows and increase people's mobility, new and efficient road links are essential. Today TBMs are customised and adapted to specific projects for almost all diameters (0.1–19 m) and ground conditions.
- *Railways* (see Figure 1.6). Goods and passenger transport are expected to almost double by 2035 compared with 2005 (OECD, 2007). New rail links are being built

Figure 1.6 Trends in infrastructure development in railway systems: (a) investment in the extension of railway traffic; (b) goods and passenger transport (courtesy of OECD 2007)

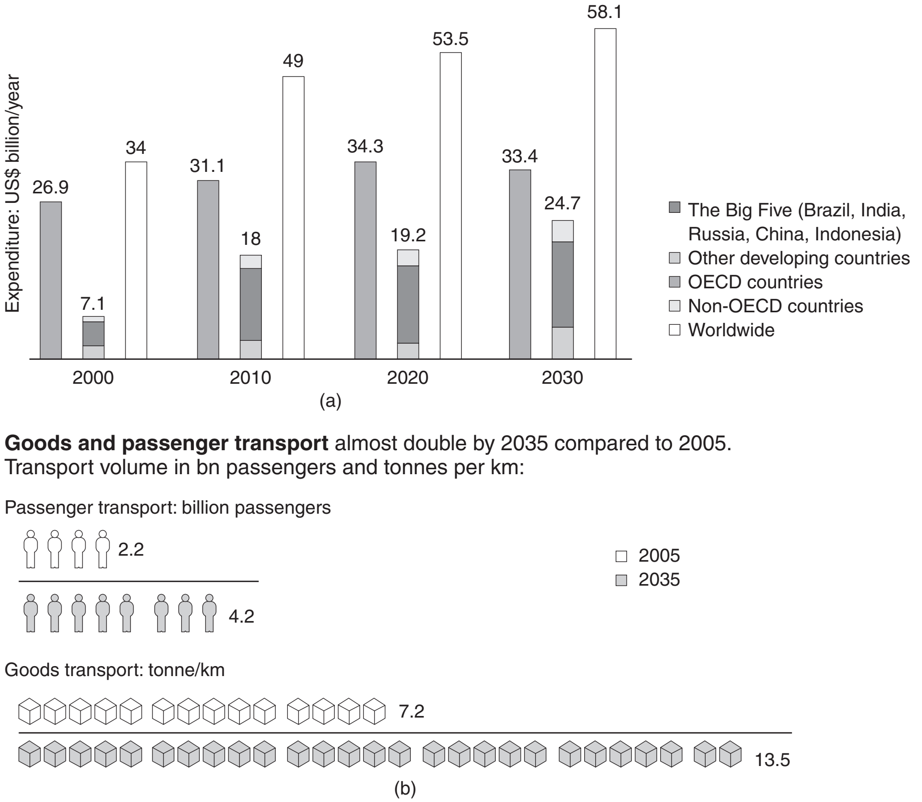
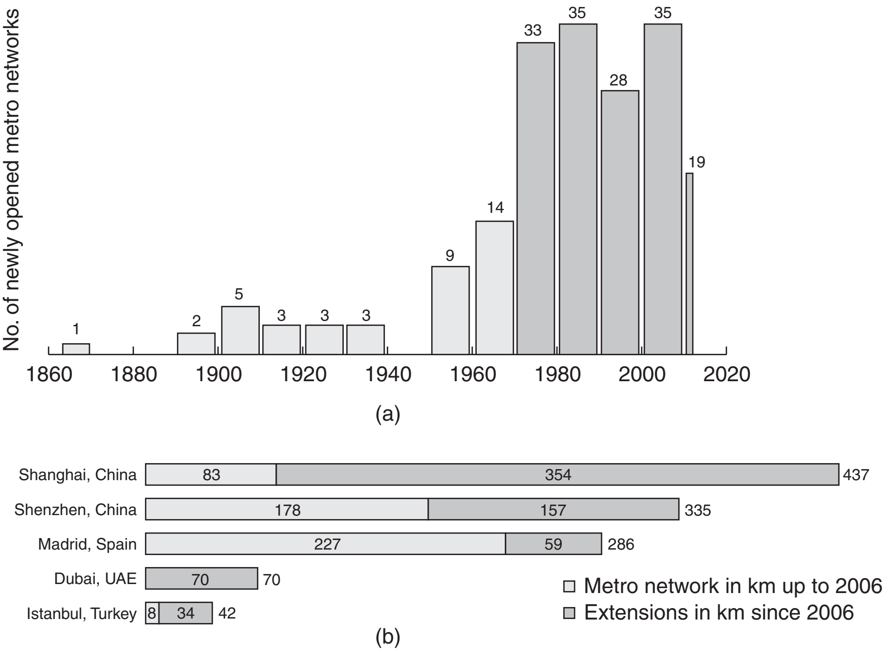


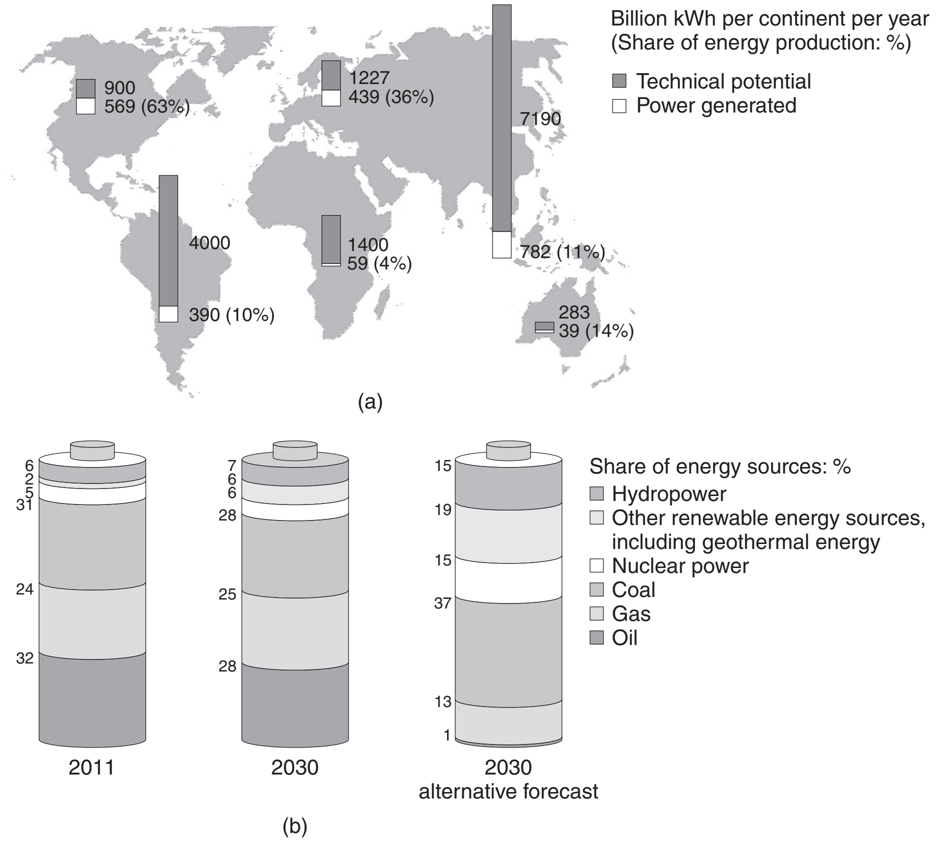
Figure 1.7 Trends in metro tunnelling: (a) number of newly opened metro networks worldwide; (b) selection of metro networks and their extensions since 2006 (courtesy of World Metro Data 2012)



to extend and connect national and international networks. Fast seamless journeys benefit both passengers and freight, and today's technology ensures fast, precise and safe rail links (e.g. transport interchange hubs such as airports, tram and bus terminals, metros and even car parking facilities can be reached easily and quickly). Mechanised tunnelling is extremely productive (0.5 man-hours/m^3) compared with current conventional tunnelling (2–4 man-hours/m^3) and the manual tunnelling methods of the 1800s (70 man-hours/m^3).

- *Metro networks* (see Figure 1.7). The scarcity of surface land is prompting cities to build new traffic routes underground. In order to increase personal mobility and economic growth, metro systems are being built and extended in cities around the world. For example, the optimisation of land use in the land-scarce country such as Singapore is vital, and it is planned to double the length of its metro line from the existing 178 km to 360 km by 2030. Due to varying geology of the island, the open-cut method, the new Austrian Tunnelling method (NATM) and TBMs have been used on this metro extension.
- *Hydropower projects* (see Figure 1.8). Hydro tunnelling and power generation from hydropower is increasing worldwide. With an installed capacity of 480 GW, the majority of hydropower plants are currently located in the OECD countries but in the future most plants will be located in Asian countries, such as India and China, and in Brazil and Africa.

Figure 1.8 Trends in Hydro tunnelling and power generation: (a) electricity generated from hydropower (www.energyieinfo.lu2013); (b) share of energy sources (BP Statistical Review of world energy, 2012; McKinsey, 2012)

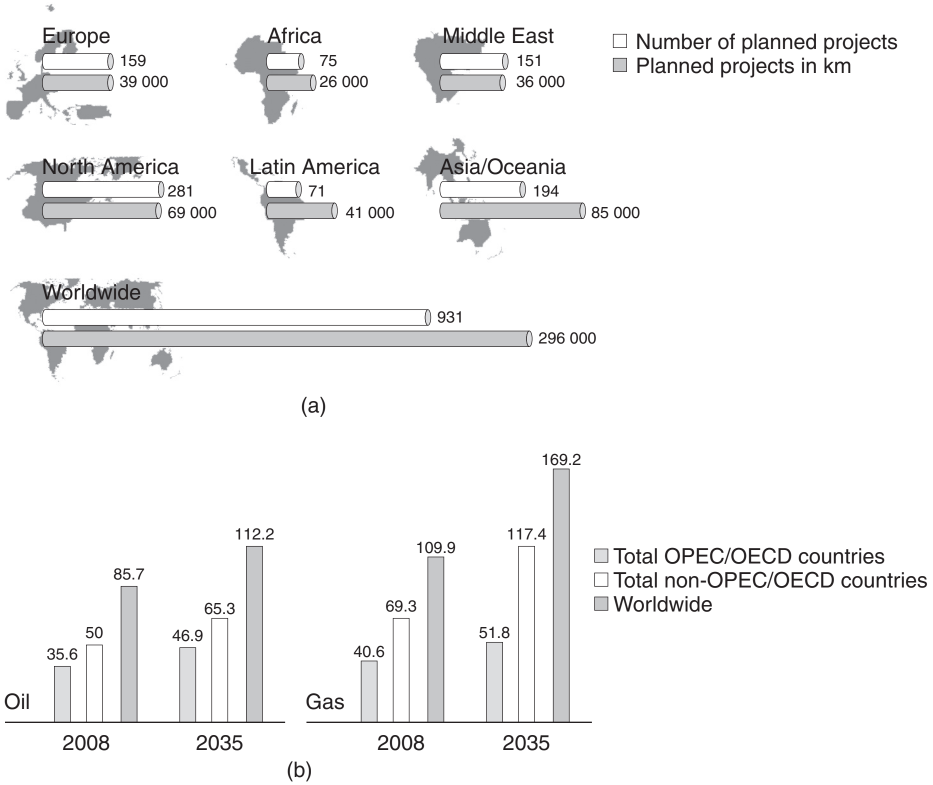


- *Pipeline networks* (see Figure 1.9). The use of HDD and AVN technologies is increasing in popularity day by day due to their utility for transporting gas and oil through pipelines. These technologies make it possible to carry gas and oil underground at faster speed economically.
- *Utilities and water infrastructure* (see Figure 1.10). For quality of life, environmental and economic reasons an urban area needs efficient infrastructure for water supply and disposal. Worldwide, the demand for water is growing, and investment in water and sewerage infrastructure will increase, especially in the BRIC countries (OECD, 2007). The trenchless technology has proven to be clean and quick for the installation of pipelines, cables and sewerage lines.

1.12. Concluding remarks

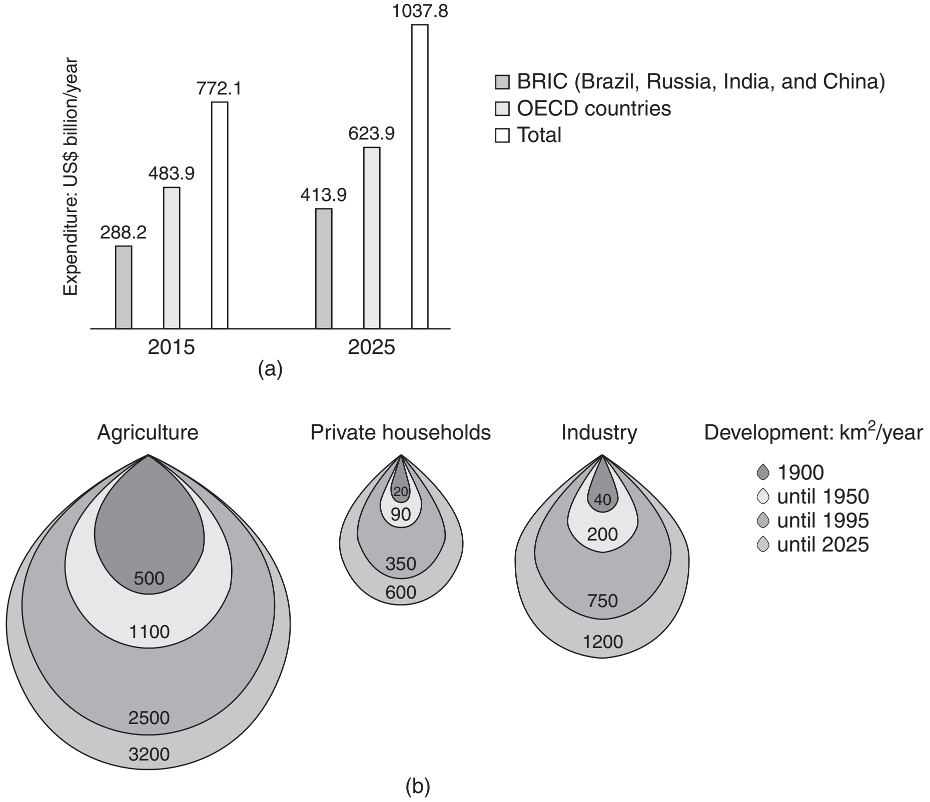
- Civil excavations are those excavations that are usually under the purview of civil and construction engineers in terms of their planning, design, execution and construction.

Figure 1.9 Trends in pipeline networks worldwide: (a) future pipeline projects by continent; (b) production quantities (Eia International Energy Outlook, 2011; Simdex Pipeline Projects Database, 2013))



- Civil excavations play an important role in the development of infrastructure in any country (see Figures 1.5–1.10). The creation of civil excavations is as old as civilisation itself. The increase in civil excavations around the world during the 19th and 20th centuries was made possible by advances in the techniques, methods and equipment required to accomplish them.
- Tunnels have almost unlimited life, and therefore the utmost precautions should be taken with regard to their siting (location), alignment, lining (support), ventilation, illumination, and emission of noise and vibrations to the local area, and the provision of cross-passages and emergency exits. Tunnels should not be located in earthquake-prone areas and should be protected against the inrush of water and gases.
- The first step in a site investigation is to gather as much as information and data as possible (see Table 1.2), and to study this thoroughly in order to achieve the optimum utilisation of resources and the maximum savings in time and project costs.

Figure 1.10 Trends in utilities and water infrastructure: (a) investment in water supply and sewerage infrastructure; (b) worldwide demand for water (courtesy of OECD)



- Proper sampling and sample analysis done by well-known and reputable laboratories is essential to ensure precise predictions and accurate site characterisation programmes for tunnelling projects.
- It is important to establish the microscopic features of rocks (Section 1.7) that are likely to be encountered as this helps in the selection of proper cutting tools such as drills and TBMs, which has a considerable bearing on the overall cost of the project.
- Recognising the type of ground, as detailed in Table 1.7, helps in decisions regarding the tunnelling method and type of ground support to be used.
- Undertaking an analysis of the geological and geotechnical factors (see Table 1.8) and the use of major engineering rock-mass classification systems (Table 1.9) could reduce the risks associated with the tunnelling operations during the construction phase of a project. The results of the analyses can be used to help in the planning of the tunnel size, shape, route and alignment, the selection of the site of tunnel portals, the design of supports, and the selection of the lining and tunnelling methods. In addition, predictions can be made about the amount and nature of water present and its disposal, the amount of muck to be handled and

disposed of, and the ground support (lining) and other services related to tunnelling that will be required. Ultimately the quality of the analysis will affect the tunnelling advance rate per unit time and thus the costs and duration of the tunnelling operations.

- Despite due care being taken during the investigations, some factors may not be properly investigated or may be underestimated, and could still become the basis of claims in a TBM project. Such factors, which can have a significant impact on TBM performance, include abnormal make-up of groundwater, excessive rock stresses (causing the TBM to get stuck), adverse ground conditions (particularly squeezing, running and swelling grounds) and abnormal geological features (such as joints, fractures, bedding/foliations etc.). Any of these will ultimately have an adverse impact on the costs and duration of the project.
- There have been a number of projects around the world that have been adversely impacted by inadequate and incorrect site investigations (see Section 10.3.1.2). The consequence has been disputes between owners and contractors, resulting in cost overruns, delays and abnormal incidents.
- A clear understanding between the geologist, planning engineer and field executors (often the contractor) is always beneficial to a project, as it optimises the use of resources and leads to timely completion of the project.
- Land is expensive and its use, both inside and outside cities, has to be evaluated carefully. The use of tunnels means lower environmental impacts, shorter routes and lower impacts of metrological events (snow, rain, etc.).
- Advances in mechanised tunnelling (see Chapters 5–8) and ground-movement management should enable the infrastructure to be built with minimal disturbance to residents in the area of construction.
- The greatest challenge in developing railway infrastructure is funding. Such developments require financial and political commitment, and the private sector is rarely interested in such projects.

1.13. Questions

1. ‘Site investigation is the foundation on which a future structure is built’. How far is this statement true?
2. What are the possible consequences of improper and inadequate site investigations?
3. What is an open-cut or surface opening? How does it differ from an underground or subsurface opening?
4. What is meant by ‘civil excavations’? Classify civil excavations on the basis of their locale.
5. Draw a line diagram to show the classification of civil excavations by their use and function.
6. List the various types of tunnel constructed for different purposes. What is the operational life of each type? List the parameters that must be adhered to for each type of tunnel during its construction.
7. What are the similarities between mining and excavation for civil and construction engineering projects? Mention the important distinction between the two types of technology.

8 Draw up a table of the unique features of civil constructions that must be adhered to.

9 What is meant by the terms ‘prospecting’ and ‘exploration’? How are they applicable to making detailed investigations of the ground prior to undertaking any civil construction project, including tunnels?

10 Geologists use a variety of tools and instruments to help them locate mineral resources. Make a list of these.

11 ‘Prospecting and exploration techniques are used to establish solid, liquid and gaseous regimes within the area of search’. Is this true?

12 Give a summary of the investigations that must be carried out when undertaking civil constructions, including tunnelling projects. You could do this in the form of a table.

13 Tabulate the factors governing the behaviour of rock. Summarise the inference you can draw from the table.

14 What is core drilling and why is it undertaken?

15 Illustrate the types of information that can be obtained from cores drilled from a borehole.

16 What is an NX size core? Is it common? What does it relate to in terms of the hole diameter and core diameter?

17 What is seismic imaging? What is tomography and what is its function? Could the interface between rock types be located using this technique? Illustrate the technique by way of a diagram.

18 What is the water injection test (the Lugeon test)? Describe it briefly, mentioning its limitations.

19 How much water loss per minute per metre of drill hole is represented by the unit 1 Lugeon (1 L)?

20 List the principal laboratory tests used for a TBM project, and note the significance of each test. What could be the impact if the test samples are not representative of the actual field conditions?

21 List the microscopic features of rocks and state their significance on the overall cost of tunnelling projects.

22 Describe rocks. What are the common rock-forming minerals? Define rocks according to the rock-mechanics concept.

23 Describe a mineral. List its physical characteristics.

24 There are six common rock-forming mineral assemblages that control the mechanical properties of most of the rocks encountered in engineering projects. List all six and give the distinguishing features of each one.

25 List the geophysical methods (surveys) used for the exploration of a site, and describe their limitations and usefulness in a tunnelling project.

26 Give the classification of the types of ground that can be encountered.

27 Tabulate the geological and geotechnical parameters that influence the cost and construction time (i.e. advance per unit time) of a tunnelling project.

28 Ground can be firm, ravelling, squeezing, running, flowing or swelling. Describe the behaviour of each type of ground and list the typical soil types associated with each one.

29 List the theories and relationships that have been proposed to identify a rock mass and characterise the ground.

30 What is meant by a ‘rock-mass classification system’? List the most important of these systems.

31 How is rock-mass classification helpful to designers and project planners? Does the classification help in cost reduction?

32 The major engineering rock-mass classification systems include the rock load, the rock-quality designation index, the rock structure rating concept, and the rock mass quality system. Describe each of these, noting the type of project where each finds its application or is commonly used.

33 List the seven construction-oriented geological parameters that can be correlated. Mention the major construction consequence of each of these parameters.

34 List the three phases of a construction project. Mention the specific issues that should be taken into account in each of the phases, and list the geological and geotechnical parameters that influence these issues. Draw up a table to illustrate the influence of these parameters on each specific issue by assigning each parameter a number (1 = critical influence, 2 = major influence and 3 = minor influence).

35 Figure 1.4 illustrates the procedure used to assess and characterise the ground along a tunnel route. How useful are these maps in assessing the amount of risk that will be encountered along the tunnel route? Does the use of these maps result in optimisation of the work plan for executing a tunnelling project?

36 What is geological model? Describe its merits and limitations.

37 List the site investigation tasks that should be completed before the onset of execution of a tunnelling project.

38 Name the laboratory test used to determine the following parameters: mechanical strength, surface hardness, abrasiveness and rock cutting.

39 Name (as per Herrenknecht) the type of ground and rocks suitable for EPB tunnelling, slurry-supported tunnelling and hard rock TBMs.

40 What are the projections drawn up by various agencies and sources with regard to the following infrastructure types up to the period 2030–2035: rail, roads, metros, hydro projects, pipeline networks and utilities?

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Chapter 2

Ground and rock fragmentation – drilling and blasting

Productivity and costs are often jeopardised when drilling and blasting operations are not properly matched. The proper selection of an explosive (an important element of the blasting operation) and its judicious use is the best way to cut costs, preserve ground stability and minimise environmental damage.

2.1. Introduction

The term 'fragmentation', when used in association with 'ground' or 'rocks', means breaking them into pieces, which can vary in size, shape and weight. Large-sized fragments are known as 'boulders'. Fragmentation can be accomplished with or without the use of explosives. When it is accomplished using explosives (except during plaster shooting, see Section 2.11), drilling is almost always necessary. This drilling is usually referred to as 'production drilling' and should not be confused with exploration drilling (see Chapter 1) and drilling carried out for installing services (e.g. drilling holes for ventilation ducts, water pipes, and compressed air and power lines). The drills used to drill into ground or rock are known as rock drills. When the holes created using these drills are charged with explosives they are known as shot holes (usually up to 40 mm in diameter) and blast holes (exceeding 40 mm in diameter). When these holes are blasted, the rock surrounding them is fragmented. Fragmentation without the aid of explosives requires the use of techniques such as ripping, cutting, crushing, boring, impact hammering, etc. This chapter describes the methods, techniques and equipment available to accomplish fragmentation using explosives. It also covers explosives and blasting techniques.

2.2. Drilling

It was the invention of explosives that brought drilling technology to the fore (Atlas Copco, 2017a). Until the early 1950s, methods of drilling were manual, primitive and arduous. The 1950s saw the introduction of Swedish drilling technology in the form of pneumatic pusher-leg drills, also known as jackleg drills, and within the next 20 years drill rigs fitted with heavy-duty drifters came into operation. This was really the beginning of mechanised drilling in the true sense. During the 1970s, the use of hydraulic power was introduced, resulting in the first generation of mechanised drilling equipment, and in the 1980s fast, heavy-duty, remote-controlled, automatic drill jumbos came onto the market. Today, drilling operations are fully automated, and a variety of drills and drilling accessories are available that can cope with the current requirements of the civil, construction and mining industries. The production drilling of holes up to 300 mm in diameter and 150 m in length is not uncommon, and drilling can be accomplished in any direction.

2.2.1 Drilling system

Basically, a drilling system involves four components (Atlas Copco, 2017a; Hartman, 1987). A prime mover converts electric, pneumatic or fluid (hydraulic) energy into mechanical energy. This energy is transferred to the rock or ground through the drill string, which consists of drill rods or pipes and bit. The bit penetrates the rock or ground and generates drill cuttings or chips. These chips are sent to the surface (out of the hole) by a flushing medium, which can be air, water or, sometimes, mud. Figure 2.1 illustrates the mechanics of drilling.

2.2.2 Rock drills – classification

Since the 1950s different mechanisms have been devised to transfer the mechanical energy produced by the prime mover to the rock or ground being drilled. These mechanisms are known as *top-hammer*, *down-the-hole (DTH) or in-the-hole (ITH)* and *rotary*. Each mechanism has its merits, limitations and field of applications (Figures 2.2–2.5) (Atlas Copco, 2017a; Hartwig and Nord, 1998; Jimeno *et al.*, 1997; Kurt, 1982).

Top-hammer drills work on the top of the drill string. The impact energy of the drill's piston is transmitted to the drill bit in the form of shock waves. This method is faster in good rock conditions. In DTH systems the drill is situated down the hole in direct contact with the drill bit, and because of this power losses are minimal. In both systems the closeness of the hammer to the drill bit gives stable guidance and minimal deviation. For deep and straight holes, it is a very simple method of operation.

Rotary crushing is a drilling method that was used originally for drilling oil wells but it is now used for rocks having a compressive strength of up to 5000 bar. In rotary drilling energy is transmitted via the drill rod, which rotates at the same time as the drill bit is forced down by the high feed force. All rotary drilling requires a high feed pressure and slow rotation. The relationship between these two parameters varies with the type of rock. In soft rock formations, low pressure and a higher rotation rate, and vice versa, are the principles usually followed.

Figure 2.1 Drilling mechanism – components and their functions

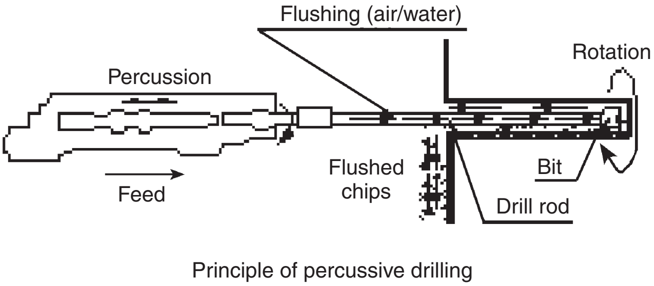
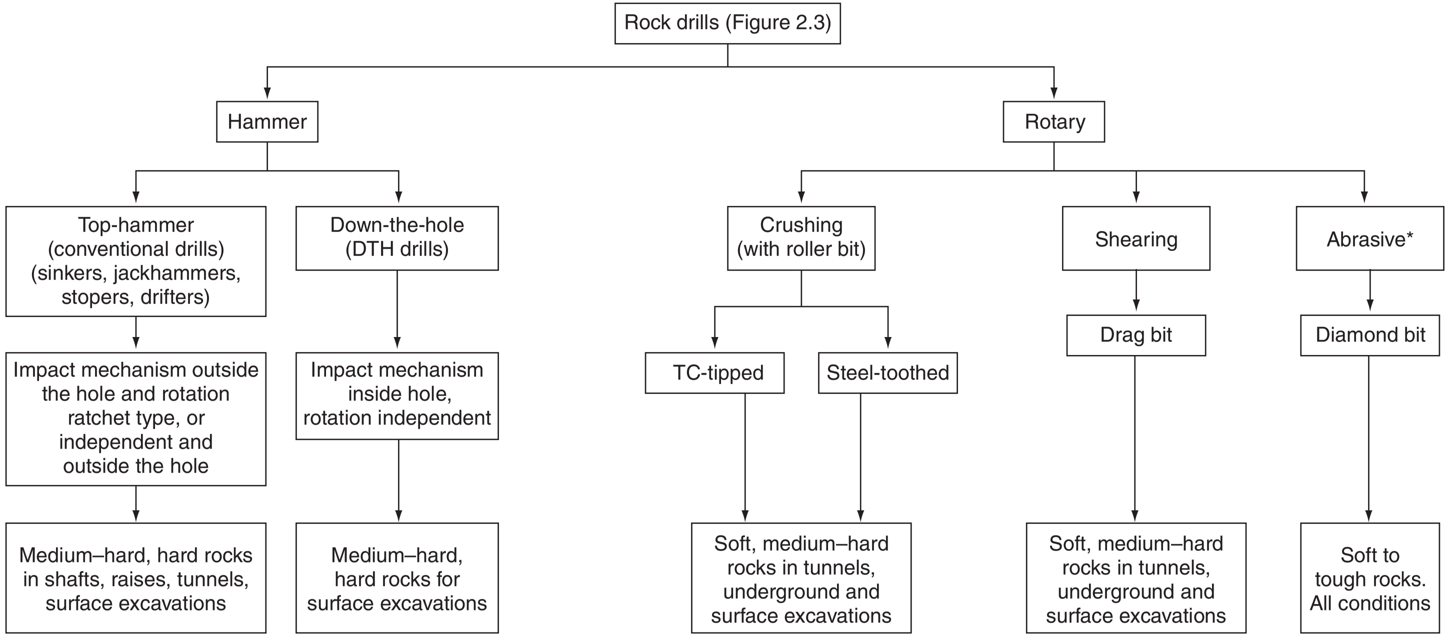
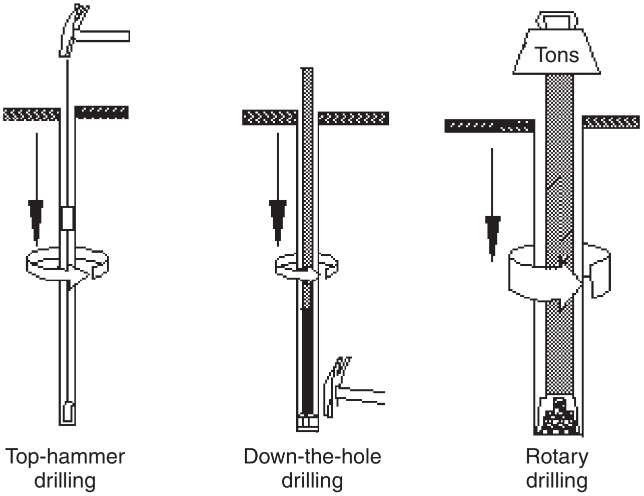


Figure 2.2 Rock-drill classification according to the mechanism of transfer of mechanical energy to the rock



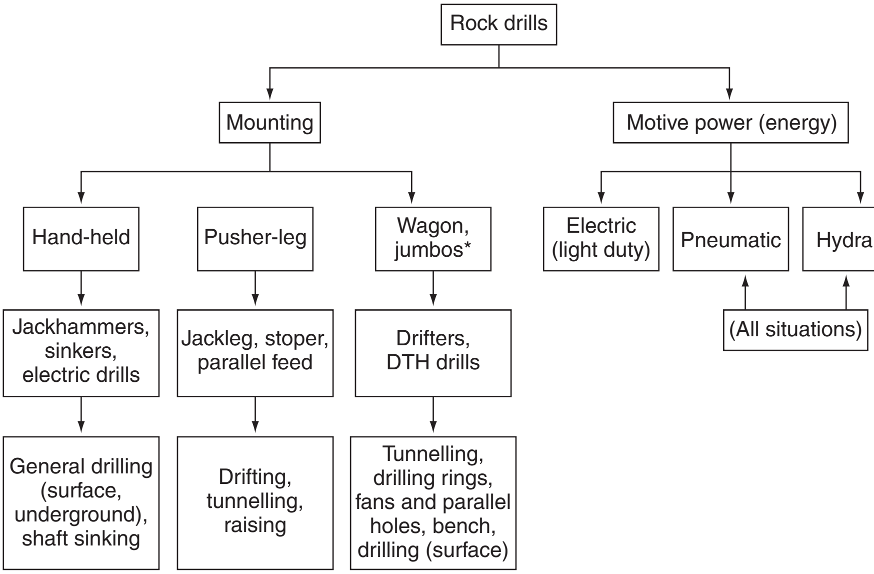
* Application mainly during exploration drilling
TC – Tungsten carbide bit

Figure 2.3 Drilling principles (courtesy of Atlas Copco)



When drilling is done by rotary crushing the energy is transmitted to the drill via a pipe which is rotated and presses the bit against the rock (Figure 2.6). The cemented carbide buttons press into the rock and break off chips (the same principle as in percussive drilling).

Figure 2.4 Rock-drill classification based on their mountings and energy source



* When drifters are fitted to boom(s), which can be one or even up to five or more, and these booms are mounted on a carrier; then they are known as *jumbos*

Figure 2.5 Historical review of rock-drilling technology. (a) Rock drills: jackleg to fully automatic multi-boom hydraulic jumbos. (b) Sinkers: DTH, rotary and top-hammer drills. (c) Sinker/jackhammer. (d) Jackleg drill. (e) Stoper, for drilling in an upward direction (courtesy of Atlas Copco)

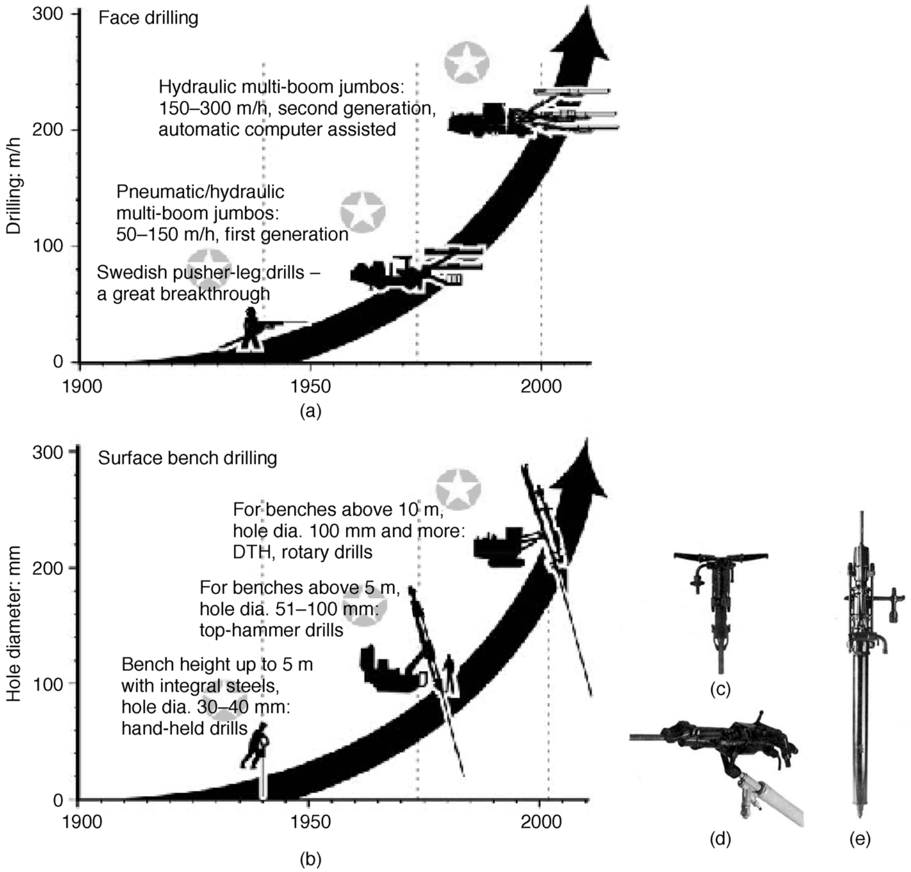
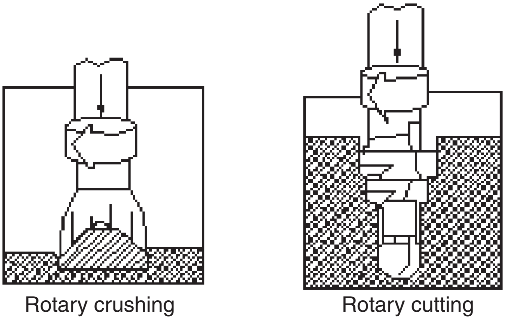


Figure 2.6 Rotary crushing and cutting (courtesy of Atlas Copco and Sandvik-Tamrock)



When drilling is done by rotary cutting the energy is transmitted to the insert via a drill tube which is rotated and presses the insert against the rock. The edge of the insert then generates a pressure on the rock and cracks off chips (see Figure 2.6). The rotary system can be used in all types of ground, including difficult ones, leading to high productivity and good penetration rates.

If drills are compared based on their motive power (see Figure 2.4), hydraulic drills are better than pneumatic drills in several respects:

- they are efficient (the efficiency of pneumatic drills depends on the generation and transmission of compressed air, which is more labour intensive)
- they have a 50% higher drilling capacity
- they are reliable, constantly
- they are flexible in terms of changing rock and drilling conditions
- they are better ergonomically, generating less noise, moisture and mist and do not produce surrounding temperature fluctuations (pneumatic drills suffer from all these features)
- they are more economical than pneumatic drills (which are therefore often replaced by the hydraulic drills).

Refer to Section 4.11 and Figure 4.17(b) which describes a modern drilling rig for tunnels, drives and caverns.

2.2.3 Drilling accessories

The function of drilling accessories and their specific location in the drill string is illustrated in Figure 2.1. Brief descriptions of each of these items are given below (Jimeno *et al.*, 1997; Matti, 1999).

2.2.3.1 Drill rods and pipes

Basically, these are of two types: integral drill steels and extension rods. In the first category the bit is an integral part of the drill steel. These steels are almost always necessary for drilling holes up to 3 m. For longer holes, particularly those exceeding 5 m, extension drill steels are essential. These steels are available in the size range 1–1.5 m. Extension drill steel is made up of an assembly consisting of a shank adaptor, coupling sleeve, extension rod and drill bit.

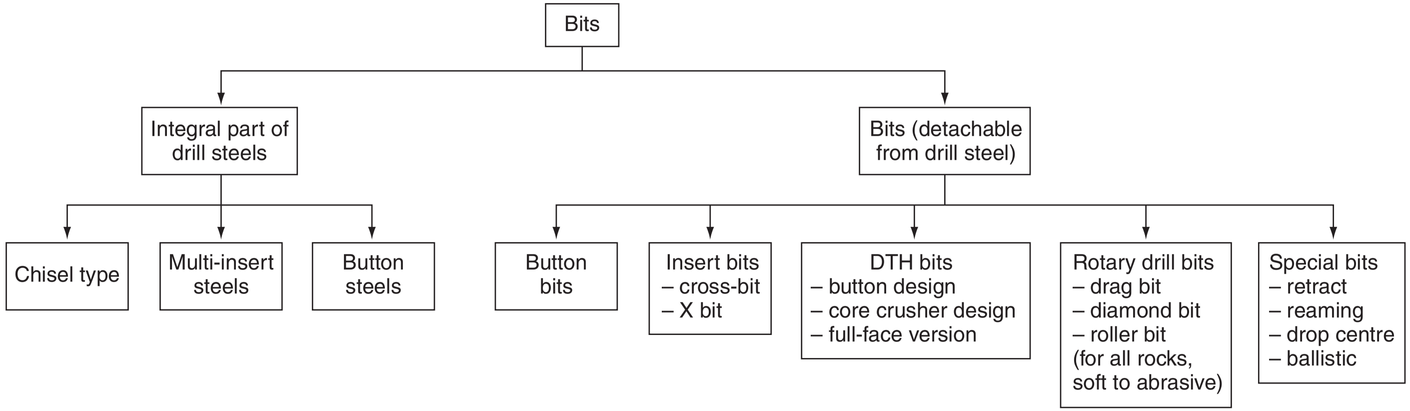
2.2.3.2 Bits

Figure 2.7 classifies drill bits of different kinds. Insert bits and button bits are used with rotary percussive drills (top-hammer and DTH drills). Insert bits come in two designs:

- Cross-bit – consisting of four tungsten carbide inserts at 90° to each other
- X bit – consisting of four inserts at angles of 75° and 105° to each other.

Bits are available in sizes from 35 mm diameter; the most common sizes are 57 mm cross-bits and 64 mm X bits, which are used in long-hole (blast-hole) drilling. DTH bits are special in that they incorporate a shank upon which the drill's piston strikes directly.

Figure 2.7 Classification of drill bits



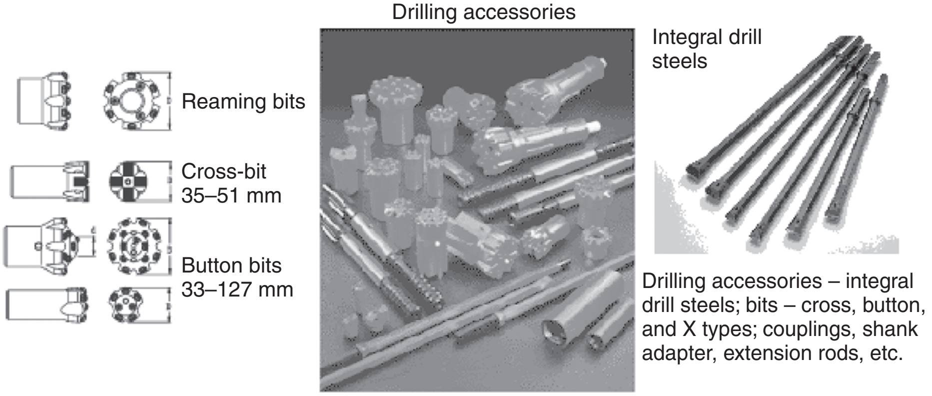
Retract – where formations' walls tend to collapse; useful in avoiding jamming and loss of drill rods.
Reaming – to enlarge cut-holes during a parallel hole round drilling.
Drop centre – excellent flushing characteristics; useful in rocks.
Ballistic – bullet-shaped buttons longer than standard to give higher penetration rates and excellent flushing; useful in soft rocks.

Table 2.1 Service life of drilling accessories during surface and underground operations (courtesy of Atlas Copco)

Accessory type	Civil works – bench blasting (rock types)		Tunnelling, drifting and underground operations (rock types)	
	Abrasive (length: m)	Slightly abrasive (length: m)	Abrasive (length: m)	Slightly abrasive (length: m)
Integral drill steels				
Regrinding interval	20–25	150	20–25	150
Service life	150–200	600–800	200–300	700–800
Threaded insert bits				
Regrinding interval	20–25	150	20–25	150
Service life	200–400	800–1200	250–350	900–1200
Threaded button bits – diameter ≥64 mm				
Regrinding interval	60–100	300	250–550	1000–3000
Service life	400–1000	1200–2500	(service life)	(service life)
Threaded button bits – diameter <57 mm				
Regrinding interval	100–150	300		
Service life	300–600	900–1300		
DTH button bits				
Regrinding interval	40–60	300		
Service life	400–1000	1200–2500		
Extension rods				
Service life	600–1800			
– Pneumatic drills			1000–1500	
– Hydraulic drills			1600–2400	
Threaded integral steels				
Service life			600–800	
Coupling sleeves				
Service life	100% of rod service life		100% of rod service life	
Shank adaptors				
Service life				
– Pneumatic rock drills	1500–2000		1200–1600	
– Hydraulic rock drills	3000–4000		2500–3500	

They are available in sizes of 85–250 mm diameter and above. Button bits are the most commonly used type of bit as they can be used for any type of rock. Insert and button bits are manufactured for normal as well as heavy-duty use, and thus can be used for a range of rock masses. The function and uses of special types of bits are described in Figure 2.7 and Table 2.1.

Figure 2.8 Drilling accessories (courtesy of Atlas Copco and Sandvik-Tamrock)



Drilling accessories – integral drill steels; bits – cross, button, and X types; couplings, shank adapter, extension rods, etc.

Rolling cone bits or roller bits are suitable for rotary drilling. They are available in different designs to suit soft to very hard formations and rocks. Rotary drilling with cutting action can be achieved using drag bits of different designs. Diamond bits are suitable for exploration drilling but they can also be used for soft rock formations such as coal, potash, salt and gypsum (Jimeno *et al.*, 1997).

Drill rods and bits are valuable accessories (Figure 2.8); if they are not used properly, the drilling cost can be abnormally high. Regular checks, regrinding, proper lubrication, systematic stacking and protection against dust and corrosion (within practical limits), handling with care and use of proper tools and appliances are some of the salient points that should be adhered to in order to obtain best results. Proper training and refresher courses on this subject area given to the drilling crews, grinding-men and supervisors can pay dividends in this regard.

2.2.4 Impact of rock-type on drilling performance

It is important to know and understand the rock properties listed below in order to effectively utilise the various rock drills and their accessories (Atlas Copco, 2017a; Jimeno *et al.*, 1997). These parameters are related to rock types:

- Abrasiveness – the ability of rock fragments to wear away the drill bit. Rock composed essentially of quartz is very abrasive. Some rocks that have a high quartz content are diorite (10–20%), gneiss (15–50%), granite (20–35%), greywacke (10–25%), mica-schist (15–35%), pegmatite (15–30%), phyllite (10–50%), quartzite (60–100%), sandstone (25–90%), slate (10–35%) and shale (0–20%).
- Hardness – the resistance to penetration by a pointed tool.
- Rock texture – angular grains are more abrasive than round ones. The lenticular shape of grains, as in schists, poses more difficulty during drilling than do round shapes such as in sandstone.

Table 2.2 Equipment used for sinking, raising, drifting, tunnelling and excavations in the civil and construction industries

Equipment	Technical details	Field of application/use
1. Jackhammer, or sinker	Available for very light to heavy duties. Weighing from less than 18 kg to over 30 kg. Capable of drilling holes 19–44 mm in diameter and up to 3.7 m in length	For general use and shaft sinking in civil and construction projects
2. Jackleg (jackhammer with pusher-leg)	More powerful than category 1. Available with cylinder bores of 60–83 mm. Capable of drilling holes 32–44 mm in diameter and up to 3.7 m in length	Small-sized drifting and tunnelling projects
3. Stoper	Available for very light to heavy duties. Weighing from 34 kg to over 45 kg. Capable of drilling holes 32–44 mm in diameter and up to 3.7 m in length	Upward holes – vertical/inclined for raising operations
4. Drifter	More powerful than category 1. Available with cylinder bores of 83–114 mm and above. Capable of drilling holes 38–127 mm in diameter and up to 30 m, or even more, in length	Small to large-sized drifting and tunnelling projects. Can drill holes in any direction (0–360°)
5. Tunnelling and drifting jumbos Jumbos for sinking operations fitted with ‘sinkers’ are also available	Drill jumbos with single or multiple booms are available. They may have rubber tyres or tracks, or may be crawler-mounted. Pneumatic as well as hydraulic jumbos are available. A multi- boom toppers jumbo could also be fitted with rock-bolting booms and stopers	Tunnelling and drifting jumbos with narrow to wide dimensions are available to suit specific needs. See also Section 4.11.1. Sinking jumbos are used for mechanised drilling in shafts

6. Rotary percussive drills	Light to heavy duty top-hammer or DTH drills mounted on a rig. Capable of drilling holes in the diameter range 76–216 mm and of depths up to 25 m, and more	Civil and construction projects: bench drilling, tieback anchoring, grouting, well drilling
7. Chipping hammers/pneumatic breakers	These are handy as they barely exceed 11 kg in weight. Tools include moil point, narrow chisel, wide chisel, wedge, digging blade, asphalt cutter, axe, spade, tampering stem, shank rod, roughing head, etc.	Suitable for tough material such as frozen ground, asphalt, concrete, coal, clay, non-consolidated rocks and a few others. Can also be used for light digging jobs. They are the most suitable demolition tools
8. Rig-mounted hydraulic breakers (these are attached to the different excavators and carriers)	Suitable for the tasks that cannot be done by pneumatic breakers and chipping hammers (see 7 above)	Efficient tools for many surface and subsurface (underground) operations. Tasks include demolition, scaling, breaking soft rocks at roads and bridges, in the process industry and splitting boulders
9. Motor drills and breakers	Units are fitted with a driving motor and mechanisms for drilling and allied tasks	Civil and construction projects. During repair and maintenance of dams, bridges, roads, railway tracks. For digging hard and frozen ground, tamping of backfills and splitting exposed rocks. Making holes for putting in signposts, pipes, and earth rods and earth anchors of different lengths and diameters

- Toughness – the resistance of the mass to the separation of the pieces from it. In other words, the capacity of the mass to undergo considerable plastic deformation up to the moment of breaking.
- Elasticity or resilience – the resistance to impact that can be seen when a tool rebounds.
- Brittle rock (shale, limestone, sandstone, coal, etc.) is fairly hard but comparatively easily crushed, and pieces separate from the mass along numerous cracks.
- Strong rock (strong sandstone, granite, magnetite, etc.) has high resistance to penetration by a tool and to separation of a piece from the mass.
- Very strong rock (quartzite, diabase and porphyry) has the highest resistance to penetration by a tool and to separation of a piece from the mass.
- Rocks that are more porous have low crushing strength and are easier to drill.
- Poly-mineral rocks such as granite, due to their heterogeneity, are more abrasive.

2.2.5 Summary – applications of rocks drills

A brief description of the equipment used for sinking, raising, drifting, tunnelling and excavations in the civil and construction industries is given in Table 2.2.

2.2.6 Modern tools

Modern drilling equipment may be equipped with laser measurement systems, global positioning systems (GPS) and communication technology, and be connected to computers for control and monitoring of operations. Deviation is a common occurrence during drilling operations for tunnels and mines, and computerised control provides the ideal combination of feed, rotation and penetration rates to avoid this problem. The developments that have taken place in the last decade in the drilling technology for tunnels and caverns are detailed in Section 4.11.1.

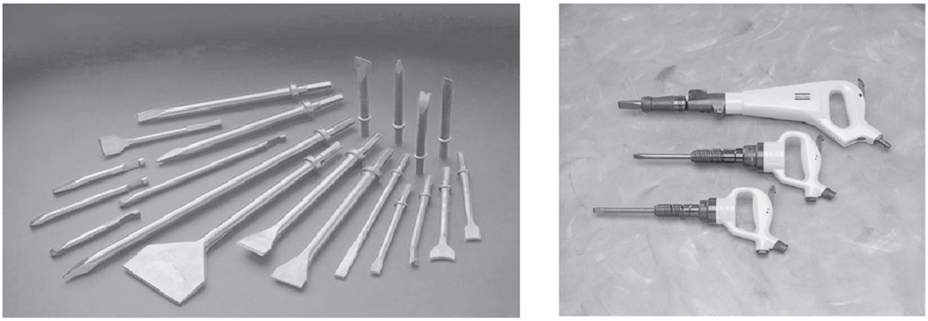
2.3. Chipping hammers/pneumatic breakers

2.3.1 Light and heavy-duty chipping hammers

Light and heavy-duty chipping hammers (Figure 2.9(b)) are essential tools in the construction industry. These pneumatic hammers and breakers are suitable for tough material such as frozen ground, asphalt, concrete, coal, clay, non-consolidated rocks and a few others (Atlas Copco, 2017a). They are the most suited tools for demolition and can also be used for light digging jobs. They are available with different design features to suit different types of jobs such as drilling, channelling, trimming, demolishing, cleaning, casting, digging, tamping and breaking frozen ground, asphalt, non-consolidated ground, hard clays and soft rocks such as coal.

Chipping hammers are useful as their weight rarely exceeds 11 kg. A silencer is attached for noise damping, and a range of tools is available that can be attached to accomplish a particular job. Such tools include (Figure 2.9(a)), among others, a moil point, narrow chisel, wide chisel, wedge, digging blade, asphalt cutter, axe, spade, tampering stem, shank rod and roughing head. Atlas Copco manufactures pneumatic hammers as their TEX series (Figure 2.9(d)) (Atlas Copco, 2017a). The hammers are run by compressed air fed from a portable compressor.

Figure 2.9 Common chipping hammers and breakers used in construction projects (courtesy of Atlas Copco)



(a) Chisels for chipping hammers

(b) Chipping hammers

(c) Motor drill breaker (silenced)

(d) Pneumatic breaker/chipping hammer

2.3.2 Rig-mounted hydraulic breakers

Rig-mounted hydraulic breakers are efficient tools for many surface and subsurface (underground) operations (see Chapter 5) (Atlas Copco, 2017a; Matti, 1999). They are suitable for the tasks that cannot be done using pneumatic breakers and chipping hammers, and in cases where the task is heavy, dangerous, awkward and difficult to access. A hydraulic breaker can be attached to an excavator, thereby extending the field of applications in which an excavator unit can be used. The following tasks can be accomplished using a rig-mounted hydraulic breaker:

- Demolition – concrete demolition in a built up area.
- Trenching – it has been advocated that trenching using a hydraulic breaker is cheaper than drilling and blasting. Use of a hydraulic breaker is advantageous where blasting is not allowed, and it does not require any stoppage of work.
- Scaling – scaling a bench, or even scaling at underground sites. Scaling is usually done with a breaker mounted on a special carrier, with a boom that can be rotated through 360°.
- Breaking soft rocks for roads and bridges – during road-cutting and making building foundations, and during service and repair work on public roads, dams and bridges.

- In the process industry – different tools are attached to the breaker to accomplish cleaning, removing scaled material and other jobs. The breaker, being slim, can fit into the ladle.
- Splitting boulders – quarrying, surface mining, road and rail route projects.

Rig-mounted hydraulic breakers are attached to different excavators and carriers; the latter should be strong and stable enough to take the breaker. In practice, based on the type of work undertaken, the breakers are attached to mini excavators, skid-steer loaders, backhoe excavators, and wheeled and tracked excavators.

2.3.3 Hand-held rock drills

These pneumatic drills are used for light bench drilling, secondary rock breaking, plug drilling and drilling for smooth blasting. They are very handy and require practically no set-up time. Drills of this type are suitable for drilling holes of 34–40 mm diameter. Hole lengths in the range 1–6 m in soft rocks and 1–3 m in hard and tough rocks (such as granite) can be achieved.

2.3.4 Motor drills and breakers

As the name suggests, these units are fitted with a driving motor and mechanisms (see Figure 2.9(c)). They are effective alternatives to heavy equipment, where job size and limited access are the main constraints. They do not require power packs or compressors that have to be hauled around. Motor drills and breakers are most suitable for undertaking jobs such as

- short-length drill holes for blasting – a drilling rate of about 0.3 m/min (1 ft/min) can be achieved
- digging hard and frozen ground
- tamping of backfills, or reinstatement work in limited-access locations
- splitting exposed rocks
- signposting – holes for putting in signposts, pipes, earth rods and earth anchors of different lengths and diameters
- pothole patching and repair work
- tie tamping, repair and maintenance of switches, turnouts, crossings, etc., at railway tracks and sites.

Atlas Copco manufactures motor drills and breakers as their FB, Pionjär and Cobra series, and silenced hammers as their Tamrock AS20 series (see Figure 2.9(c)). Similar machines such as cutter-crushers and concrete pulverisers are used when other methods fail or cannot be employed due to safety or economic reasons.

Atlas Copco's petrol-driven Cobra Combi is ideal for smaller jobs (Atlas Copco, 2017b). It is not only a self-contained breaker, it is a powerful drill as well. It can sink holes to the depth of 2 m and drill up to 30 cm/min in solid granite. With a wide range of different tools, it can be used for everything, from cutting and breaking to drilling, driving and compacting. It meets US emission regulations EPA 1 and fulfils the European emission directive (NED). Its petrol-driven Pionjär 120 is a combined drill and breaker that can be used for a range of tasks, including drilling, rock splitting, concrete breaking, asphalt cutting and tie tamping.

2.4. Explosives

2.4.1 Introduction – historical review and applications

'Black powder' (gunpowder) was invented in China in the 11th century, since when it has found wide application during times of both war and peace. During wartime it is the leading material that causes mass destruction due to its use in the manufacture of ammunition, including bombs. In warfare black powder is used in weapons to destroy target areas in enemy territory, and it has also become a weapon used by terrorists to damage people and property.

In times of peace and prosperity the use of black powder is extensive, and we cannot do without this important commodity. The discovery of black powder was a major breakthrough in mining, tunnelling and excavation operations. Minerals are essential materials, and the majority of comes from mines, where explosives are used to fragment ores (that portion of a mineral deposit which is of use and can be mined profitably). Explosives are also used in the making of tunnels and on construction sites, where in most cases they are the cheapest option for fragmenting rocks and ground. Commercial/industrial explosives are also used in seismic prospecting, stimulating and perforating oil and gas wells, bonding dissimilar metals and synthesising industrial diamonds (Baker Hughes, 2017).

Explosives are also used in fighting particular types of fire, such as those involving oil fields, forests or entire cities. An explosion can serve as the mechanism by which a firebreak is created, which can aid in preventing the spread of a fire.

2.4.2 Explosives' ingredients

An explosive is a chemical substance or a mixture of chemical substances (Table 2.3) that on the application of a suitable stimulus (fire, heat, friction, a jolt, a shock, an impact, a current or pressure, or their combination) releases an enormous volume of gases and heat, which cause disturbance to the surrounding media, which could be solid, liquid or gas, or their combination (Dick *et al.*, 1983; Ganpathy, 1978; Gregory, 1979; Jimeno *et al.*, 1997).

These gases are generally simple substances such as carbon monoxide, carbon dioxide, nitrogen (or oxides of nitrogen), steam and oxygen. The simultaneous release of heat causes the gases to expand so rapidly that they exert an exceedingly high pressure on the surrounding medium. Nitroglycerine, for example, explodes to form a mixture of steam, nitrogen, carbon dioxide and oxygen:

$$4C_3H_5N_3O_9 \rightarrow 12CO_2 + 10H_2O + 6N_2 + O_2$$

When nitroglycerine detonates it generates a volume of gas that is about 10 000 times the original volume and raises the surrounding temperature to around 5000°F (3000°C). The increase in pressure derived from the expansion of the gases causes an *explosion*. Hence, the name given to all such substances is *explosives*. Strictly speaking, an explosive is a

Table 2.3 Constituents of explosives and blasting agents

Explosive/blasting agent	Ingredients		
	Oxidiser (size of oxidisers)	Fuel	Sensitiser
Nitroglycerine (NG) based (dynamites)	Solid nitrate salts (0.2 mm)	Solid metal absorbents	Liquid NG, voids/bubbles, friction
Ammonium nitrate–fuel oil mixture (ANFO)	Solid nitrate salts (2 mm)	Liquid diesel oil	Voids/friction
Slurry	Solid/liquid salt solutions, nitrate salts (0.2 mm)	Solid/liquid, aluminium, carbonaceous	Fine aluminium, bubbles
Emulsion	Liquid salt solutions (0.001 mm)	Liquid oils, waxes	Bubbles

substance that propagates an expansion of gases at velocities that exceed the speed of sound (i.e. it generates detonation waves).

When explosives are placed in a hole and detonated the results are

- rock fragmentation
- rock throw (displacement)
- the generation of shock waves (vibrations) in the surrounding media
- an air blast that is heard as a loud bang.

2.4.3 Classification

Explosives that generate detonation waves are known as *high explosives*. In some explosives the rate of release of energy is rapid but below the speed of sound. This is known as *deflagration*, and these substances are known as *low explosives*.

Low explosives, as used by the Chinese in the 11th century, are the earliest known explosives. They consist of a mechanical mixture of ingredients such as charcoal, sulphur and potassium nitrate. Commercially, they are known as gunpowder or black powder. Fireworks are in this category. Black powder has been used as a gun propellant in the West since 1320. Such explosives are initiated by ignition (deflagration). Decomposition is slow and therefore the flame propagates slowly (a few m/s), and burning particles are liable to remain in contact with the surrounding atmosphere for a considerable time. They produce considerable amounts of noxious gases, rendering them unsuitable for use in underground tunnels and mines. They have a heaving effect on rock and are spoiled by water.

High explosives generate detonation waves that do useful work. To initiate these waves, an initiating cap known as a *detonator* is needed. The detonator itself consists of the following three types of explosive:

1 pyrotechnic

2 primary, or initiating, explosives
3 secondary explosives.

Pyrotechnic compositions are used to initiate burning in the primary explosives (described below) and are deflagrating explosives. They are also used as delay elements in the manufacture of detonators and also as electric explosive devices (EED), known as fuse-heads, match-heads or squibs. Pyrophoric metals (e.g. zirconium and cerium), oxidising agents (e.g. lead peroxide, red lead, chlorate of potassium, peroxides of barium and lead) and fuels (e.g. silicon and charcoal) are used in delay elements and EEDs.

Primary or initiating explosives may be defined as those explosive substances that respond to stimuli such as shock, impact, friction, flame, etc., and pass from the state of deflagration (a high rate of burning) to detonation. Examples include mercury fulminates, lead styphnate, diazonitrophenol (DDNP) and tetrazene. They are used in the manufacture of detonators, detonating fuses and boosters. The mixture of lead styphnate, lead oxide and aluminium powder, known as ASA mixture, is also used as a primary explosive. As they possess high energy and sensitivity, primary explosives are used as initiators for secondary explosives.

Secondary explosives are substances that are capable of detonation, which is initiated by a primary explosive and not by deflagration. These explosives have a high rate of detonation and form the bottom charge of detonators. Examples include pentaerythritol tetranitrate (PETN), RDX and tetryl (2,4,6-trinitrophenyl-*n*-methylnitramine).

2.4.3.1 Commercial/industrial explosives – high explosives

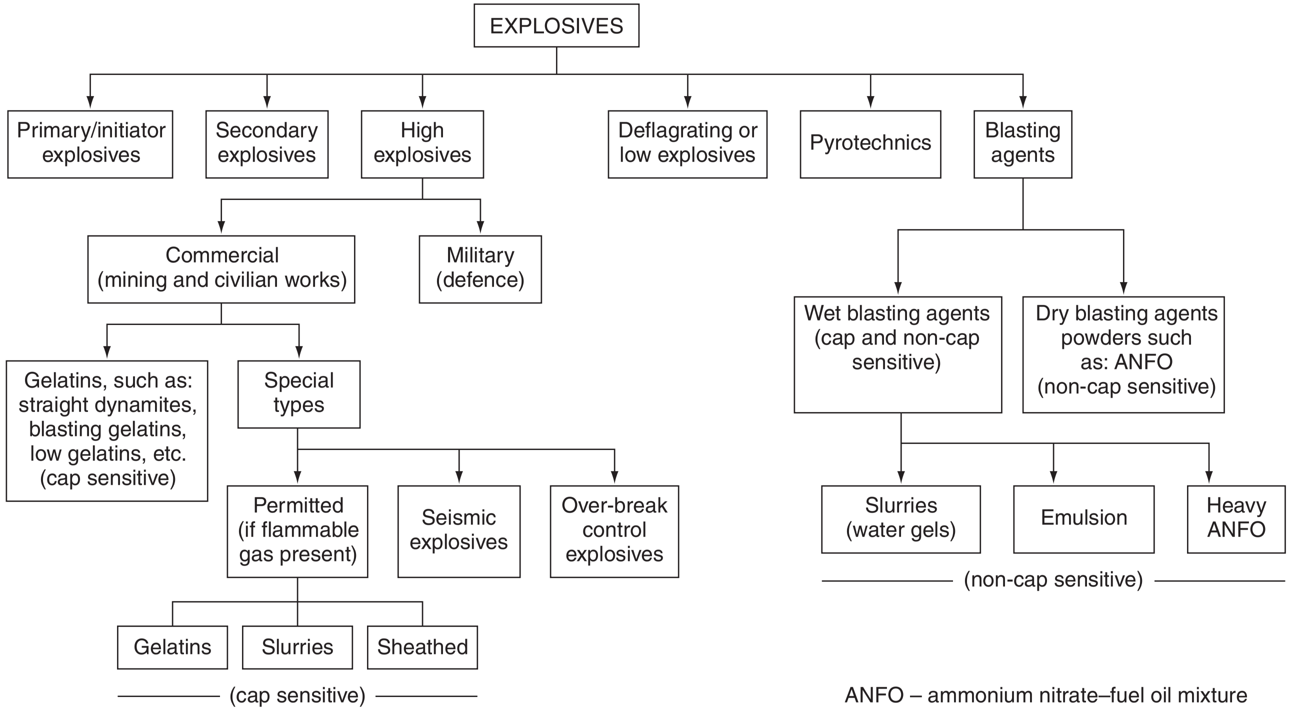
High explosives are substances that cannot be initiated easily by stimuli such as impact, friction or flame, but require the application of a shock pressure wave or a detonation wave. They are sensitive to detonators and react supersonically. Examples include trinitrotoluene (TNT), nitroglycerine (NG) and slurry explosives. These explosives can be further classified as commercial and military explosives (Figure 2.10).

2.4.3.2 Nitroglycerine-based explosives

Dynamite is the name given to the high explosive that was invented by Alfred Nobel and which came into use during 1867–1875 (Baker Hughes, 2017; Ganpathy, 1978). Any high explosive containing nitroglycerine (NG) as a sensitiser is known as dynamite. Nitroglycerine is an explosive oil, and is so sensitive that it can explode with a little shock of any kind. Commercially, such explosives are available in three consistencies: gelatinous, semi-gelatinous and powdery. Higher NG content explosives are gelatinous; those having lower NG content (up to 10%) are powdery. NG-based explosives can be further divided into three classes:

1 dynamites – straight dynamite, ammoniac dynamite (a mixture of ammonium nitrate (AN)), NG and $NaNO_3$
2 blasting gelatin (92% NG and 8% nitrocellulose) – the most powerful of the NG-based explosives
3 semi-gelatin (low NG, or high AN).

Figure 2.10 Classifications of explosives



ANFO – ammonium nitrate–fuel oil mixture

Important properties of NG-based explosives are given later in this chapter (see Tables 2.7 and 2.8). Their properties include high density, strength and water resistance but poor fume quality (i.e. harmful gases are generated).

2.4.3.3 Military explosives

Military explosives have higher densities, higher detonation velocities and higher explosion pressures than the commercial explosives. They have simple compositions to yield high energy and long storage life, and are less sensitive than commercial explosives.

2.4.3.4 Blasting agents

A blasting agent is a mixture of combustible and oxidising substances that are not of an intrinsically explosive nature by themselves. For example, ANFO, which is a mixture of AN (an oxidiser) and fuel oil (a combustible substance), neither of which is an explosive. A blasting agent can be wet (aqueous) or dry. ANFO is a dry blasting agent. The blasting agents that contain more than 5% water by weight are referred as *aqueous or wet blasting agents*, and they are known as slurries, water gels, emulsions and heavy ANFO (Table 2.4).

2.4.3.5 Slurry explosives

These blasting agents were introduced to the market in the 1960s on a commercial scale and their used gained momentum very quickly. Today they are considered to be safe, water-compatible products with good fume quality. Slurry is a high-density aqueous explosive containing solutions of AN, usually together with other oxidisers such as nitrates of sodium, potassium and/or calcium, sensitised with a fuel, and thickened and cross-linked to a gelatinous consistency (see Table 2.4). Slurry explosives are also known as *water-gels*.

Table 2.4 Composition of some slurries and emulsions (wet blasting agents)

Ingredients	Aluminium-sensitised slurry	Water-gel slurry	Explosives sensitised slurry	Emulsion
Fuel/sensitiser	Al – 10%	Amine nitrate – 13%	TNT or nitrostarch – 25%	Wax or oil – 6%
Water	15%	15%	25%	14%
Oxidiser	NH_4NO_3 – 44%	NH_4NO_3 – 63%	NH_4NO_3 – 44%	NH_4NO_3 – 76%
Thickener	Guar gum – 1%	Guar gum – 1%	Guar gum – 1%	Guar gum – 1%
Other oxidisers	$Ca(NO_3)_2$ – 25% Ethylene glycol – 5%	$NaNO_3$ – 5% Ammonium perchlorate – 3%	$NaNO_3$ – 15%	
Micro-spheres				Hollow micro-spheres – 2%

2.4.3.6 Emulsions

Emulsions (see Table 2.4) are composed of two liquids; microscopic droplets of aqueous nitrates of salts (chiefly AN) are dispersed in fuel oil, wax or paraffin using emulsifying agents. In addition, they contain micro-spheres, microscopic glass particles or plastic air-filled bubbles, and AN droplets form the oxidiser. Emulsions are mostly mixed on site prior to charging into holes, but are also available in cartridge packs. They have better water resistance and strength than other slurries.

2.4.3.7 Heavy ANFO

Heavy ANFO is a 45–50% AN emulsion mixed with prilled ANFO, which increases the density of the ANFO. It is mostly mixed on site prior to charging into holes, but it is also available in cartridge packs.

2.4.3.8 Dry blasting agents – powder explosive ANFO

In addition to being an excellent fertiliser, AN is also used by the military – as Amatol it was used in both world wars. Amatol is a 80% + 20%, or 50% + 50% mixture of AN and trinitrotoluene (TNT). The explosive properties of AN became known accidentally when a shipload of fertiliser-grade AN blew up suddenly due to a fire incident. AN (an oxidiser) is mixed with diesel oil (a combustible material) to form the ANFO blasting agent. This has performed extremely well worldwide for a variety of applications in the mining, civil and construction industries. One of the major applications of prilled AN coated with an anti-caking agent is in the manufacture of powder explosives, which are used either as the powder itself or in the form of cartridges. Caking, bad fumes, poor water compatibility and low density are some of the drawbacks of AN. However, its low cost and ease of manufacture, handling and use have led to it being widely used in surface excavations as well as underground tunnels and mines. The following equations demonstrate the correct proportion of ingredients to obtain a suitable mixture.

$$\underset{94.2\%}{3NH_4NO_3} + \underset{5.8\%}{CH_2} \rightarrow 7H_2O + CO_2 + 3N_2 + \underset{\text{oxygen balanced}}{0.93\,\text{kcal/g}} \tag{2.1a}$$

$$\underset{92.0\%}{2NH_4NO_3} + \underset{8.0\%}{CH_2} \rightarrow 5H_2O + CO + 2N_2 + \underset{\text{oxygen balance negative; fuel in excess}}{0.81\,\text{kcal/g}} \tag{2.1b}$$

$$\underset{96.6\%}{5NH_4NO_3} + \underset{3.4\%}{CH_2} \rightarrow 11H_2O + CO + 4N_2 + 2NO + \underset{\text{oxygen balance positive; oxidiser in excess}}{0.60\,\text{kcal/g}} \tag{2.1c}$$

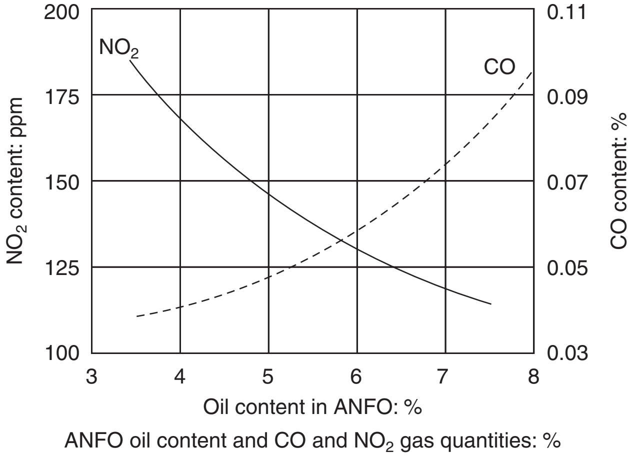
The above equations and Figure 2.11 illustrate that an oxygen-balanced mixture generates minimum harmful gases and maximum energy.

2.5. Blasting

2.5.1 Mechanism of rock fragmentation (blasting)

When a cylindrical charge is fired in a blast hole, the detonation moves up the explosive column from the primer and a high-pressure stress wave travels into the rock mass (Bauer and Crosby, 1990; Jimeno *et al.*, 1997; Matti, 1999; Pradhan, 1996). A horizontal

Figure 2.11 Impact of an incorrect mixture of AN and fuel (oil) on the fume quality (i.e. on generating harmful gases)



section through this charged blast hole (Figure 2.12(b)) shows how the area surrounding the hole is divided into radial fractures at different points in time (stage I – A, B, C) by the compression shock waves. These waves are reflected back from the free face as tensile stress waves (stages II and III). As rocks are weaker in tension than compression, these tension waves cause the rock mass to fracture more and more (Figure 2.12(a)). The desired fracture or fragmentation will occur when there is proper burden and the rock mass subjected to this phenomenon is free from natural discontinuities such as fractures, joints, etc. In any blasting operation, only 3% of the explosive energy is used by the compression wave, and boulders will be formed if this energy is not sufficient to return back after travelling up to the free face (Linehan and Wiss, 1980). The compression waves only enlarge the radial cracks, but tension waves cause the rock to fragment.

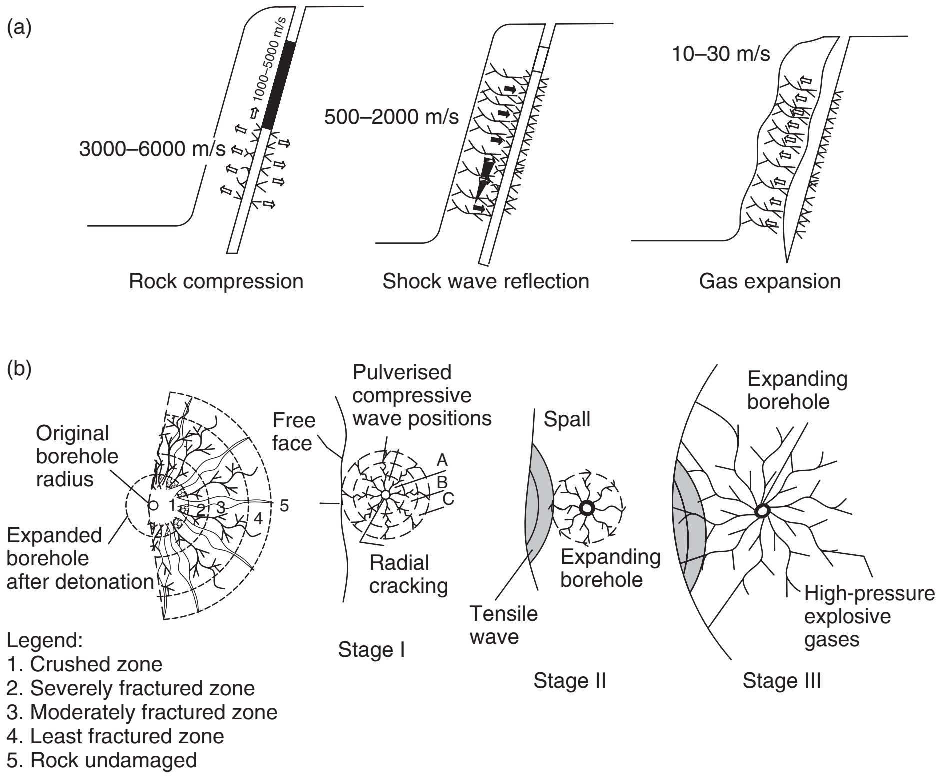
The rapid expansion of gases in the blast hole causes flexure or bending. The gas pressure also causes radial cracks through the rock mass (up to the burden) and then its displacement. For a spherical charge, when blast holes are of large diameter, the crater theory is applicable (as described in Section 9.2.4.1).

2.5.2 Explosives' adverse impacts

As stated in Section 2.4.2, an explosion results in fragmentation, throw, vibrations and noise. Explosives, when not used judiciously, may result in overbreaking or underbreaking of the rock or ground. Overbreak would weaken the surroundings and involve costs in terms of

- excessive drilling that might need to be done
- excessive use of explosives (or over-charge)
- ore dilution (or mixing with undesirable rocks) and generation of an additional amount of muck, thereby causing an additional handling cost for unwanted rocks

Figure 2.12 Mechanism of blasting: (a) physical phenomena during blasting; (b) various stages during blasting



- formation of loose material and its scaling; excessive material will require additional costs in terms of support and reinforcement.

Similarly, under-breaking would result in a reduced advance/blasting round in tunnels, and irregular and under-sized excavations that will need further drilling, blasting, scaling, mucking and other operations. This is how the productivity and costs of an operation are non-optimal when explosives, drilling and blasting operations are not properly matched.

2.5.2.1 Ground/land vibrations

Explosives, when detonated, produce shock waves. The part of shock waves that is not used in the rock fragmentation causes vibrations in surrounding rock mass and structures sited within a certain radius of the blast site. The impact of shock waves on the surroundings depends on the geology (the type of rock and the presence of discontinuities, if any) and geomechanical properties (seismic velocity, density and elastic constants) of the surrounding rocks. Fissured and/or jointed rocks could dampen vibrations. The geomechanical factors that most influence the impact of shock waves are described below.

EXPLOSIVE-RELATED PARAMETERS

(Franklin and Dusseault, 1989; Hendron and Oriard, 1975; Jimeno *et al.*, 1997)

- *Charge weight/delay*: the magnitude of ground and air vibrations at a specific point (structure) depends on the distance from the place of blast and the amount of explosive used (Pradhan, 1996). When more than one delay is used in the blast, the total charge does not matter; the largest charge per delay determines the magnitude of the damage. The peak particle velocity v (mm/s) is the best indication of whether or not a particular blast is likely to cause structural damage. The relationship given by the United States Bureau of Mines (USBM), $v = a(\mathrm{SD})^b$ can be used to determine this: a and b are dimensionless site factors; SD is the scaled distance (m/kg$^{1/2}$), determined by $\mathrm{SD} = [D/W^b]$, where $b = 1/2$; D is the distance (m) between the blast site and structure and W is the maximum charge/delay (kg). (*Note:* No scaled distance graph is given here, but such graphs can be found in any standard book on blasting and explosives. The USBM uses square root scaling, whereas some institutions use cube root scaling.)
- *Soundness of the structure*: in terms of its age, condition, and its material and quality of construction.
- *Peak particle velocity*: Table 2.5 illustrates peak particle velocity as a measure of vibration levels and their effect on the surroundings (Franklin and Dusseault, 1989).
- *Powder factor* (explosive in kg/m^3): lowering the powder factor helps to reduce the particle velocity to some extent, but when the reduction is too great it works to the contrary. In a trial, when the powder factor was reduced by 20% from the optimum, the measured vibration levels were two to three times higher as a consequence of poor confinement and spatial distribution of the explosive charge, leading to a lack of displacement and swelling energy (Jimeno *et al.*, 1997).
- *Type of explosive*: explosives with a lower blast-hole pressure generate lower levels of vibrations. ANFO is one of these explosives. It generates fewer vibrations than slurry explosives and water-gels.

Table 2.5 Peak particle velocity and its influence on nearby structures

Peak particle velocity: mm/s	Effects
600	New cracks form in the rock mass
300	Fall of rock in unlined tunnels
190	Fall of plaster and serious cracking in buildings
140	Minor new cracks, opening of old cracks
100	Safe limit for lined tunnels, reinforced concrete
50	Safe limit for residential building
30	Feels severe
10	Disturbing to people
5	Some complaints likely
1	Vibrations are noticeable
0.1	Merely perceptible vibrations

- *Delay period*: some of the studies that have been undertaken suggest that a successive delay interval of 17 ms could eliminate the summing effect of vibrations.
- *Blast-hole diameter*: larger-diameter holes have adverse effects, as they can accommodate more explosives per unit length, and thereby sometimes result in an excessive weight per delay.
- *Bench height*: as a rule of thumb, $H > 2B$. That is, the bench height H should be greater than twice the burden B to obtain good fragmentation, eliminate toe problems and reduce ground vibrations (Jimeno *et al.*, 1997).

BURDEN AND SPACING

If the burden is excessive the explosion gases find resistance to fragmentation and rock displacement, thereby causing the gases to transform themselves into seismic energy (vibrations). If the burden is too small the explosion gases result in fine rock fragments and their uncontrolled throw. Part of the energy is also converted to more noise and air-blast. Similar effects are noticed with incorrect hole spacing. This factor is equally applicable to, and follows almost the same logic during, tunnel blasting.

SUBGRADE DRILLING

Excessive subgrade drilling often results in uneven floors, large vibrations, unwanted expanses of drilling and unwanted explosive consumption. The amount of drilling should, therefore, be decided after conducting trials. Inclined, rather than vertical, holes during bench blasting allow better use of energy and result in reduced vibrations.

STEMMING

Stemming that is too high could, of course, give better confinement, but it often becomes the cause of excessive ground vibrations.

DECK CHARGING

When properly planned, based on the rock types, deck charging yields good fragmentation, reasonable throw and a reduced vibration level.

DISTANCE FROM POINT OF BLAST

As the distance from the point of blast D increases, the vibrations diminish according to the following relationship: $v = 1/D^b$. The value of b given by the USBM is 1.6. The magnitude of v can reduce rapidly if an overburden consisting of soil is present because a large part of the blast energy is used in overcoming friction between particles and in displacing them (Jimeno *et al.*, 1997).

2.5.2.2 Air-blast and noise

Air-blast is the pressure wave that is associated with the detonation of an explosive charge, whereas noise lies in the audible and infrasonic part of the spectrum (20 Hz to 20 kHz) (Jimeno *et al.*, 1997). Low-frequency air vibrations (<20 Hz) are considered as air-blasts. They can cause damage to the structures surrounding the blast site due to (Linehan and Wiss, 1980)

- ground vibrations that are caused by an explosion (the rock pressure pulse)

- gases escaping from the blast hole when the stemming is ejected (stemming release pulse); under-stemmed or unstemmed holes can also increase the blast magnitude
- gases escaping through the fractures that are created during the blast (gas release pulse)
- detonation of the initiating blasting cord in the air
- rock displacement (air pressure pulse)
- collision between the projected fragments.

High-frequency vibrations are more prominent during a blast and they can be felt in windows, dishes, doors, etc. Air-blast overpressures greater than 0.7 kPa (0.1 psi) can break windows, and overpressures exceeding 7 kPa will certainly break windows (Franklin and Dusseault, 1989), and, even in the absence of damage, complaints and legal actions resulting from annoying levels of noise and vibrations can close operations.

2.5.2.3 Rock throw

The function of explosives is not only rock fragmentation but also its displacement from its original place. But if this throw is excessive, it becomes a nuisance and could damage the structures surrounding the blast site. Explosives with a high bubble energy, such as ANFO, produce more rock throw than those having a high strain energy, such as dynamite (NG-based explosives). Insufficient stemming also leads to more throw. Bottom/indirect initiation should be preferred. Fissured and fractured rocks also facilitate throw more than massive and homogeneous rocks. Proper blast design is the key to minimising the problem of excessive throw. As stated earlier, throw is a desired and inherent property of explosives. In urban areas, coverings of different types are used to cover the blast site. Jimeno *et al.* (1997) suggest that a covering system should have the following features:

- be economical and reusable
- allow gas to escape
- be lightweight with high resistance, and easy to place and shift.

In practice, the following means are used:

- Covering with sand: material, such as sand, from a neighbouring site is dug and spread over the blast. The recommended thickness of backfilled material should be equal to the stemming length and not below 0.8–1 m (Jimeno *et al.*, 1997).
- Used and discarded lengths of conveyor belts are overlapped and pinned to the ground using sandbags.
- Metal screens or mesh, nylon nets, or rubber tyres (with overlapping) are some of the other means that are used.

When covering the blast site using any of the above practices it must be ensured that the connections of the blast round (i.e. the blasting circuit) are protected.

The energy that is not used in rock fragmentation and rock throw is sometimes more than 85% of that developed during the blast. This energy can badly damage the structural strength of rock, even sometimes outside the theoretical radius of influence. This is how rocks get weakened. Joints, fissures and cracks already present in the rock get widened, and new fissures and cracks are developed. This results in a reduction in the overall rock mass cohesion, which can cause overbreak and even leave fractured ground open (a potential source of collapse).

2.5.3 Control/contour blasting

As noted in the preceding section, a mechanism (control) is required that will minimise damage due to blasting. The technique used for this purpose is contour blasting. The technique consists of creating a joint or fracture plane from the combined effects of the shock-wave action and explosion gases (Jimeno *et al*., 1997; Matti, 1999; Olofsson, 1997; Pradhan, 1996). Contour-blasting techniques can be divided into:

- pre-splitting
- cushion or trim blasting
- buffer blasting
- line drilling
- smooth blasting.

Special explosives to charge the line holes have been developed by different explosives manufacturers worldwide for use during controlled blasting (Table 2.6) and for mining dimension stones such as granite, marble, etc. (Matti, 1999). These explosives, known as *decoupled charges*, are pipe shaped and are available with *self-centring* devices.

In civil construction it has become increasingly important that the rock wall remaining after the blast is of good quality in order to avoid or minimise rockfall, rockslides and excessive stabilisation work. Two methods used to produce stable and smooth rock contours are pre-splitting and smooth blasting.

Table 2.6 Explosives available for controlled blasting, and guidelines given by DuPont and Nitro Nobel for pre-splitting holes

Hole diameter: mm	Loading density: kg/m	Spacing: m	Remark
38–44	0.12–0.38	0.30–0.45	Recommended by the DuPont Explosives Co.
51–64	0.12–0.38	0.45–0.60	
76–89	0.20–0.75	0.45–0.90	
102	0.38–1.12	0.60–1.20	
25–32; 11 mm Gurit	0.11	0.2–0.3	Recommended by Nitro Nobel explosives for pre-split holes
25–41; 17 mm Gurit	0.23	0.4–0.5	
41–51; 2 × 11 mm Gurit	0.46	0.5–0.7	
41–51, 22 mm Gurit	0.42	0.5–0.7	
51–64; 22 mm Emulite*	0.45	0.6–0.8	

* Paper cartridges are taped to the detonating cord down the line.

2.5.3.1 Pre-splitting

The aim of pre-splitting is to isolate the blasting area from the rest of the rock formation by creating an artificial crack along the intended excavation plane. In this technique the holes in the last row are drilled to a smaller diameter and at closer spacing than the holes for the main blast. Decoupled explosive charges are used for blasting. The row of smaller holes is blasted prior to the main rows, thereby creating a fracture or joint plane in the rock mass before firing the production blast. In this technique holes of 50–100 mm diameter are usually spaced at 10–20 times the hole diameter. Figure 2.13 gives a guide for the hole diameter relative to distance. The pre-splitting holes are charged with about one-tenth of the normal charge. This could be blasted together with the main blast but, given the initial delay, the pre-split row must be blasted first. Guidelines given by DuPont, as shown in Table 2.6, could also be used.

This technique is used mostly in surface blasting, such as for road cuts, foundations where a concrete lining or structural concrete is poured directly against the rock wall, etc. For best results, detonating cords or instantaneous detonators should be used for initiation (Figure 2.14). Noise may be a problem, as pre-split holes should not be stemmed. Another problem can be excessive ground vibrations.

2.5.3.2 Cushion blasting

The guide given in Figure 2.13 can be used to determine the hole spacing in cushion blasting. In surface mines or surface cuts, when cushion blast holes have the same diameter as that of the production or main blast holes, the technique is known as *trim blasting* or *slashing*. The hole diameter varies from 50 mm to 164 mm. The charge is usually fired with no delay, or minimum delay, between the holes. A detonating cord is the best means

Figure 2.13 Guide for selecting the spacing between holes during cushion blasting and pre-splitting

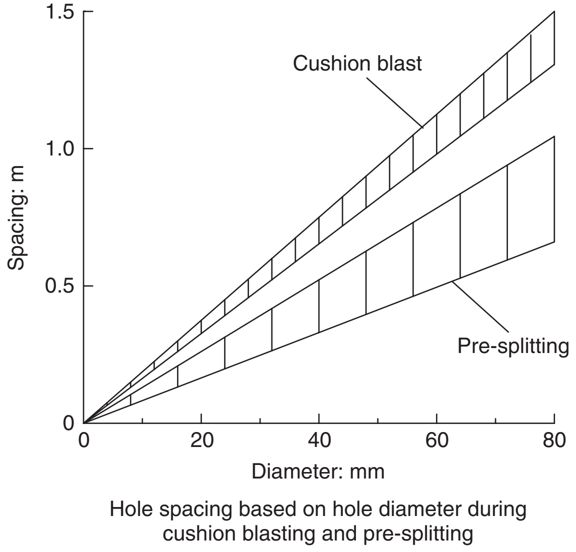
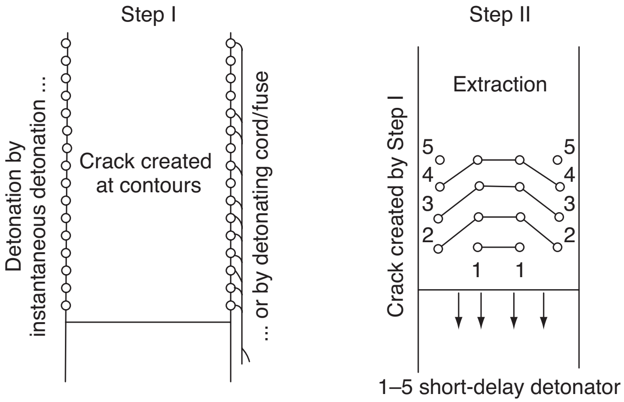


Figure 2.14 Pre-splitting as applicable during bench blasting



of initiation where noise or air-blast is not a problem. Holes are charged by taping (tying) the small-diameter cartridges (25–32 mm) to the detonating cord. The cartridges are spaced at a distance of 30–50 cm depending on the hole diameter. The space between the charges and the hole wall is filled with inert material such as sand or crushed rocks. Executing the main blast, including mucking out the broken rock before the cushion blast, is mandatory. This technique functions well in incompetent formations in surface excavations and requires less drilling than pre-splitting (Olofsson, 1997).

2.5.3.3 Smooth blasting and buffer blasting

This technique is used mainly for underground tunnels, large caverns, chambers and openings. Smooth blasting was developed in Sweden during the 1950s and 1960s. This technique is almost mandatory to achieve a better correlation between the actual cross-section and the designed one. In smooth blasting, extra care is taken while drilling and blasting the line holes (peripheral holes in the case of tunnels, and the last row of holes during bench or surface blasting), as described in Sections 4.5.4 and 4.13. When used in conjunction with surface excavations this technique is also known as *buffer blasting*. Its applications at the surface include road cuts, cuts for foundations, etc. Closely spaced holes are drilled in the contour and then charged with small-diameter light charges, which produce a relatively low detonation velocity and low gas volumes. Suitable explosives are, for example, 11, 17 and 22 mm diameter Gurit tube charges, but detonating cords with a 40 or 80 g/m core load are frequently used. The blasting of the contour holes is carried out in conjunction with the rest of the round. The contour holes are given the highest period number. The holes closest to the contour must have well-balanced charges. If the charge concentration is too high there is a risk that these holes will result in overbreak.

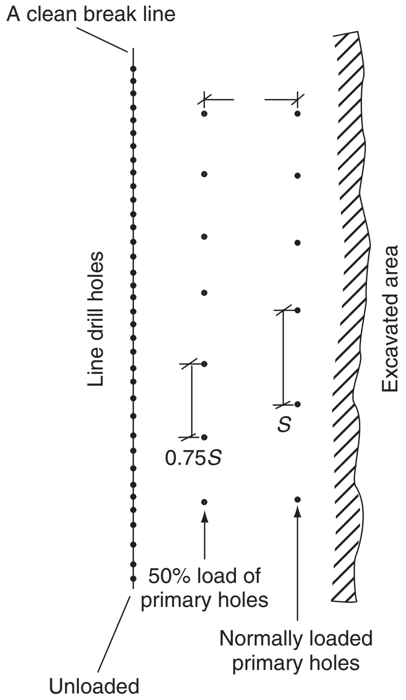
When the contour is sequenced to blast the rest of the holes in a round, the spacing and burden can be calculated using the following:

$$E = 15, \ldots, 20d \tag{2.2a}$$

$$V = 1.25E \tag{2.2b}$$

where E is the spacing (mm), V is the burden (mm) and d is the hole diameter (mm).

Figure 2.15 Line drilling applied during bench blasting. *B*, burden; *S*, spacing



The hole spacing in the counter line depends mainly on the rock tenacity, hardness and solidity.

2.5.3.4 Line drilling

When drilling is done skin-to-skin (i.e. without any spacing) or with very little spacing, the technique is known as line drilling (Figure 2.15). The technique is popular for 'block separation' during quarrying of dimension stones, such as marble. It is an expensive technique in which holes of 40–75 mm diameter are drilled 100–150 mm apart along the perimeter of the required excavation. Holes should be drilled prior to blasting the main blast. The holes are not loaded but their presence protects the surrounding rock from the damage that may be caused by the main blast. It is the drilling of a large number of holes with precision that makes the process costlier than other techniques. However, it is the preferred technique where explosive and other methods do not work efficiently, or where there are technical restrictions. Its use is mandatory when even lightly charged explosives could cause damage beyond the excavation line.

2.6. Blasting accessories

The following accessories are essential during blasting operations:

- detonators
- safety fuses

- boosters
- shape charges
- exploders
- explosive charging devices/loaders
- blaster's tools.

2.6.1 Detonators

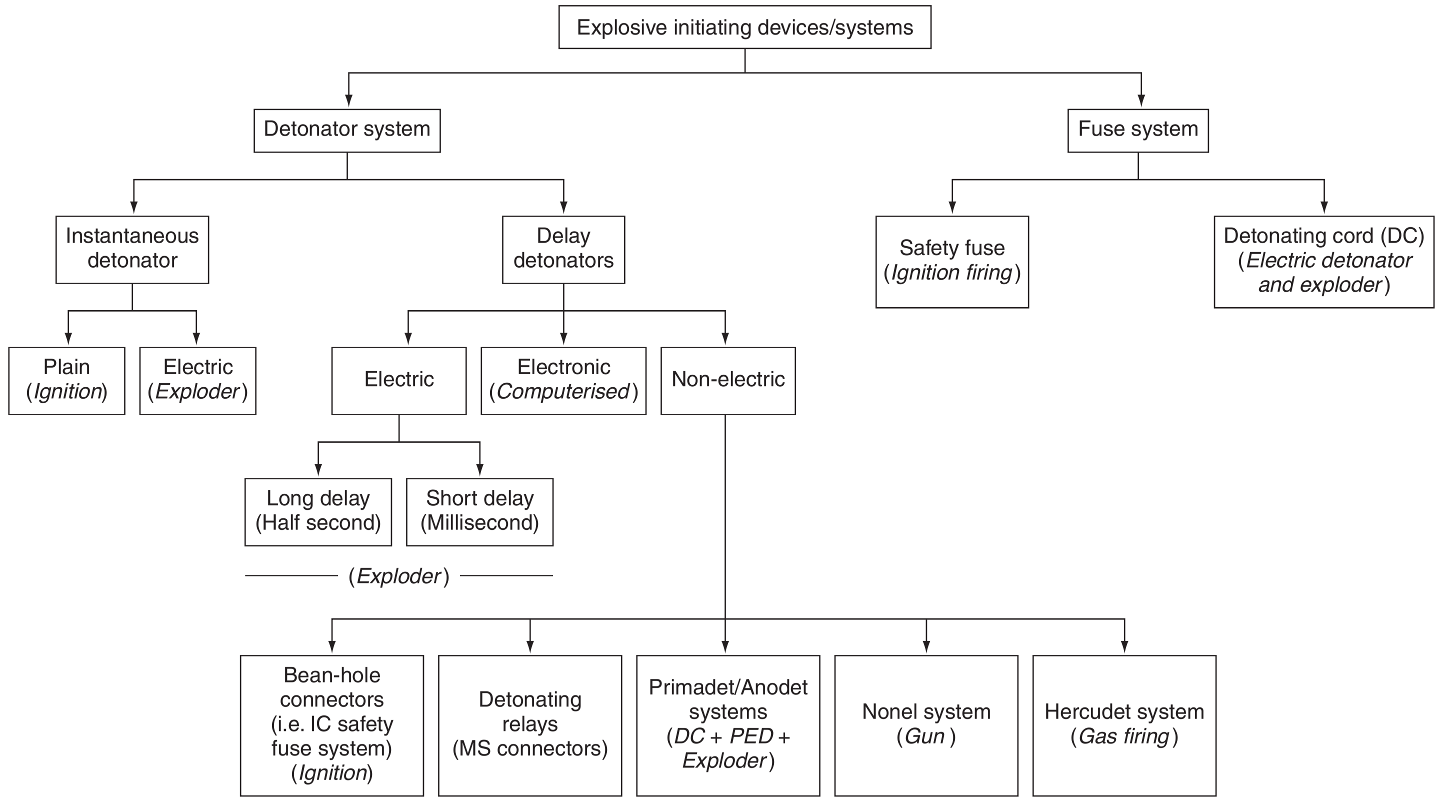
Also known as blasting caps, detonators are made of aluminium or copper (the latter is used for incendiary detonators for mines and tunnels that contain flammable gases such as methane). Detonators are classified as shown in Figures 2.16 and 2.17, the difference between the various types of detonator is illustrated in Figure 2.16. The function of the cap is to initiate detonation waves in an explosive column. Ordinary caps are used with safety fuses; a plain electric detonator can be used with a detonating cord.

The safety fuse and plain detonators were invented originally to initiate black powder, but firing more than one shot was risky. These detonators were not suitable for initiating high explosives, and therefore plain or ordinary electric detonators were developed, and with the advent of pyrotechnics, delay detonators were brought onto the market. These detonators represented a great breakthrough in the execution of tunnel and benching rounds. When ANFO began to be used in tunnelling and stoping (large ore blocks in mines are known as *stopes* and the process of blasting them is known as *stoping*) operations underground, the use of antistatic detonators came into operation. This was essential because ANFO is charged in the holes pneumatically using specially designed loaders known as ANFO loaders. Charging holes pneumatically generates an electrostatic charge, and if a hole contains a primer containing an electric detonator it could initiate while the charging operation is in progress. In order to avoid the hazard of premature firing of electric detonators while charging holes, due to generation of electrostatic charge, antistatic detonators (e.g. Anodet, Orica Mining Services, and Primadet, P.T. Empat Enam Jaya Abadietc) were developed.

Primadet is a shock-tube system. The shock tube (Primacord, Ensign-Bickford Aerospace & Defense) is a small-diameter laminated plastic tube coated with 0.45 kg of reactive material per 30.480 m. It transmits a low-energy signal from the point of initiation to the delay cap at about 1981 m/s. The detonator has a millisecond delay and can initiate a cap-sensitive explosion. It has a delay tag and J-hook to facilitate connection to a Primacord detonating cord trunkline (Baker Hughes, 2017).

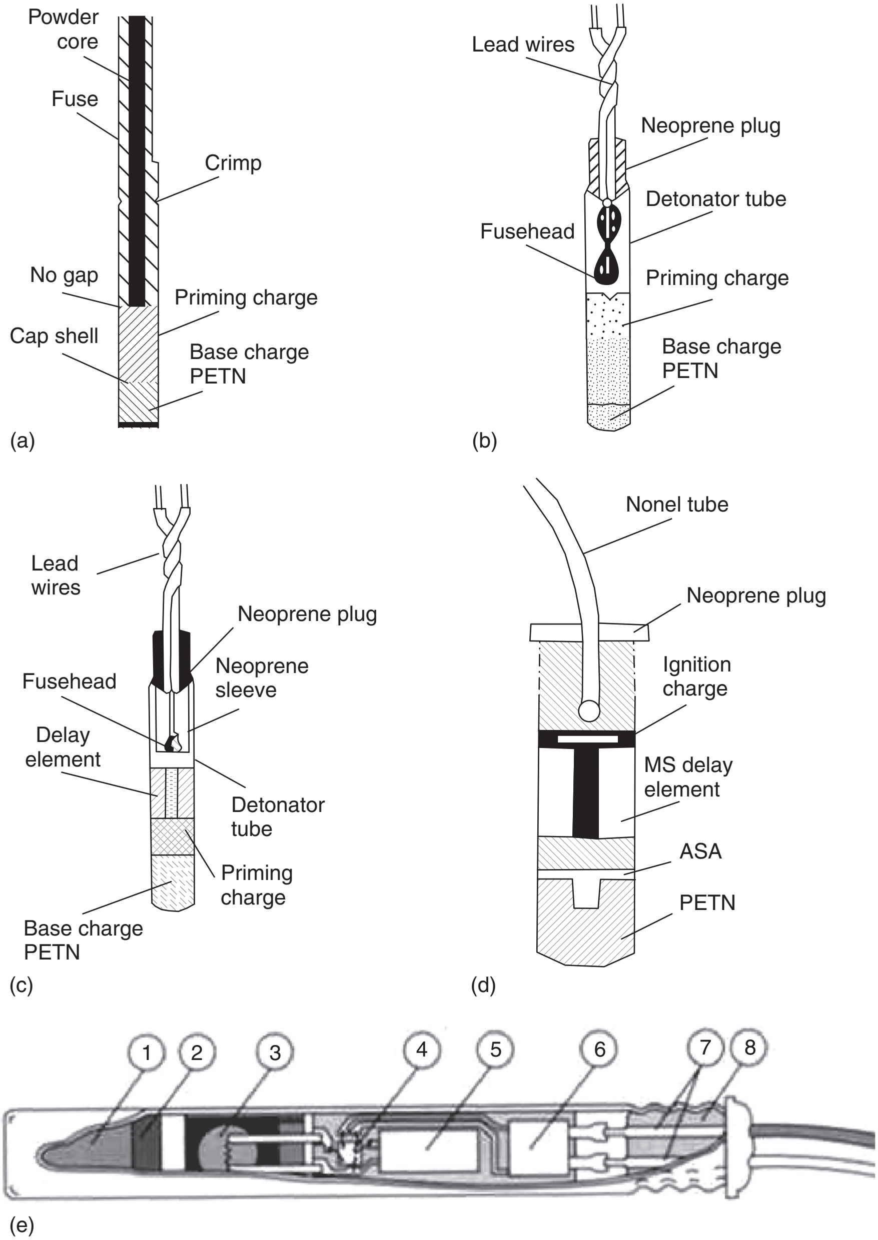
Detonating cord and an ordinary electric detonator used outside the holes are essential for initiating the explosive. Other non-electric detonators, such as Hercudet (Hercules Inc.) and the Nonel system (Dyno Nobel) (see Figure 2.17(d)), were launched at around the same time. Hercudet is based on gas firing, while the Nonel system has a specially designed 'gun' to fire the explosive. Both systems use pyrotechnic explosives to incorporate delay in the detonators. Within the last decade, electronic delay detonators have been brought onto the market that impart a delay to a detonator. In fact, it is the stored energy device incorporated in the system that provides energy for the timing and firing

Figure 2.16 Classification of explosive initiating devices/systems. The firing device/means is indicated in parentheses



DC – detonating cord, PED – Plain electric detonator.

Figure 2.17 Detonators (blasting caps) of different types: (a) ordinary non-electric; (b) electric; (c) electric delay; (d) Nonel system (antistatic and non-electric); (e) electronic: 1 – base charge (PETN), 2 – primary explosive (lead azide), 3 – matchhead with bridge wire, 4 – integrated circuit chip, 5 – capacitor, 6 – overvoltage protection circuitry, 7 – lead wires, 8 – sealing plug (courtesy of Sandvik-Tamrock)



circuits. Some prominent manufacturers are developing this system on a commercial scale. Electronic detonators have some unique features:

- the shortest delay time is 1 ms and the longest is 5.25 s
- a maximum of up to 500 detonators can be connected to the blasting machine
- the combination of a filter and a toroid gives protection against parasite currents, (static electricity produced during pneumatic charging of explosives or radio-frequency signals)
- extremely precise (±0.2 ms)
- the limitation at present is their cost, which is 10–15 times that of the conventional caps.

In order to provide a delay in a blast using only detonating cord, a device known as a *detonating relay* can be incorporated. This is how the delay between holes charged with detonating cord, together with other explosives, can be achieved.

2.6.1.1 Fuse, primers, boosters and shape charges

Safety *fuse* is a string or core of black powder wrapped in a textile and some waterproof material. It is used to initiate a plain detonator. Detonating cord is a string or core of some high-detonation-velocity explosive, such as PETN, wrapped in a plastic cover. It provides continuity to the detonation of an explosive column in long blast holes, and can also be used to initiate antistatic detonators such as Anodet and Primadet detonators. An ordinary electric detonator is used to initiate the cord.

A *primer* is a cartridge of high explosive that contains a detonator. Primers can initiate charged columns of high explosives, dry blasting agents such as ANFO or non-cap-sensitive slurries.

A *booster* is also a high explosive cartridge which is used to initiate detonation in non-sensitive blasting powders. In a long blast-hole, more than one booster can be used at intervals to maintain continuity of detonation. Due to its inherent properties that make it cheap and easy to use and manufacture, ANFO is widely used, particularly in dry conditions, during tunnel blasting.

A *shape charge* is an explosive cast in a special shape or geometrical configuration. Such charges are is used for formation fracturing in the petroleum industry and in demolitions.

2.6.2 Blaster's tools and appliances

Explosive charging and firing devices include the following (Atlas Copco, 2017a; Matti, 1999):

- stemming rod (wooden stick) – for charging explosive cartridges manually
- cartridge loaders – for mechanised loading of explosive cartridges
- loaders (pressure or ejector loaders, or their combination) – for charging ANFO pneumatically

- circuit testers – to check for resistance, leakage and the continuity of the blasting circuits
- exploders – dynamo and condenser types, single and multi-shot exploders
- power mains – for mains firing (i.e. firing using electric mains supply)
- other blasting tools – crimper, to crimp safety fuse into a plain detonator; pricker (made of wood or a non-ferrous material), to prick into an explosive cartridge to prepare the primers; knife, to cut safety fuse; scraper; shot-firing cable; stop watch (when safety fuse is used); and suitable warning signboards or signalling arrangement.

Other arrangements that need to be made include setting up the magazine to store explosives of different classes, organising explosives vans to transport the explosives, and the provision of ANFO mixing and/or slurry manufacturing plant and their storage facilities.

2.7. Properties of explosives

The following properties of explosives are described in this section (Dick *et al.*, 1983; Hartman, 1987; Matti, 1999):

- strength
- density, detonation velocity and detonation pressure
- water resistance
- completion of reaction, oxygen balance and fume characteristics or class
- critical diameter of explosive charge and sensitivity
- handling and storage qualities.

2.7.1 Strength of explosives

The strength of an explosive is expressed as bulk strength or weight strength, which are the measures of energy released per unit volume and weight, respectively. The strength of an explosive is a measure of its capability to produce shattering effects (detonation), throw (gas volume) and explosion temperature and pressures (energy release). Hard and tough rocks require high-strength explosives (e.g. dynamites), while weak and medium hard rocks require low-strength explosives (e.g. ANFO, heavy ANFO and emulsion explosives). The latter result in low level noise, vibration and throws. Knowledge of the rock strength can help in selecting a suitable explosive. The weight strength of an explosive can be determined using Langefors formula:

$$s = \frac{5e}{6} + \frac{V}{6} \tag{2.3a}$$

$$e = \frac{4250Q_\text{v}}{500\,000} \tag{2.3b}$$

$$V = \frac{V_1}{850} \tag{2.3c}$$

where s is the strength per unit weight, e is the energy coefficient, Q_v is the heat of explosion (kcal/kg) and V_1 is the gas volume at 0°C and 1 atm.

Table 2.7 Comparison between important properties of explosives

Explosives	Density: g/cm^3	Relative weight strength (ANFO = 100)	Relative bulk strength (ANFO = 100)	Relative cost/unit volume (ANFO = 100)
AN	–	–	–	67
ANFO	0.85	100	100	100
ANFO (dense)	1.10	100	135	130
15% Al/ANFO	0.85	135	135	183
15% Al/ANFO, dense	1.10	135	175	237
Pelletised TNT	1.0	90	106	392
1% Al/NCN slurry	1.35	86	136	397
20% TNT slurry	1.48	87	151	421
40% dynamite	1.44	82	139	551
25% TNT slurry/15% Al slurry	1.60	140	264	722
95% dynamite	1.40	138	193	824

NCN, nitrocarbonitrate.

2.7.2 Density, detonation velocity, detonation or borehole pressure

These are interrelated parameters that can be expressed by the following relationship:

$$p = 2.5\rho v^2 \times 10^{-6} \tag{2.4}$$

where p is the detonation pressure (kbar), ρ is the explosive density (g/cm^3) and v is the velocity of detonation (m/s). Explosives of higher density and velocity of detonation can result in mass destruction and heavy damage. Such explosives are used for military applications and are not suitable for rock fragmentation due to the potential for extensive damage to the surroundings, besides being very costly. Commercial explosives meant for proper rock fragmentation should be chosen based on rock strength. Tables 2.7 and 2.8

Table 2.8 Basic properties of nitroglycerine (NG)-based explosives

NG-based explosive	Specific gravity	Detonation velocity: ft/s*	Water resistance	Fume quality
Straight dynamite	1.3–1.4	9000 to 19 000	Poor to good	Poor
Extra dynamite	0.8–1.3	6500 to 12 500	Poor to fair	Fair to good
Blasting gelatin	1.3	25 000	Excellent	Poor
Straight gelatin	1.3–1.7	11 000 to 25 000	Excellent	Poor to good
Extra gelatin	1.3–1.5	16 000 to 20 000	Very good	Good to very good
Semi gelatin	0.9–1.3	10 500 to 12 000	Fair to very good	Very good

* 1 ft/s = 0.3049 m/s.

give comparisons of different commercial explosives. In addition, for any explosive there is a critical density beyond which it cannot reliably detonate. For example, for TNT this density is 1.78 g/cm^3 and for ANFO it is >1 g/cm^3.

2.7.3 Water resistance

Water is frequently present during benching and tunnelling operations. Explosives that are hygroscopic in nature and relatively unresistant to water, such as ANFO, are not suitable in these conditions. Emulsion and slurry explosives are excellent in these circumstances. Dynamites (NG-based explosives) have the best water resistance but are the most costly.

2.7.4 Completion of reaction, oxygen balance and fume characteristics or class

An explosive should be a well-balanced mixture of oxidisers, fuel and sensitisers that result in non-toxic gases and maximum energy release (maximum heat). It can be seen from Equations 2.1a–2.1c that an ANFO with a balanced composition of AN and fuel oil yields non-toxic gases and maximum heat values, whereas when the oxidiser is less than desired ANFO yields toxic gases such as CO and less energy. Similarly, a higher percentage of oxidiser in the ANFO will yield even more toxic gases and less energy. This aspect is also important from the health, safety and environmental point of view. The generation of toxic gases requires more ventilation and is injurious to health.

2.7.5 Critical diameter of explosive charge and sensitivity

The minimum diameter of a charge, below which the detonation does not proceed, resulting in misfire, is called the *critical diameter*. At a lower diameter, even if the explosive is sensitive, the reaction in the cartridge may be incomplete. The *sensitivity* is a measure of an explosive's propagation property, its ability to bridge the gap between two consecutive cartridges or a column of an explosive charge.

2.7.6 Handling and storage

Explosive should be easy to handle, transport, load (use) and store. ANFO, being hygroscopic, absorbs moisture and becomes caked. Dynamite lowers the blood pressure and could cause headaches. ANFO could cause skin irritation if handled without gloves. Explosives must be stored in a magazine and be handled with due care by a trained and competent person who has been authorised to do so. In order to have safe manufacture, transport, handling and end use of an explosive, various tests are made on the ingredients and final product. The tests include the impact test (fall hammer test), friction pendulum test, torpedo friction test, projectile impact test and bullet sensitivity test.

2.8. Blasting cost

This is one of the most important considerations when selecting an explosive. ANFO is at the top of the list and is very widely used due to its low overall cost. However, the purpose for which the explosive is needed determines the final choice. The cost of the explosive should be judged against the overall cost of the blasting process, including the costs of drilling, main blasting (explosives accessories), secondary blasting (if required), mucking, transportation and crushing:

$$C_{\mathrm{tot}} = C_{\mathrm{d}} + C_{\mathrm{b1}} + C_{\mathrm{b2}} + C_{\mathrm{m}} + C_{\mathrm{tr}} + C_{\mathrm{h}} + C_{\mathrm{cru}} + C_{\mathrm{mis}} \tag{2.5}$$

where C_{tot} is the total cost of production per ton of rock, and C_{d}, C_{b1}, C_{b2}, C_{m}, C_{tr}, C_{h}, C_{cru} and C_{mis} are the cost per ton of drilling, primary blasting, secondary blasting, mucking, haulage, hoisting, primary crushing and miscellaneous aspects, respectively. Plus or minus signs should be used when comparing the costs of two systems with respect to the unit operations in Equation 2.5: a plus sign is used if the cost is greater than with the aid of explosives, and a minus sign if it is less. In this manner, an overall cost difference between various systems can be assessed and the efficiency of the system can be judged.

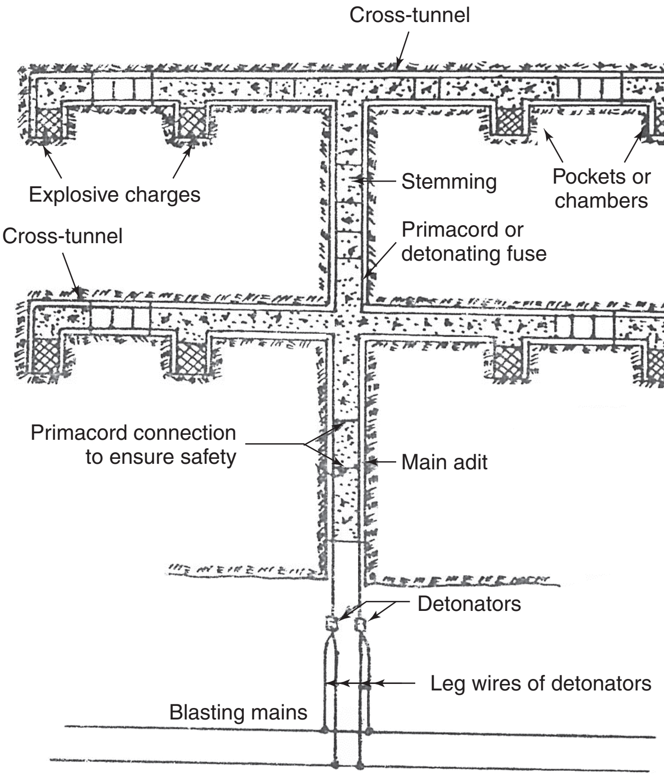
2.9. Coyote blasting

A coyote is small wolf found in North America that makes small horizontal tunnels (openings) in hills as its dwelling place. The name ‘coyote’ is given to a non-nuclear mass blasting technique that involves the use of a bulk quantity of explosives to blast a huge rock mass without drilling blast holes or shot holes for the placement of explosives. Rather, small pockets are driven into the rock to accommodate the explosive.

This technique involves the preparation of a surface topography map of the intended blast site with contour intervals of 3 m or less. Important features such as roads, buildings, benchmarks and all other prominent structures should be shown on the map. Ideally, no permanent structures (roads, etc.) should pass through the blast site. An adit (a horizontal passage) is driven at a right angle into the face line of the intended site. For optimum results the length of adit should be restricted to 0.6 times the height (thickness) of the overburden above the blasting horizon (i.e. the horizon (elevation) at which the adit is driven). From this adit, cross-cuts are driven almost parallel to the face line of the blast site at intervals of 6–12 m (Figure 2.18). Pockets are cut into the cross-cuts at intervals of 5–9 m (centre to centre) to accommodate the explosive charge. The number and dimensions of the pockets are calculated to be just sufficient to accommodate the explosive’s cases. The pockets should never be facing the entering adit but driven in an offset direction. The thickness of overburden above the pockets (Table 2.9) and the spacings between cross-cuts and pockets is determined by the rock type and the presence of geological discontinuities such as joints and their directions. Useful guidelines are given by Singh (1993).

As the volume of rock covered by each of the pockets differs, the amount of explosive that needs to be placed in each pocket also differs. To calculate the explosive charge required in each pocket, its cross-section and toe distance should be properly determined using the surface topography map. Then, taking into account the interval between pockets, the volume of rock mass to be blasted is determined. An explosive with a suitable powder factor is selected for the type of rock mass and the degree of fragmentation required, and the quantity of explosive to be charged in each pocket assessed. An example of this type of blast is described in Tatiya (2013): four pockets measuring 1.8 m × 1.8 m × 1.8 m were driven and about 2.4 ton of NG-based explosive (dynamite) was charged in each pocket.

Figure 2.18 Coyote blasting



If the area to be covered is large, then a number of adits need to be driven. These openings for the coyote blast are made using jackleg drilling, conventional explosives, manual mucking and wheelbarrows to transport the muck. If mini-sized drill jumbos and matching loading and transportation units are available, these could be deployed to achieve faster progress.

Table 2.9 Overburden thickness based on the nature of the strata

Nature of strata	Proposed overburden thickness: m	Remark
Strata with numerous well-defined vertical or nearly vertical joints	≤40	For larger overburden thicknesses a two-tier arrangement (two lifts or benches) may be essential
Strata with not so well-defined vertical joints	≤30	
Strata with horizontal bedding planes combined with almost vertical secondary joints	15–18	

Charging the pockets with explosives is a very skilful task and should be done carefully. Detonating fuse/cord (Primacord) is used to initiate the explosive charges loaded in each pocket. A primer is made using special gelatin cartridges which are tied with Primacord. The cord is laid out starting from the adit mouth through to each of the pockets, where a primer for each pocket is tied on using a suitable knot. These knots should be properly tapped and covered. In order to ensure safe laying of the cord it should be laid over sand-filled bags, and where there are two separate lines of cord each should be covered with a layer of sandbags. Alternatively, the cord could be laid along one side of the openings (adit and cross-cuts) on wooden hangers that have been specially prepared for this purpose and placed at regular intervals to ensure the initiation process is foolproof. In order to limit the explosion to safeguard against heavy vibrations to the surroundings, detonation relays can be introduced between the cords of two adjacent pockets. To do this the cord line is cut and a detonating relay is crimped to the two cut ends of the cord. A plain electric detonator is connected to the two ends of the cord (one from each of the separate lines) and the electric detonators are hooked to the main blasting circuit. When only a few adits are driven to execute the blast, millisecond detonators should be used to sequence the blast. A detonating relay is the assembly of two delay detonators in an aluminium sleeve with a total delay of 15 ms.

Equally important is the proper stemming of all the tunnels (adits and cross-cuts). Sandbags are generally used for this purpose, or broken muck that was generated while driving the openings could be used. Care should be taken that the stemming material does not damage the cord, detonating relays or any other explosive material placed for the blast. Stemming is started at the innermost pocket or cross-cut and run continuously up to the adit mouth through which the access was made. An example of a coyote blasting schedule for a civil construction project is given in Case Study 2.1.

Case study 2.1

The blasting schedule for a civil construction project

A civil construction project is used here to illustrate the complete procedure of a coyote blast.

Figure 2.19 shows the cross-sections through the explosive chambers of the three adits used in the mass blasting, details of the charging of the three adits, including the quantity of explosive and the blasting sequence, and the blasting circuit diagram.

Table 2.10 gives the computed volume of rock to be blasted by each pocket, the explosive charge of each pocket, and details of detonation relays and detonators.

Table 2.10 Rock quantity likely to be blasted by each of the pockets and the amount of explosive charged, and the sequencing of the coyote blast

Adit No.	Pocket No.	Toe distance: ft	Overburden: ft	Pocket spacing: ft	Volume: yd^3	Powder factor: lb/yd^3	Explosive: lb	Cases 25 lb	Delay No.	Remarks
1	1	25	73	30	1403	0.5	700	14	0	Electric detonator 0
	2	40	75	30	1956	0.5	1000	20	0	
	3	44	42	30	1350	0.5	700	14	0	
	4	30	97	30	2833	0.5	1450	29	15	Detonating relay introduced
	5	30	96	30	2833	0.5	1450	29	15	
	6	30	69	30	1933	0.75	1450	29	15	
	7	30	121	30	3650	0.6	2200	44	30	Detonating relay introduced
	8	30	113	30	3483	0.6	2100	42	30	
	9	30	79	30	2467	0.8	2000	40	45	Detonating relay introduced
2	1	26	67	30	1343	0.5	700	14	65	Electric detonator 2 + detonating relay
	2	22	86	30	1467	0.5	750	15	65	
	3	22	71	30	1234	0,6	750	15	65	
	4	30	123	30	3436	0.5	1750	35	80	Detonating relay introduced

	5	30	122	30	3600	0.5	1800′	36	80	
	6	30	96	30	2783	0.5	1700	34	80	
	7	30	154	30	4617	0.6	2300	46	95	Detonating relay introduced
	8	30	156	30	4633	0.5	2350	46	95	
	9	30	143	30	3933	0.5	2400	48	110	Detonating relay introduced
3	1	20	49	30	689	0.6	450	9	130	Electric detonator 4 + two detonating relays
	2	31	52	30	1206	0.5	600	12	130	
	3	35	61	30	1517	0.5	750	15	130	
	4	30	90	30	2317	0.6	1400	28	145	Electric detonator 2 + detonating relay
	5	30	64	30	1933	0.75	1450	29	145	
	6	30	68	30	3150	0.6	1300	26	145	
	7	30	106	30	3217	0.6	1850	37	160	Electric detonator 2 + detonating relay
	8	30	82	30	2433	0.8	1946	39	160	
	9	30	94	30	2650	0.75	1987	40	175	Electric detonator 2 + detonating relay

Figure 2.19 (a) Section through the explosive chambers/pockets used to determine the rock-mass volumes. (b) Explosive charging (loading) scheme. (c) Circuit diagram for the coyote blast

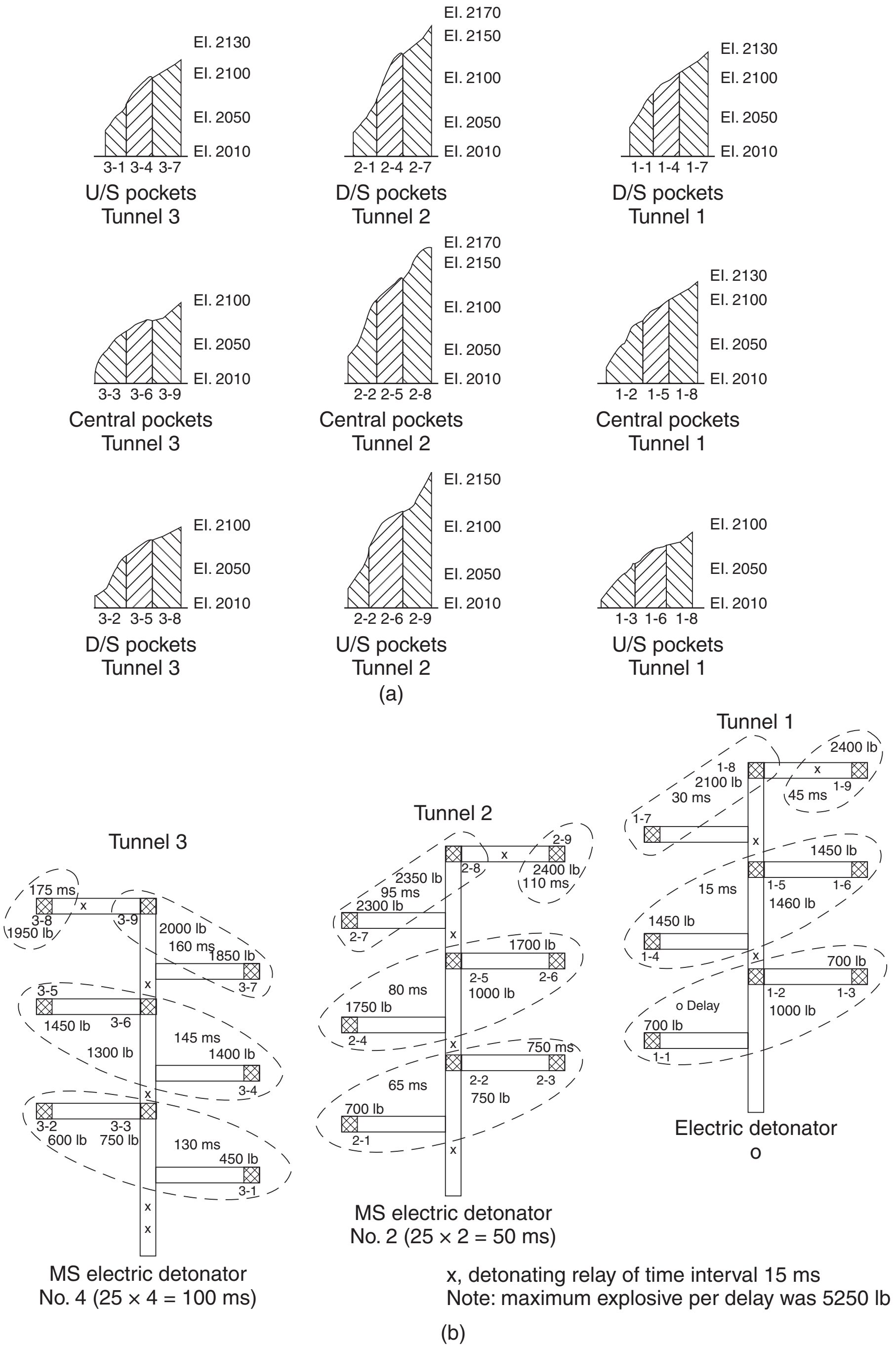
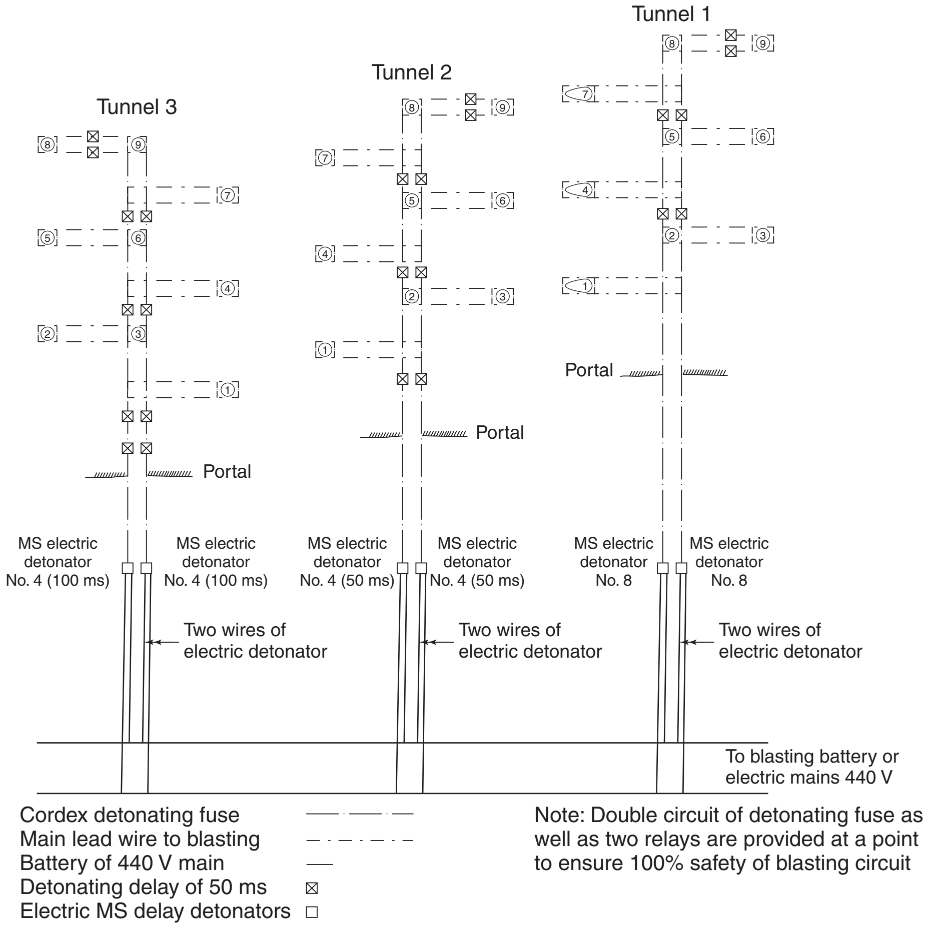


Figure 2.19 Continued



(c)

2.9.1 Precautions

- All the precautions necessary to undertake subsurface excavations should be strictly observed. As explosive in bulk quantity needs to be handled, transported and loaded into the coyote pockets, the rules on explosives laid out by the safety authorities of the country of operation must be strictly complied with.
- When undertaking such a heavy blast/mass-blasting the use of delay detonators and incorporating detonating relays in the Primacord to achieve the sequential firing are essential so that amount of explosive per delay remains within the allowable limits of the vibration that will be produced.

2.9.2 Applications

The above description has illustrated how a huge rock mass can be dislodged in hilly terrain using only explosive and without drilling. The coyote blasting technique finds application in construction projects such as dams, highways and other types of infrastructure where a huge rock mass must be safely dislodged at the work site within the shortest time. The technique also finds application in the removal of overburden while undertaking quarrying, whether by open-pit or open-cast mining.

The coyote technique can also be used to blast the hilly terrain over an area mined-out by underground mining so that the muck generated fills the underground voids and thus safeguards against sudden collapse of the ground above, thereby preventing a potential ‘air-blast’. Case Study 2.2 describes such a blast.

Case Study 2.2

Heavy blasting at a copper mine

Some 36 years ago the author had the opportunity to be the officer in charge of undertaking a heavy blast at an underground copper mine at Khetri in India. To execute this blast 22 ton of explosive was used to blast a rock mass of about 105 000 ton. The explosive was charged in rings designed to wreck the rib pillars between two worked-out stopes, caving rings and coyote chambers.

The site of blast was the two uppermost stopes, which were adjacent to one another and had a strike length of about 180 m, a height of 60 m and a width in the range 15–20 m. The volume of worked space after stoping amounted to around 180 000 m^3. As these were open stopes (i.e. without any artificial support), with the passage of time they might collapse at any time, causing a heavy ‘air-blast’. To avoid this disaster it was essential to block all the entries (access ways) to the stopes. The ore blocked in the rib pillar between these two stopes was also to be recovered. The blast was planned taking into consideration all these aspects. First, the rib pillar between the two stopes was drilled in the form of rings of parallel holes using the blast-hole drills. Then rings of holes were drilled in the hanging wall side of the stopes in planes almost parallel to the steeply dipping orebody that was present in these stopes. To avoid any risk of failure, caving rings and four coyote chambers (1.8 m × 1.8 m × 1.8 m) were driven at a distance of about 9 m from the last caving rings (Figure 2.20).

The rings were charged with ANFO and the coyote chambers with NG-based conventional explosive (dynamite). The stemming and packing of the coyote chambers was carried out using sandbags. Packing was supplemented by alternate rows of gypsum and sandbags. The firing sequence was planned as: (1) pillar rings, (2) hanging-wall caving rings and (3) the coyote chambers (Table 2.11). The sequence was selected so that the draw points and bottommost portions at the sill-level of the stopes would be filled with the ore from the rib pillar, and this would then be blanketed by the waste rock from the hanging wall. This waste rock cover would then be further blanketed by the waste rock generated by blasting the portion between the last hanging wall ring and the coyote chambers.

The following observation was made by the author who was present during the execution of the blast.

Some pipes (6 m long, 15 mm diameter) and other material such as timber, etc., were lying near the mouth (portal) of the adit, which was the access from the surface to the blast site. These materials were not removed before the blast, the expectation being that nothing would happen to them. However, immediately after the blast a cloud of blasting fumes was seen moving out from the portal with very high velocity, and these materials were thrown to a distance of more than 200 m, like bullets from a gun. In addition, all the electric power and telephone lines, which were outside the mine at the surface at a distance of more than 200–300 m from the blast site, were severely damaged.

2.10. Safety

Explosives safety begins with treating them with respect. Based on their composition and characteristics, the US Department of Transportation classifies explosives as (Pradhan, 1996)

- Class A: explosive possessing detonating or otherwise maximum hazards
- Class B: explosives possessing flammable hazards
- Class C: class A or B explosives, or both, but in limited quantities.

2.10.1 Precautions during handling, storage and transport of explosives

The golden rules. *Explosives should be protected against: flame/fire/heat/friction/naked light, pressure/jolt/throwing, tampering/breaking from their original form, and handling by unauthorised/untrained/unknown person (i.e. avoid pilferage)*.

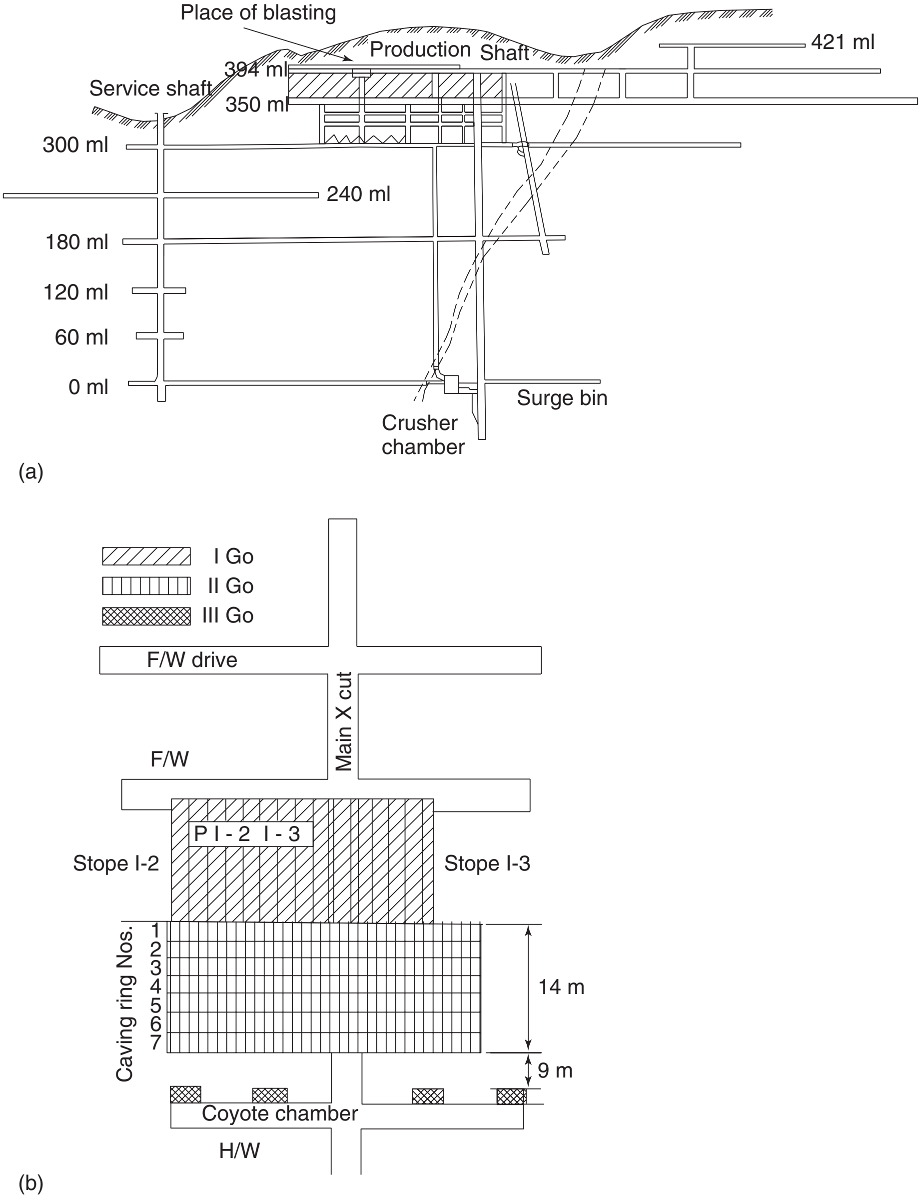
Every country has its own rules, regulations and laws that direct the use, handling and transport of explosives. You will find that most of these regulations are based on the golden rules above. The following guidelines should be adhered to:

- Explosives should be stored in an approved magazine. Different categories/classes of explosives should be stored separately. For example, there should be separate annexes for detonators, powder explosives and cartridge explosives.

Table 2.11 Application of the coyote blast and the blasting of the underground pillars in the underground copper mine

	Ore/ waste	Purpose	Long-hole drilling: m	Explosive charge: kg	Ore/waste blocked: ton
Pillar rings	Ore	Blasting rib pillars	3770	4554	16 605
Caving rings	Waste	To induce caving	6106	8525	44 704
Coyote chambers	Waste	To induce caving and summing up	–	8975	44 000
Total			9876	22 054	105 000

Figure 2.20 Details of heavy blasting at Khetri Copper Complex using coyote and long-hole/blast-hole blasting techniques. (a) Longitudinal section. (b) Details of the workings at the 394 m level, showing the relative positions of the rings and fans drilled in the ore, the caving rings drilled in the H/W waste, the coyote chambers and the blast sequence (I–III)



- A proper record of stock, issue, return and consumption must be readily available. All measures should be taken to avoid pilferage of explosives. Security personnel should be deployed around the clock to properly guard the magazine.
- The same vehicle should not be used to transport detonators and explosive cartridges.
- The majority of accidents that involve explosives can be prevented. However, prevention can only be accomplished when the user knows the safe procedures for transporting, storing and handling explosives. The presence of fire personnel is usually only essential at the scene of an explosion if the explosive manufacturer's instructions and warnings have been taken too lightly.

2.11. Terminology

(Ganpathy, 1978; Goddoy and Viera, 1982; Gregory, 1979; Jimeno *et al*., 1997; Olofsson, 1997; Pradhan, 1996)

Airdox. A cartridge in the form of a shell charged with compressed air, which when fired acts as an explosive to fragment coal. *Hydrox* is a similar cartridge containing a powder which when ignited generates nitrogen and water vapour. *Cardox* is a similar type of cartridge charged with liquid carbon dioxide.

ANFO. A blasting agent consisting of ammonium nitrate prills and fuel oil (usually No. 2 diesel fuel).

Arcing. A malfunction of an electric blasting cap caused by excessive firing current applied for too long a duration.

Back break. Rock broken beyond the limit of the last row of holes.

Back holes. The top holes near the roof of a tunnel or drift round; holes in the roof during stoping operations.

Black powder/gunpowder/blasting powder, or *low explosives*. The earliest known explosives belong to this class. They are commercially known as gun powder or black powder. They are a mechanical mixture of ingredients such as charcoal (15%), sulphur (10%) and potassium (75%).

Blast area. The area near a blast within the influence of flying rock fragments or concussion.

Blast hole. A hole drilled in the rock, ground or any other material for the purpose of placing an explosive charge.

Blaster. A competent person in charge of a blast. A blaster must undergo a qualifying test conducted by government-approved authorities.

Blasting agent. A mixture of fuel and oxidiser. It is not classified as an explosive, and cannot be detonated by a detonator (No. 8) when unconfined. A dry blasting agent is a granular, free-running mix of solid oxidiser (usually ammonium nitrate) prilled into porous pellets which absorbs a liquid fuel or propellant.

Blasting cap. Another term for a *detonator*.

Blasting circuit. An electric circuit that connects electric detonators/caps together and to blasting cable, which is ultimately connected to an exploder/blasting machine.

Blasting switch. A switch that connects the blasting circuits to the power source.

Blasting tools. Exploder, multi-meter and circuit tester. Other blasting tools include: crimper, for crimping the safety fuse into plain detonators; pricker, made of wood or a non-ferrous material, for pricking into an explosive cartridge to prepare the primers; knife, for cutting the safety fuse; stemming rod; scraper; flame safety lamp (in coal mines and tunnels); shot firing cable; stopwatch (when safety fuse is used); suitable warning signboards or signalling arrangement; and tamping rod, for pushing or compressing stemming material or explosive charge into the hole.

Booster. A special type of explosive which is powerful enough to complete the initiation work of the primer in the explosive column, and create zones of high energy release along the length of the explosive column.

Borehole. A hole that is used to accommodate an explosive charge.

Bottom priming. The method where the primer is placed at the bottom of hole to be charged, with the charge placed on top of it. See also *top priming*.

Bulk strength. The strength of an explosive is expressed as the amount of energy released per unit volume.

Cap. See *detonator*.

Cartridge. A cylindrical-shaped explosive or blasting power stick; available in a variety of diameters and lengths.

Cast blasting. Mass blasting of rock or ground resulting in casting of the fragmented rock or ground into the neighbouring area. Also known as ‘explosive casting’ or ‘controlled trajectory blasting’.

Circuit tester. In electric firing it is essential to check the resistance of the circuit, its continuity and the presence of short-circuiting, if any. This is achieved by the use of a galvanometer and blaster’s multi-meter. See also *multi-meter*.

Coyote blasting. A mass blasting in which a large mass of rock or ground is blasted without drilling. It is usually used in hilly terrain where access is made through an adit (an opening) and cross-cuts are driven to cover the area above which rock mass is to be blasted. The explosive charge is accommodated in small chambers (pockets) made in the cross-cuts.

Cross-cut. A passageway driven between the entry and a parallel air course or air courses for ventilation purposes.

Deck charging. The provision of a lighter charge to some length of a hole, or even not charging that length with explosive and instead placing some inert material, or even air. It can be used for strata of varying rock strength within the same bench height. When undertaking controlled blasting, use of this technique is almost mandatory.

Decoupling. The separation between the wall of a hole and the surface of explosive cartridges (charge).

Decoupled charge. The use of explosive cartridges of significantly smaller diameter than the borehole diameter. It is applied during controlled/contour blasting to minimise overbreak.

Deflagration. The process of burning of the explosive's ingredients at an extremely rapid rate (but well below the speed of sound).

Delay blasting. The procedure whereby delay detonators or connectors are used to achieve sequential firing (rather than instant/simultaneous firing) of the shot/blast holes when blasting a round.

Delay connector. A non-electric delaying device used with the detonating cord to achieve delay.

Demolition. The breaking of a man-made structure by blasting or other mechanism.

Detonating fuse/cord. A cord having a primary explosive, such as PETN, as its core and a wrapping of textile fibres, wire and plastic coverings around this core.

Detonating relay (MS connector). A device used in conjunction with detonating cords to blast a large number of holes, these devices introduce millisecond delay intervals between blasts in holes or rows of holes (manufactured with delay intervals of 15, 17, 25, 35, 45, 50, 60 and 100 ms). A detonating relay consists of a long aluminium tube with two mini-delay detonators, one on each side, and an attenuator in the centre. The opening at each end can be crimped to detonating cord. Such relays are easy and safe to handle, and can provide better fragmentation, reduced ground vibration, a better muck pile and a reduction in overall costs.

Detonation velocity. The speed at which the detonation wave travels through the explosive column.

Detonation wave. The shock wave that results from the initiation of an explosive charge.

Detonation. The process of the propagation of the shock waves through an explosive charge.

Detonator. A capsule of sensitive explosive material that delivers a strong shock (or detonation) to initiate high explosives and the blasting agents. Also known as a ‘cap’.

Direct and indirect initiation. indirect initiation. When charging a hole with explosive, a primer is put at the bottom of hole and the rest of the charge (explosive cartridges) is placed afterwards, filling the hole towards the collar. *Direct initiation:* the primer is placed near the collar after placing the main charge in the hole.

Drift. An almost horizontal underground opening or passage that follows a vein or deposit (compare with ‘cross-cut’ and ‘level’).

Drive/driving, sinking, winzing and raising. The process of excavating horizontally or at a certain inclination in the rock massif is known as *driving*; the process of excavating in a vertically downwards direction is known as *sinking* (usually with a cross-sectional area $>10\ \mathrm{m}^2$) or *winzing* (usually with a cross-sectional area $<10\ \mathrm{m}^2$). When an excavation is made in an upwards direction it is known as *raising*.

Dry blasting agents (powder explosives). One of the major applications of prilled ammonium nitrate coated with an anti-caking agent is in the manufacture of powder explosives.

Dynamite. Nitroglycerine-based explosives are called dynamites.

Emulsion. A two-liquid phase containing microscopic droplets of aqueous nitrates of salts (chiefly ammonium nitrate) dispersed in fuel oil, wax or paraffin using emulsifying agent.

Exploder. A machine designed to fire electric detonators.

Explosive. A substance or mixture of substances which on the application of a suitable stimulus, such as a shock, an impact, heat, friction, ignition or spark, undergoes an instantaneous chemical transformation to produce an enormous volume of gases having a high temperature, heat energy and pressure. This, in turn, causes a disturbance in the surroundings, which may be solid, liquid or gaseous, or their combination.

Extraneous electricity. Electrical energy, other than the firing current, which may be hazardous to electric detonators/caps. Induced stray current, static electricity, lightening, radio-frequency energy or high-voltage power lines could be the source of extraneous electricity.

Face. The end of an excavation (a tunnel or mine) that is exposed to the air.

Fly rock. A rock fragment that is propelled through the air by the energy of the blast.

Fumes. Noxious or toxic (poisonous) gases that are liberated from a blast.

Fuse lighter. A device used to ignite the safety fuse.

Gelatin. An explosive or blasting agent having a gelatinous consistency.

Hercudet. An initiation system for explosives that uses gas for detonation.

Hertz. The unit to express ground vibrations and air blast. One hertz (1 Hz) is equivalent to one cycle per second.

Initiation. The process of detonating high explosives using a detonator, a mechanical device or other system.

High explosives. Explosive substances that cannot be initiated easily by a stimulus such as impact, friction or flame but require the application of a shock pressure wave or a detonation wave for initiation.

Igniter cord (IC). A type of fuse used to initiate an explosive device or charge. It is cord-like in appearance and when ignited the flame passes along its length at a uniform rate. It is available with three rates of ignition, which are colour coded: fast, 3.5 s/ft (black); medium, 5–10 s/ft (green), and slow, 15–20 s/ft (red). It can be used for lighting any number of safety fuses in a desired sequence in surface blasting and blasting in non-gassy underground mines and tunnels. Special connectors are required to use this cord.

In situ. In the natural or original position.

Incline. An inclined passage of limited cross-section driven from the surface to access the orebody and/or provide mine services. The angle of incline needs to be suitable for a conveyor or rope haulage/hoisting.

Inclined shaft. A steeply inclined passage of limited cross-section driven from the surface or underground giving access to the orebody. It serves deeper levels, and could be tracked or trackless.

Instantaneous detonator. A detonator without any delay element.

Jumbo. A carrier equipped with a number of drills known as ‘drifters’.

Kerf. A face/space created by undercutting or shearing the rock vertically or diagonally. This term is also used for the cut that joins the two stables of a longwall face to provide the initial free area to begin the face.

Level. Any underground horizontal or almost horizontal roadway driven almost parallel to the strike direction of the deposits.

Magazine. A building, structure or container specially constructed to store explosives, blasting agents and blasting accessories such as detonators, safety fuse, detonating cord etc. It is constructed according to specifications set by the safety authority of the country and must comply with certain basic design considerations. It should be located in an isolated and remote area.

Mat. A covering made of used conveyor belts, scrap tyres, woven cables or any other suitable material to hold down the blast fragments and prevent them from flying through the air.

Micro-balloons. Tiny hollow spheres of glass or plastic which are added to the explosive material to enhance its sensitivity by ensuring an adequate content of entrapped air.

Misfire. The failure of a blasting charge to blast or fire for any reason.

Mohs scale. An arbitrary qualitative scale indicating the scratch hardness of a mineral.

Multi-meter. An instrument for a number of purposes in a blast using electric detonators. It is used to check line voltage, firing circuits, current leakage, stray currents and other factors that pertain to electric blasting. Such meters should be approved by the government-approved safety/competence authorities in the country.

Nitrous fumes. Brown coloured fumes composed of gases such as NO, N_2O and NO_2 that are the products of high explosives.

Noxious gas. Harmful gases found in the atmosphere in a mine, such as methane, carbon dioxide, carbon monoxide, hydrogen sulphide and nitrous fumes.

Ore. The portion of any mineral deposit that can be mined at a profit.

Outcrop. A part of a rock formation that appears at the surface of the ground.

Overbreak. Excessive breakage of rock beyond the desired excavation profile.

Overbreak factor. After blasting the face (of a tunnel or any underground opening) there is usually breakage of the face that is additional to designed breakage. The overbreak factor is the ratio of the area of breakage after blasting, including the overbreak, to the designed breakage.

Overburden. The rock or material overlying the rock to be blasted.

Oxidiser. An essential ingredient of an explosive or blasting agent. The oxidiser combines with the fuel to form the gaseous products. Ammonium nitrate is the most common oxidiser in commercial explosives.

Percentage pull. The ratio of the length of the round drilled to the effective linear advance obtained after blasting. A pull below 100% indicates inefficient drilling and blasting.

Permitted explosives. Explosives designed to be used in underground coal mines to avoid a methane–coal dust explosion. A cooling agent is incorporated in all permitted explosives. Common cooling agents are sodium chloride, potassium chloride and ammonium chloride.

Plaster shooting. The blasting of a large chunk of rock (a boulder) by placing an explosive charge in close contact with the boulder, covering it completely with mud (as if plastered over) and firing.

Pop shooting. The blasting of a large chunk of rock (a boulder) by drilling shot holes and placing the charge in them.

Portal (collar). The entrance at the surface of an underground inclined or horizontal opening such as an adit, incline or decline. For a vertical or steeply inclined shaft this is called the *collar*.

Powder factor. The amount of an explosive (in kilograms) required to blast one ton or one cubic metre of rock.

Prill. A tiny sphere of ammonium nitrate capable of absorbing more than 6% by weight of fuel oil.

Primary explosives. Explosive substances that respond to a stimulus such as a shock, an impact, friction, flame, etc., and pass from the state of deflagration (a high rate of burning) to detonation.

Primer. A cartridge of cap-sensitive explosive that contains a detonator or other initiator.

Production drilling. The drilling of shot holes, blast holes and big blast holes.

Propellant explosive. Usually an explosive that deflagrates and causes propulsion.

Reserve station. An underground store of explosives.

Roadway. An underground drivage in any rock and any heading, cross-cut, tunnel or level.

Rocks. The crust of Earth consists of different types of rock which are composed of one, or more frequently more than one, mineral element or chemical compound. The common rock-forming minerals are quartz, calcite, feldspar, hornblende, mica and chlorite.

Round. A planned pattern of holes fired in sequence during tunnelling, driving, raising or winzing.

Safety fuse. Introduced by William Blackford in 1983 to initiate gun powder/black powder. It consists of a core of fine-grained gun powder/black powder wrapped with a layer of tape or textile yarns and has a waterproof coating to guard against moisture and shock. It burns at a rate of 600 mm/min.

Scaling. The removal of loose rocks from the roof or walls using a long scaling bar.

Seam. A deposit limited by two more or less parallel planes, a shape that is typical of sedimentary rocks.

Secondary breaking. The process of breaking oversized boulders (lumps) which can be generated during a primary blasting operation.

Secondary explosives. Explosive substances that can be detonated by a primary explosive, not by deflagration. Thus these explosives have a high rate of detonation and are initiated by the primary explosives.

Sedimentary rocks. Rocks that have been formed by weathered material from the solid crust of the Earth which has disintegrated and become sedimented at river mouths and on the beds of prehistoric seas.

Seismograph. An instrument used to measure earth-borne vibrations induced during an earthquake and/or blasting operation. In blasting it is also known as ‘blast monitor’.

Sensitivity. The measure of an explosive’s propagation property to bridge a gap between two consecutive cartridges or a column of an explosive charge. For example, if a cartridge is cut into two halves, which are then placed with a gap between them and blasted unconfined in a paper tube by initiating one of the halves, the sensitivity is reflected by the size of the gap that will allow the other half to receive the propagation wave.

Shaft. A vertical passage of limited cross-section driven from surface or underground, giving access to an orebody. It serves deeper levels, which could be tracked or trackless.

Shock wave. A pressure pulse that propagates at supersonic velocity.

Shooting. The process of blasting shot holes.

Shot holes, blast holes and big blast holes. Holes drilled and charged with explosives to fragment rock are termed *shot holes* if their diameter is <40 mm, *blast holes* if their diameter is 40–100 mm and *big blast holes* if their diameter is 100–300 mm.

Site-mixed slurry (SMS). Slurry that is produced by mixing the ingredients at the work site before discharging/delivering it into the hole.

Slurry explosive. A semi-solid or pasty suspension of oxidisers, fuel, sensitisers, etc., in a thickener like guar gum. Inorganic cross-linking agents are added to prevent the separation of solid and liquid phases during storage. The final product is a cross-linked water gel.

Split. A current of air that has been separated from the main intake to ventilate a district or section of a mine.

Stink damp. The unpleasant smell (rotten eggs) of hydrogen sulphide (H_2S), which is produced by the reaction between an acid and sulphur, which is found in various forms in mines.

Stope. A block of ore of convenient size that can be won (exploited/extracted) safely and efficiently.

Stoping. The process of extracting rock around the cut area in a tunnel blast. In mining, the process includes ore fragmentation and its removal from a stope.

Sublevel drive. A drive between and in almost the same direction as two main levels.

Subsidence. The lowering of the overlying surface as a result of the underground mining of ore deposits.

Subsonic. Slower than the speed of sound (343 m/s).

Sulphur dioxide. A gas that has a burning and choking effect. It is produced in mines mainly by spontaneous heating, explosives, fire oxidation, etc.

Sump. An excavation made for the purpose of mine water storage and its onward pumping to the surface.

Supersonic. Faster than the speed of sound (343 m/s).

Top priming. The method of placing the primer on the top of the explosive charge in a hole near the collar. See also *bottom priming*.

Toughness. The resistance to fracture that comes essentially from the tensile strength of the rock.

Track system. A system where tracks or rails are laid out for the purpose of transportation. A mine with such a system is known as a *tracked mine*.

Trackless system. A transportation system that does not involve tracks or rails but uses transporting units with rubber tyres. A mine with such a system is known as a *trackless mine*.

Trunk line. A detonating cord line that is connected to other detonating cord lines for a blast. It is usually laid along each row of blast holes.

Tunnel. A horizontal or almost horizontal passage of limited cross-section that is open to the atmosphere at both ends.

Undercut. An excavation beneath a block of ore. The process of making an undercut is known as *undercutting*.

Underhand stoping. Where the direction or posture of winning the ore is from the upper level towards the lower level.

Vein. A zone or belt of mineralised rock lying within boundaries that clearly separate it from the neighbouring rock.

Ventilating pressure. The pressure (in kg/m^2 or kg/mm^2) of water gauge required to produce a flow of air through the mine. It can be calculated using the Atkinson equation.

White damp. This is caused by carbon monoxide (CO), a poisonous gas, which has no smell. Common sources of CO are spontaneous heating, explosives and diesel engines.

Winze. A vertical or steeply inclined excavation or opening that connects two levels. It is driven (sunk) from the upper level to the lower one.

2.12. Concluding remarks

- Excavation accomplished using explosives requires production drilling by the use of rock drills. Charged holes up to 40 mm in diameter are termed ‘shot holes’ and those exceeding 40 mm in diameter are termed ‘blast holes’.
- Excavation without aid of explosives requires techniques such as ripping, cutting, crushing, boring, impact hammering, etc., as detailed in Chapters 5–9.
- Today, drilling operations are fully automated and a variety of drills and drilling accessories are available that can cope with the current requirements of the civil, construction and mining industries. Production drilling holes up to 300 mm in diameter and 150 m in length are not uncommon. Drilling can be accomplished in any direction.
- To use the rock drills and their accessories effectively it is important to know and understand the properties of rock, such as abrasiveness, hardness, rock texture, toughness, elasticity or resilience, brittleness, rock strength, and porosity and permeability.
- Laser measurement systems and GPS can be used with modern drilling equipment. Computerised drilling control provides the ideal combination of feed, rotation and penetration rates.
- Light- and heavy-duty chipping hammers are essential tools in the construction industry. These pneumatic hammers and breakers are suitable for tough material such as frozen ground, asphalt, concrete, coal, clay, non-consolidated rocks and a

few others. They are mostly used as demolition tools, and can be also used for the light digging jobs. They are available with different design features to suit different types of job.

- Rig-mounted hydraulic breakers are efficient tools for many operations at surface and subsurface locales, as described in Chapter 5. They are suitable for tasks that cannot be done using pneumatic breakers and chipping hammers, and when the task is heavy, dangerous, awkward and difficult to access. A hydraulic breaker can be attached to an excavator, thereby extending the field of applications in which an excavator unit can be used. Hydraulic breakers can be used to accomplish tasks such as demolition, trenching, scaling, breaking soft rocks for roads and bridges, in the process industry, splitting boulders, etc.
- An explosive is the cheapest option to fragment rocks at civil tunnels and construction sites. The first explosive was black powder, which was used in China during the 11th century. Since then explosives have found wide application in both war and peace time.
- Explosives that generate detonation waves are known as high explosives. 'Dynamite', which was invented in 1867–1875 by Alfred Nobel, is one such explosive. It contains nitroglycerine (NG) as a sensitiser, which is so sensitive that it can explode with a slight shock of any kind. Commercially high explosives are available as dynamites (a mixture of ammonium nitrate (AN), NG and sodium nitrate ($NaNO_3$)); blasting gelatin (92% NG and 8% nitrocellulose), which is the most powerful NG-based explosive; and semi-gelatin (low NG or high AN).
- A blasting agent is a mixture of combustible and oxidising substances that are not themselves intrinsically explosive. Blasting agents can be wet (aqueous), such as slurry and emulsion, or dry, such as ANFO. Ease of manufacture, use and handling, low cost and reasonable strength are some of the features that have made ANFO a popular blasting agent for use in surface and subsurface locales. Emulsions having better water resistance and fume qualities, and are gaining in popularity and have a bright future.
- In order to initiate explosives and blasting agents (which often require a primer of high explosive which is non-cap-sensitive) plain, long-delay and short-delay detonators are used. These can be electric or non-electric. The selection of blasting agent is based on blast size, necessary safeguards against electrostatic charge, lightning and stray current, delay interval and the precision required in the delay timings. Electronic detonators meet these requirements and are finding increasing use, but their higher cost is a big constraint.
- Explosive when initiated in a hole releases a high volume of gases at very high temperature and pressure, which ultimately results an explosion, hence the name 'explosive'. A controlled explosion causes rock fragmentation, displacement of the rock, the generation of shock waves (vibrations) and an air-blast that is heard as a loud bang. The success of an explosion lies in the proper selection and judicious use of explosive, to cut costs, preserve ground stability and minimise adverse impacts on the surrounding environment.
- In order to achieve the desired configuration of the excavation and minimise overbreak, reduce vibrations and preserve the ground stability, a technique known as 'contour blasting' is in vogue. It finds application in surface blasting, such as

for road cuts, foundations, dams and highway construction. The contour blasting technique can be subdivided as follows:
  - Pre-splitting is undertaken to isolate the blasting area from the rest of the rock formation by creating an artificial crack along the intended excavation plane. This is done before the main blast or by applying an initial delay to the pre-split holes and a subsequent delay to the main blast. It requires closed spaced drilling and a larger explosive-charge than smooth blasting.
  - Cushion blasting functions well in incompetent formations for surface excavations and requires less drilling than pre-splitting. Executing the main blast, including mucking out the broken rock before the cushion blast, is mandatory. The technique involves the use of a decoupled charge. In larger diameter holes explosive cartridges that are 0.2–0.5 times the hole diameter are charged by tying them with detonating cord. These cartridges are set 30–50 cm apart and the gap between the wall of the hole and the cartridges is filled with some inert material.
  - In smooth blasting for surface excavations, a single row of holes is drilled along the neat excavation line, and loaded with light, well-distributed charge. The charge is fired either together with the bulk holes giving the last delay, or after them as a separate blast. Smooth blasting when used for underground tunnels and caverns is described in Chapters 4 and 9.
  - When drilling is done skin-to-skin (i.e. without any spacing, or with very little spacing) the technique is known as ‘line drilling’. Its use is almost mandatory when even lightly charged explosives could cause damage beyond the excavation line.
- Coyote blasting is a non-nuclear mass blasting technique involving a bulk quantity of explosives to blast a huge rock mass without drilling. Rather, small-sized pockets are driven to accommodate the explosive.
- Precision of production drilling, and selection of the correct quantity and quality of explosive results in the desired fragmentation, which is the key to optimising the overall cost per unit of rock broken.
- To gain the maximum from this cheapest source of energy and to avert accidents explosives must be respected. The golden rule is to protect explosives against heat, pressure, jolting, tampering and handling by unauthorised persons (i.e. avoid pilferage). Laws in most countries the world over concerning the use handling, transport and storage of explosives follow these guidelines.

2.13. Questions

1. What is meant by ‘fragmentation’? How can it be achieved? What are boulders?
2. What does the term ‘production drilling’ refer to? How does it differ from exploration drilling?
3. What are rock drills? Give brief history, particularly since 1950, of the development of rock drills, including their current status in terms of their capability (hole diameter and length). Other than in production drilling, where are rock drills used?
4. Differentiate between: shot holes and blast holes; rotary crushing and rotary cutting; cross-bits and X bits.

5 List the techniques for achieving fragmentation without the aid of explosives.

6 A drilling system involves four components – list them. Illustrate the drilling mechanism.

7 Give a classification of rock drills through the use of a line diagram based on: (a) the transfer of the mechanical energy to the rock; (b) motive power (energy) of the drills; and (c) drill mountings.

8 Make a list of drilling accessories, noting their types, uses and size details (specifications in terms of their diameter and length ranges).

9 Is it true that drill rods and bits are valuable accessories? How can we ensure their effective utilisation to achieve their maximum service-life?

10 List the properties of rock that must be known and understood thoroughly in order to effectively utilise rock drills and their accessories.

11 List the types of drill that you would deploy when undertaking following operations: sinking, raising, winzing, drifting, tunnelling and making large-sized openings (caverns). Give details of the drills in terms of their capability with regard to their length and diameter ranges.

12 Describe hydraulic drills. List their merits and limitations.

13 List the components of an integral drill steel. Name the type of bit used with extension drill steels.

14 What is a drill jumbo? What are its components? Describe briefly the uses of the following jumbos: roof bolting jumbos; down-the-hole (DTH) drill jumbos; wagon drill jumbos; fan drilling jumbos; shaft jumbos; and drifting and tunnelling jumbos.

15 List the types of chipping hammers and breakers commonly used in construction projects.

16 Where do rig-mounted hydraulic breakers find application? Describe their features briefly.

17 When are ‘motor drills’ and breakers used? List the activities/jobs for which they are most suitable. Describe Atlas Copco’s petrol-driven Cobra Combi and state the function it is used to perform.

18 When and where was black powder invented? How do we use explosives during war and peace time? List the applications of explosives.

19 Define an explosive. What makes it so powerful/energetic? Is it the cheapest source of energy?

20 Differentiate between an explosive and a blasting agent. Tabulate the ingredients (oxidisers, fuels and sensitisers) that constitute explosives and blasting agents.

21 Differentiate between an emulsion and slurry. Tabulate the composition of some slurries and emulsions known to you.

22 It is advocated that the use of emulsions has a better future? Is this true? Justify your answer.

23 Draw a line diagram to classify explosives, including blasting agents.

24 Make a list of commercial explosives and describe each one. Differentiate between the following: commercial and military explosives; low and high explosives; deflagration and detonation; primary and secondary explosives.

25 What is dynamite? When and by whom was it invented?

26 ANFO is composition of ammonium nitrate and fuel oil. What should be the proportion of these constituents to make the ANFO oxygen balanced? What could be consequences if the percentage of fuel oil is more or less than required for the reaction to be oxygen balanced?

27 What are the static hazards associated with loading ANFO pneumatically. What precautions should be taken?

28 Describe and illustrate by means of suitable diagrams the mechanism of blasting. Cover the following aspects: (a) physical phenomena during blasting; (b) various stages during blasting.

29 List the adverse impacts of explosives and explain how they could be minimised.

30 What is meant by 'control blasting'? Is it same as 'contour blasting'?

31 List the contour-blasting techniques. Describe each technique, giving suitable diagrams/sketches.

32 List the blasting accessories that are essential during blasting operations.

33 What is a blasting cap/detonator? Give its composition/constructional details.

34 List the different types of detonators/blasting caps, and draw sketch of each one to show its construction.

35 Differentiate between the following:
(a) an ordinary detonator and a plain electric detonator
(b) a plain electric detonator and an electric delay detonator
(c) a Nonel and a Hercudet initiation system
(d) an electric and an electronic detonator
(e) a long-delay and a short-delay detonator
(f) safety fuse and detonating cord
(g) a primer and a booster
(h) primary and secondary explosives
(i) plaster shooting and pop shooting
(j) dry and wet blasting agents
(k) direct and indirect initiation.

36 Why is the use of electronic detonators becoming more popular? What are their limitations?

37 What are fuses, primers, boosters and shape charges? Describe each one and give its field of application.

38 In your company you are required to undertake blasting operations for both surface and subsurface excavations, including tunnelling. What are the blasting tools that you require? List them, giving the use of each one.

39 List the properties of explosives that should be considered prior to making a selection for a specific use.

40 Density, detonation velocity, and detonation or borehole pressure are interrelated parameters. Give the equation that expresses their relationship (define the notation used).

41 Draw up a table to compare the important properties of different explosives. Which of the explosives in your table would satisfy the following requirements:
(a) cheapest
(b) most expensive
(c) most water resistant

(d) most powerful (highest strength)
(e) least water resistant
(f) highest detonation velocity
(g) good fume quality
(h) poor fume quality
(i) highest density
(j) least dense?

42 The cost of an explosive should be judged in terms of the overall cost of the blasting. List the operations for which the cost/ton or cost/m^3 of rock production should be taken into account. (*Hint*: Use an equation with + or − signs to express the costs of the operations that should be considered.)

43 We must learn to 'respect explosives' – is this true? If yes, then how?

44 Classify explosives according to the prevalent laws and legislation of your country. Also classify them according to the US Department of Transportation.

45 What is the 'golden rule' with regard to the safety of explosives during their storage, handling, transportation and use that should be observed?

46 When can an uncontrolled explosion occur while dealing with explosives that will require the assistance of fire-personnel other than, of course, in the event of a fire?

47 When can an explosive generate excessive toxic gases that require increased ventilation to avoid injury to health? How can this occurrence be prevented?

48 What can be the result when drilling and blasting operations are not properly matched?

49 Proper selection of an explosive and its judicious use is the best way to cut costs, preserve ground stability and minimise environmental damage. Is this true? If so, how can it be achieved?

50 What is peak particle velocity? What is its significance? Give the equation used by the United States Bureau of Mines (USBM) to determine it.

51 What is a Nonel system? Who developed this system and how does it work?

52 How would you initiate a detonating cord? Name an initiating system that is based on gas firing.

53 Name the antistatic detonators and give their uses.

54 List the specialties of the blasting agent ANFO. How it is manufactured?

55 What is the Mohs scale? Where does it find its application?

56 Define the following terms: (a) round, (b) misfire, (c) decoupling, (d) deck charging, (e) nitrous fumes, (f) buffer blasting, (g) arcing, (h) blasting agent, (i) blasting circuit, (j) cartridge, (k) cast blasting, (l) delay connector, (m) detonating relay, (n) detonation wave, (o) exploder, (p) extraneous electricity, (q) fly rock, (r) fumes, (s) gelatin, (t) magazine, (u) instantaneous detonator, (v) sensitivity, (w) site-mixed slurry, (x) trunk line.

57 Draw up a table of the explosives available for controlled blasting, as proposed by DuPont and Nitro Nobel. Mention their significance.

58 What are the likely impacts if the recorded peak particle velocity is (in mm/s): (a) 600, (b) 300, (c) 190, (d) 100, (e) 50, (f) 10, (g) 1, (h) 0.1.

59 Calculate the detonation pressure of the explosive ANFO if its density is 0.85 g/cm^3 and the velocity of detonation is 2900 m/s.

60 Calculate the explosive density of an explosive that is capable of producing a detonation pressure of 30 kbar and a velocity of detonation of 3000 m/s.

61 What are permitted explosives? Give their usual composition and their applications.

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Chapter 3

Earth movers, excavators and open-cut excavations

The proper matching of equipment, methods, techniques and layouts will yield optimum results. In a properly designed and executed blast only 20% of the energy does useful work, while the other 80% is converted into ground vibrations, air-blast, etc. (Betra, 1990).

3.1. Introduction

Civil excavations and excavations done to obtain minerals from mines produce rock and other material from the Earth's crust amounting to millions of tons every day. To cope with these large volumes of material, specialist equipment is required. A *bucket wheel excavator* is capable of breaking up ground at a rate of up to 10 000 m^3/h, and is the largest type of man-made equipment on Earth. Off-highway trucks with up to 320 ton capacity and bucket excavators such as draglines, dipper shovels and hydraulic excavators are the result of the growing demand for a highly productive equipment fleet in this specialised field.

Muck is the material that is produced after digging, excavating or fragmenting *in situ* rock mass or ground, with or without the aid of explosives. Removing this muck from its place of generation is known as *mucking* or *loading*. The equipment used for this purpose is known as a *mucker*, *loader* or *excavator*. Other nomenclature is used to designate different types of equipment meant for excavating operations, and is discussed in the following paragraphs. Together these types of equipment are known as *earth-moving machinery*. Such machinery is used for mucking, scraping, digging, casting, pushing, shifting, ripping, dozing, levelling and dragging the material. Their multiple uses are shown in Table 3.1 (Fiat-Hitachi, 2000). They meet the requirements of many industries as well as the tasks carried out by public utilities.

3.2. Classification – earth excavation, loading and casting units

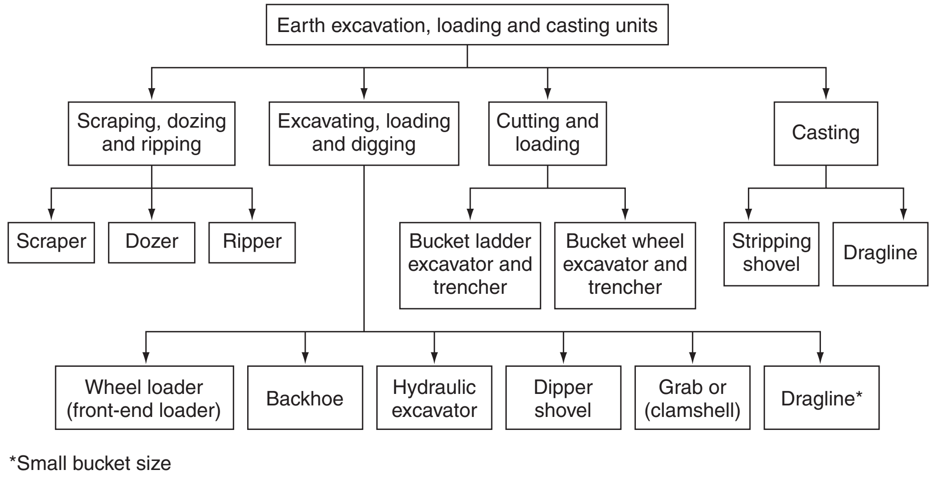
In Figure 3.1 earth movers are classified according to their uses and the operation(s) they undertake. Column 1 in Table 3.1 lists the common activities involved in various construction and civil projects, and columns 2–14 describe the suitability of common earth movers to accomplish these activities. The various types of earth-moving units are described briefly below.

Table 3.1 Applications of the different earth movers used in construction and civil projects (courtesy of Komatsu, Japan)

Activity	Hydraulic excavator	Mini hydraulic excavator	Bulldozer	Dozer shovel	Wheel loader	Mini wheel loader	Dump truck	Crawler carrier	Motor grader crane	Trash compactor	Backhoe	Skid steer loader	Recycling equipment
River maintenance	●	○	○		○	○	○	○			○		○
Road construction	●	●	●	○	○	●	●	○	●		●	●	○
Harbour and airport construction	●	○	●	○	○		●	○	●		○		○
Building and demolition	●	○	○	○	○	○		○			○	○	●
Earth-moving	●	○	●	○	○	○	●	●	○		○	○	●
Water-main and sewer construction	●	●			○	●		○			●	○	○
Landscaping	○	●	○	○	○	●		○			○	●	○
Agricultural engineering	●	○	●	○			○	●	○		○	○	○
Livestock raising	○	○	●	○	○	●						●	○
Lumber and forestry	●	○	○	●	●	●		○	○		○		●
Cargo industry	○	○		○	●	○					○	○	○
Mining and quarrying	●		●	○	●	○	●		○		○		●
Waste management	●		●	○	○		○	○		●		●	●
Tunnel construction	●				●		●	○					○

●, Main equipment; ○, secondary equipment.

Figure 3.1 Classification of excavating, digging, cutting, loading, mucking and casting units



3.3. Equipment details

This section briefly describes various earth movers such as scrapers, rippers, dozers, loaders, trenchers, graders and excavators. Scraping, ripping and digging are the techniques commonly used for removing soft and weak material such as clay, silt, sand, shale, weathered rock and topsoil. Such equipment works best in ground that has a seismic velocity lower than 1000 m/s (Blyth and Freitas, 1988) (see Figure 3.2 as a guide for the application of such units). Knowledge of parameters such as the spacing of fractures and other discontinuities (their continuity and orientation) and the in situ seismic velocity of the ground, etc., can be used to determine the ease with which a rock or soil may be excavated.

3.3.1 Bulldozer

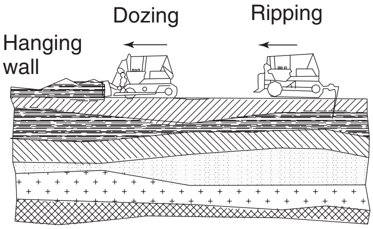
A bulldozer (Figure 3.2(a)) is a crawler-mounted or wheeled tractor unit fitted with a blade (Caterpillar, 2016). It is capable of excavating, moving and stockpiling the earth or rock (ground). Based on the duties this unit can perform, it is usually classified as:

- extra heavy duty (>300 hp)
- heavy duty (150–300 hp)
- medium duty (100–150 hp)
- light duty (20–80 hp).

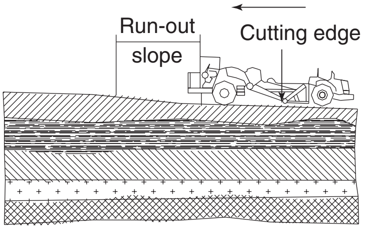
The operating cycle of a bulldozer consists of cutting off a horizontal or inclined slice from the ground, forming a dragging prism, moving the latter and then dumping it.

When selecting this unit, a proper match between the tractor (in terms of its power and weight) and the type of blade should be considered. Selection of the blade will depend on

Figure 3.2 Excavators used for the earthwork, rock extraction and ore mining

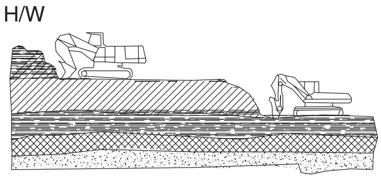


(a) Dozer and ripper

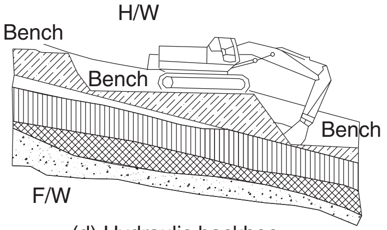


(b) Scraper

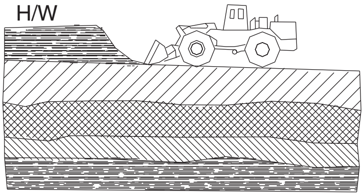
Single-bucket excavators



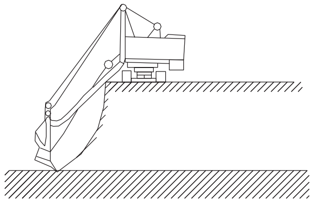
(c) Hydraulic front shovel



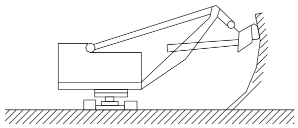
(d) Hydraulic backhoe



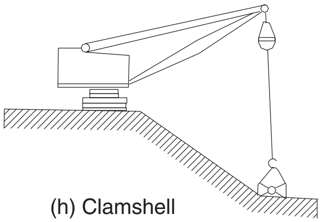
(e) Wheel loader



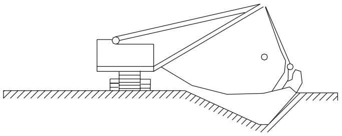
(f) Backhoe



(g) Dipper shovel



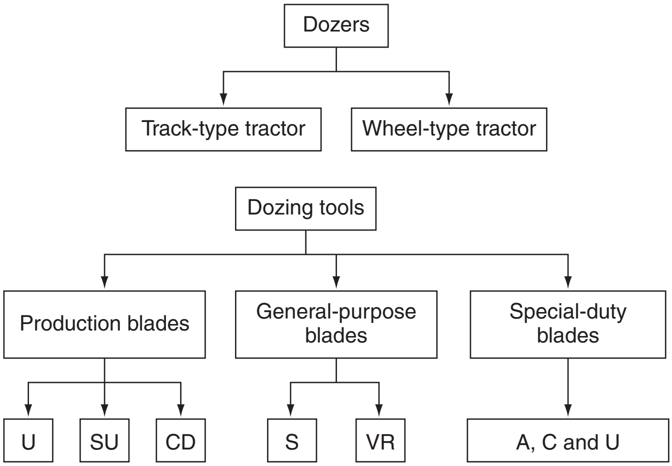
(h) Clamshell



(i) Dragline

the type of material to be moved. Most materials can be handled using a dozer. However, the dozer performance will vary with the material characteristics such as *particle size and shape*, the *presence of voids* and *water content*. A brief description of prominent blades that could be attached to a dozer is given below (Figure 3.3).

Figure 3.3 Classification of dozing tools (see text for abbreviations used)



- U – Universal blade: suitable for moving big loads over long distances, as in land reclamation, stockpiling, charging hoppers and trapping for loaders.
- SU – Semi-U blade: suitable for working in tightly packed materials and for handling a wide variety of materials in production-oriented applications.
- CD – Carry dozer blade: its bucket-like shape allows it to carry several cubic metres of material in the bucket.
- S – Straight blade: this blade is most suitable for heavy loads. It provides excellent versatility. It is smaller than SU or U blades which allows it to handle a variety of materials.
- VR – Variable-radius blade: an excellent tool for land improvement, soil conservation, site development or general construction.

3.3.1.1 Special application dozing tools

- A – Angling blade: can be positioned straight or angled 25° to either side. Suitable for side casting, pioneering roads, back-filling, cutting ditches and similar tasks.
- C – Cushion blade: used for on-the-go push loading. Rubber cushions allow the dozer to absorb the impact of contacting a scraper pushback.
- U: can move high volumes of non-cohesive materials such as coal and wood chips.

Other special-duty blades include: landfill, two-way dozer, V-type cutter, rakes, K/G blades and many others.

3.3.1.2 Dozer production

The output from a dozer (Tables 3.2 and 3.3) can be calculated using the following relationship:

$$P_{\mathrm{S}} = D_{\mathrm{bcap}} \frac{K_{\mathrm{ff}}}{K_{\mathrm{sf}}} N O_{\mathrm{e}} \qquad (\mathrm{m}^3/\mathrm{shift}) \qquad (3.1)$$

Table 3.2 The operating efficiency (O_e) of earth-moving/excavating equipment

Job conditions	Management conditions			
	Excellent	Good	Fair	Bad
Excellent	0.83	0.80	0.77	0.70
Good	0.78	0.73	0.70	0.64
Fair	0.72	0.69	0.66	0.60
Bad	0.63	0.61	0.59	0.54

where P_s is the production per shift (m^3), D_{bcap} is the dozer's blade capacity (m^3; the blade capacity for a loose volume can be obtained from the manufacturer's manual), K_{ff} is the fill factor of blade, K_{sf} is the swelling factor of the material, N is the number of journeys (i.e. cycles) per shift, and O_e is the operational efficiency (correction factor), which is based on the operator's experience and the working conditions (see Table 3.2).

$$N = \frac{CT}{t} \tag{3.2}$$

Table 3.3 Job condition correction factors

Factors	Track-type tractor	Wheel-type tractor
Operator		
Excellent	1.00	1.00
Average	0.75	0.60
Poor	0.60	0.50
Material		
Loose stockpile	1.20	1.20
Hard to cut	–	–
Frozen with tilt cylinder	0.80	0.75
Without tilt cylinder	0.70	–
Cable-controlled blade	0.60	–
Hard to drift, 'dead' (dry non-cohesive material) or very sticky material	0.80	0.80
Rock ripped or blasted	0.60–0.80	–
Slot dozing	1.20	1.20
Side-by-side dozing	1.15–1.25	1.15–1.25
Visibility – dust, snow, fog or darkness	0.80	0.70
Job efficiency		
50 min/h	0.83	0.83
40 min/h	0.67	0.67
Gradient factor	As shown in Figure 3.4	As shown in Figure 3.4

where T is the effective working hours per shift, C is the time factor (effective minutes) and t is the duration of the journey or round trip made by the dozer. $t = t_1 + t_2$, where t_1 is the duration of a full journey (loaded) and t_2 is the duration of the return journey (empty). Also, $t_1 = H_d/v$ and $t_2 = H_d/v_e$, where H_d is the hauling distance (km), v is the travel speed (loaded) and v_e is the travel speed (return, empty) (speeds are taken, for a particular gear, from the dozer manufacturer's table).

3.3.1.3 Dozer production using performance chart/curves supplied by the manufacturers

Dozer production, measured in loose cubic metres per hour (Lm^3/h) or loose cubic yards per hour (Lyd^3/h) is determined by

$$\mathrm{Lm^3/h\ (or\ Lyd^3/h)} = \text{maximum production} \times \text{overall correction factors} \tag{3.3}$$

Note: The soil density can be taken as 1370 kg/Lm^3 or 2300 lb/Ly^3. The maximum production is assessed from the production chart (dozing distance versus dozing production for a particular model, e.g. Figure 3.4) supplied by the manufacturer. Readers are advised to refer to the handbooks supplied by the manufacturers.

3.3.2 Scrapers

Scrapers are known as excavators (see Figure 3.2(b)) (Aiken, 1973; Caterpillar, 2000; Church, 1981; Peurifoy and Oberlender, 1989). Basically, they are integrated load, haul and dumping units (LHDs). Their applications are many. Prominent tasks in civil works are road, dam and dike constructions. Mining applications include stripping overburden and the movement of minerals from stockpiles at mineral processing plants. Scraper units can be classified as

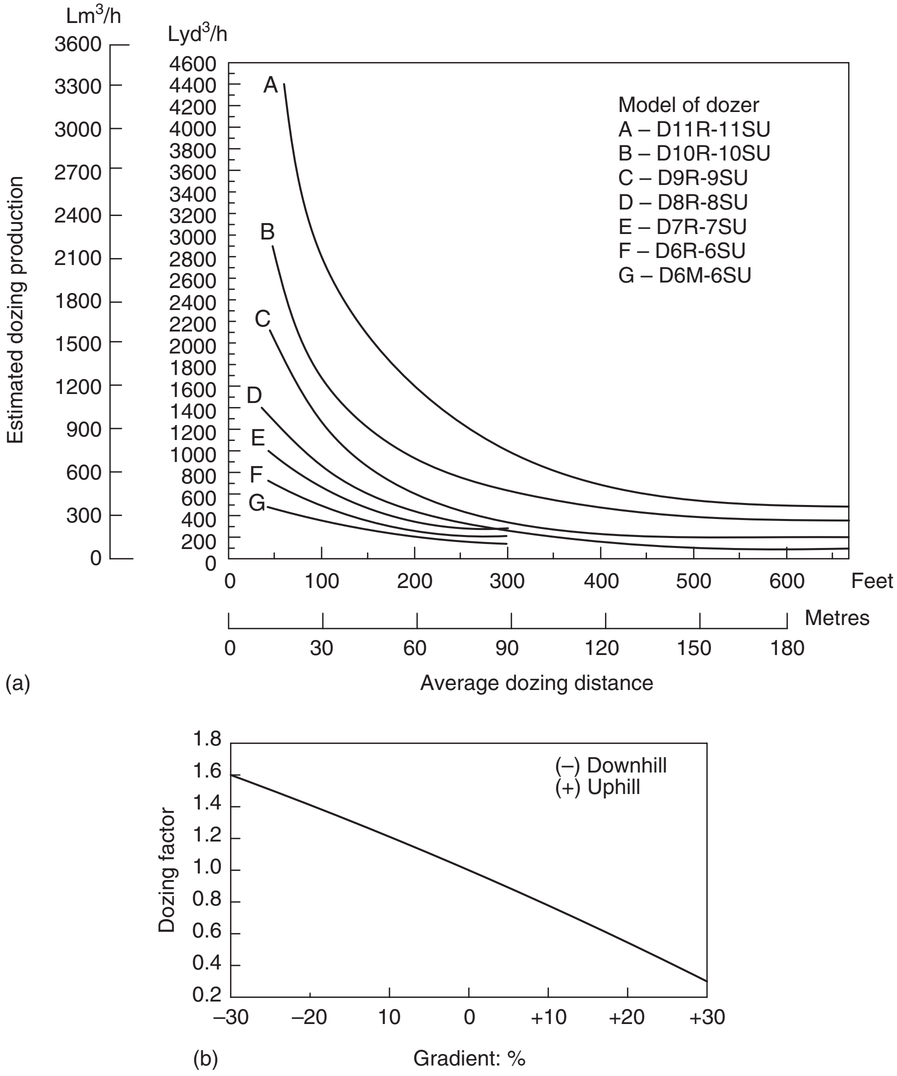
- wheeled-tractor scrapers
- crawler-tractor-towed scrapers.

Many manufacturers produce scraper units with a number of models in each class to suit the particular needs of the client. Sizes range from 3 m^3 to 70 m^3, but sizes up to 20 m^3 are the most popular. Wheeled-tractor scrapers are of four types: single-engine, tandem powered, elevating and auger (Figure 3.5).

Single-engine scrapers are conventional and are available with two or three axles. Except in very easy, downhill conditions, a pusher tractor is needed for loading. These units do not perform well where there are steep gradients, high rolling resistance and poor floor conditions, or where haul distances are short.

Tandem power units have double engines that provide a high power/weight ratio and tractive effort. This feature allows them to be deployed in adverse conditions (poor floor, high rolling resistance and steeper gradients) than single-engine units. Normally these units also operate with the assistance of a pusher tractor, but in downhill situations they may not require such assistance.

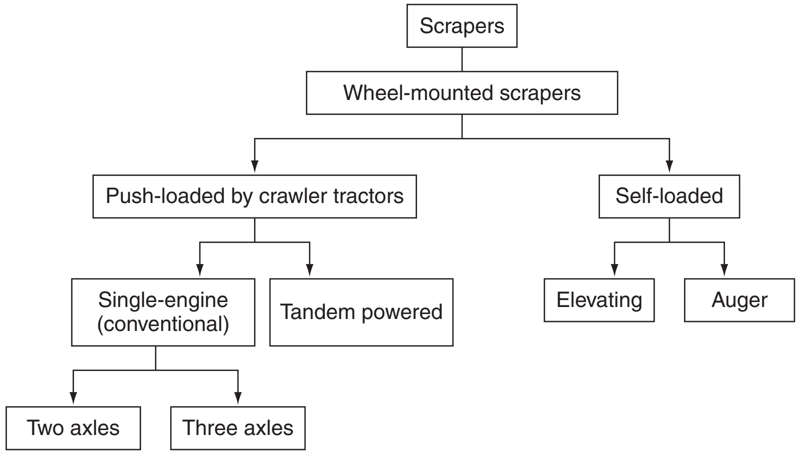
Figure 3.4 Determination of a dozer's production based on dozing distance: (a) performance curves based on field experience and trials; (b) grading curve (courtesy of Caterpillar)



Elevating scrapers are self-contained units capable of self-loading their bowls. They perform well in easy digging conditions but not in adverse gradient or high rolling resistance situations. They are best suited for short to medium hauling distances. These units are not suitable for sticky conditions or for large-sized boulders (>200 mm).

An auger scraper is a self-contained unit with a self-loading feature using an auger placed in the centre of the bowl. The material input by the cutting edge is spread within

Figure 3.5 Classification of scraper units



the bowl by the auger. This unit can cope with a variety of situations and is best suited for short cutting distances and fragments smaller than 300 mm.

Wheeled scrapers (Table 3.4) are used to excavate ground and to haul and dump material at a predetermined destination. This destination could be a dump yard or even a haulage unit. A hopper is essential in the latter case.

The output from wheeled scrapers can be calculated using the following relationship:

$$P_S = S_{cap}(K_{ff}/K_{sf})N \qquad (m^3/shift) \tag{3.4}$$

where P_S is the production per shift (m^3), S_{cap} is the capacity of the scraper's bowl (m^3), K_{ff} is the fill factor of the bowl, K_{sf} is the swelling factor of the material and N is the number of journeys per shift.

$$N = \frac{CT}{t} \tag{3.5}$$

Table 3.4 Fill factors and swelling factors for wheeled-tractor scrapers (Atkinson, 1992)

Digging conditions	Fill factor, K_{ff}	Swell factor, K_{sf}
Easy, dry	0.95–1.00	1.15–1.25
Medium, common earth	0.90–0.95	1.2–1.3
Medium-hard clays	0.85–0.90	1.35
Weak rocks	0.85–0.95	1.35–1.45
Hard, wet clay	0.70–0.80	1.4
Well-broken rocks	0.75–0.80	1.5
Extreme, broken basalt, etc.	0.50	1.5–1.6

where T is the effective working hours per shift, C is the time factor (effective minutes) and t is the duration of the journey or the round trip by the scraper. $t = t_1 + t_2 + t_3 + t_4$, where t_1 is the filling time, t_2 is the duration of full journey (loaded), t_3 is the dumping time and t_4 is the duration of return journey (empty). Also, $t_2 = H_d/v$ and $t_4 = H_d/v_e$, where H_d is the hauling distance (km), v is the travel speed (loaded) and v_e is the travel speed (return unloaded) (speeds are taken, for a particular gear, from the manufacturer's table). Most scrapers are of the hoe type (Church, 1981). Usually high-capacity scrapers are loaded by pushing them with a bulldozer. In elevating scrapers, the rock separated from the solid is delivered into the scraper's bowl by an elevator that serves as the front wall of the bowl; these scrapers are suitable for loose rocks.

When a pusher tractor is used in excavating compact and broken rocks with heavy-duty hoe-type scrapers, the bowl fill factor increases by 10–12% (or even sometimes by up to 20–30%), the bowl filling time reduces by 30–35% and the wear of the scraper diminishes (Peurifoy and Oberlender, 1989). One pusher tractor can serve 2–4 scrapers.

The choice between push-loaded and self-loaded scrapers depends on the nature of rock/earth and the kind of job (Church, 1981). Soft and medium formations favour self-loading, and medium to hard rock/earth favours the push-loaded machines. When a job requires excavations in several locations at the same time, the self-contained self-loading unit is more economical (e.g. civil works – cuts in confined home cuts). When mass excavation is confined to one cut, the push-loaded scraper is preferred.

3.3.3 Rippers

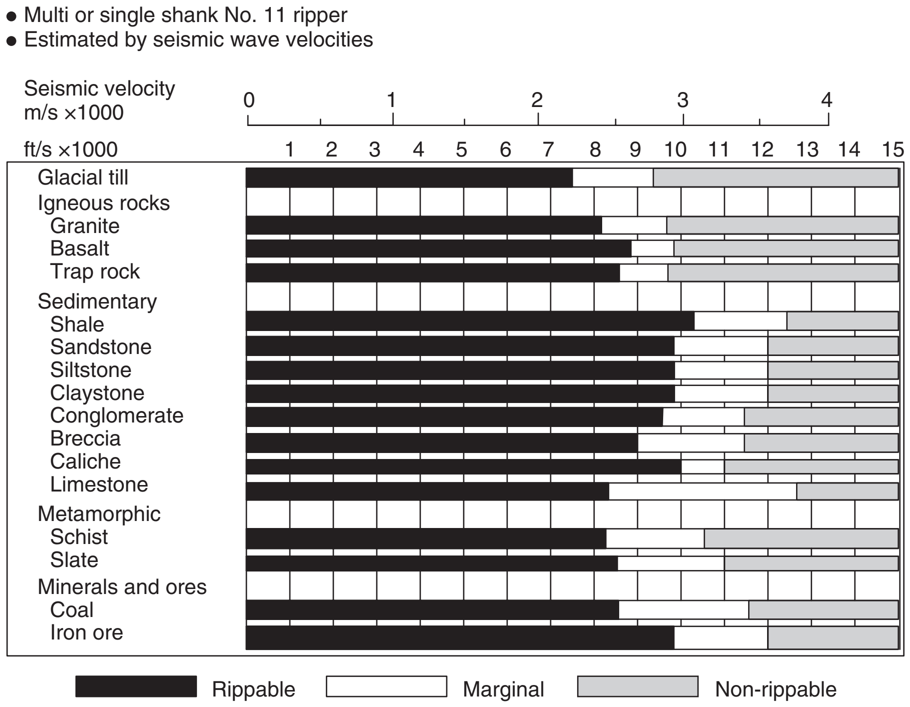
Ripping is one of the methods of loosening the rock or earth (see Figure 3.2(a)). Ripping is a skilled task, and the efficiency of the operation depends on the skill and experience of the operator, which is why this operation is still considered an art not a science. Important factors for a successful ripping operation include:

- The tooth penetration into rocks, particularly the homogenous rocks such as mudstone, clay stones and the fine-grained caliches. The same logic is applicable for tightly cemented formations such as conglomerates, glacial tills and caliches containing rock fragments.
- The degree of seismicity of the material is one of the indicators of rippability but it is not the sole parameter. Low seismic velocities of sedimentary strata are an indication of rippability but much depends on the presence of fractures and bedding planes. The presence of such discontinuities may not allow effective tooth penetration and, hence, ripping.

Pre-blasting or pop shooting is carried out in some rock formations for effective results, but the overall economics of the operation should be assessed before taking such decisions.

Based on its field trials and experience, Caterpillar has developed seismic velocity charts for their different operational units. Figure 3.6 shows such a chart for the D11R ripper.

Figure 3.6 Seismic velocity chart for different formations/rock types (courtesy of Caterpillar)



The classification of rippers is given in Figure 3.7 (Buckeridge *et al.*, 1982; Caterpillar, 2000). A radial ripper is the oldest and simplest of the tractor-mounted rippers. Usually it has one tooth and that is set at a constant angle to the main tool beam, and therefore it is not possible to vary the angle of penetration except by varying the depth.

The fixed parallelogram ripper maintains a constant inclination of the ripper shank, and hence a constant angle of penetration, regardless of depth. This feature enables it to yield higher production performances in most ground/material (once the best penetration

Figure 3.7 Classification of ripper/tractor unit design

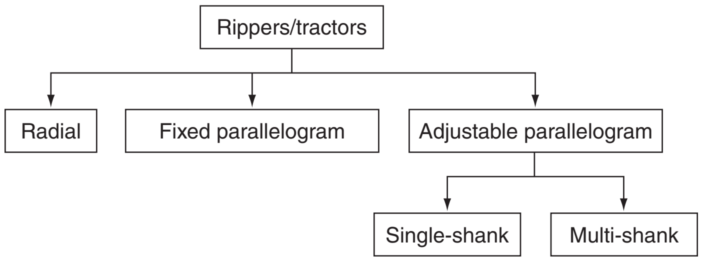


Figure 3.8 Three types of tip for ripping and the critical angle *A* for tip penetration into the formation. The angle may be varied by the configuration of the tip itself, by the type of shank and by the angular adjustment of the shank. Angular adjustment of the tip is possible in the adjustable parallelogram ripper. The short tip is used when the penetration is most difficult and the shock is most severe. The long tip is used for highly abrasive rocks when breakage is not a major consideration. The intermediate tip is suggested for abrasive rocks that are hard enough to break the tip. These tips are reversible and self-sharpening. This feature means they have good penetration and a long life (courtesy of Caterpillar)

angle has been found). Features of the adjustable parallelogram-type rippers include:

- the backward position of the tip provides an aggressive tip angle for entry into the formation
- once the tip has entered and reached the desired depth of ripping in the formation, its best angle is chosen by adjusting the shank to the near-vertical position
- for prying out particles, the shank is adjusted to the forward position.

All these adjustments differ from formation to formation, and the operator can fix them after some trials. Three types of tip for ripping together with the critical angle *A* for tip penetration into the formation are shown in Figure 3.8, which also describes their important features. The ripped rock/earth needs to be displaced or removed from its original place to a predetermined destination, which could be a dump yard, casting site, etc. Any of the following equipment can be deployed depending on the type of job:

- bulldozers
- scrapers
- bucket loader – shovel, dragline, backhoe, bucket wheel excavator or any other loader
- portable and movable belt loaders.

Tractor rippers are most commonly used with scrapers, and ripping is undertaken parallel to the scraping path. Where the situation permits, wetting the formation with water prior to ripping results in higher productivity, lower costs and less wear and tear of the ripper's shank and tips (Church, 1981; Pradhan, 1996). It also favours scraping by the scrapers, or loading operations if bucket excavators are subsequently deployed. In desert or areas of water scarcity this logic may not be a practical possibility. The presence of water reduces tyre life; this aspect should be thoroughly studied before adopting a water-wetting programme.

Estimation of ripping production. The following methods are in vogue:

1 time study
2 cross-sectional method
3 measure distance method.

In the time-study method, the time spent for ripping is noted and the material ripped is weighed. If payment is to be made on a volume basis, then using the average density of the material the amount can be converted into the volume ripped. Volume divided by time spent gives the ripping rate per hour or minute.

In the cross-sectional method, a cross-section of the area to be ripped is measured prior to ripping and the time spent to rip a certain portion of this is noted. The cross-section of the same area is measured again. The difference between the two cross-sections (volume) divided by the time spent gives the ripping rate per hour or minute.

For quick estimation, the measure distance method can be adopted. In this method, the average time spent for a ripping cycle, including delays and manoeuvring time, is noted. The average rip distance, rip spacing and depth of penetration are measured. These data give the volume of material ripped per cycle. This method usually gives results that are 10–20% higher than those from the cross-sectional method (Caterpillar, 2000).

3.3.4 Trenchers (ditchers)

The use of trenches or ditches is increasing, and a number of techniques are available to undertake this operation, as shown in Figure 3.9 (Church, 1981; Ditch Witch, 2017; Fiat-Hitachi, 2000; Komatsu Mining Systems, 2017; Jimeno *et al.*, 1997; Matti, 1999; Smith, 2017). They can be made with or without the aid of explosives. Trenchers, also known as ditchers, have a wide range of applications in this modern era (Figures 3.10 and 3.11), and trenchers of different types are available for the various applications (Figure 3.12).

Figure 3.9 Trenching techniques

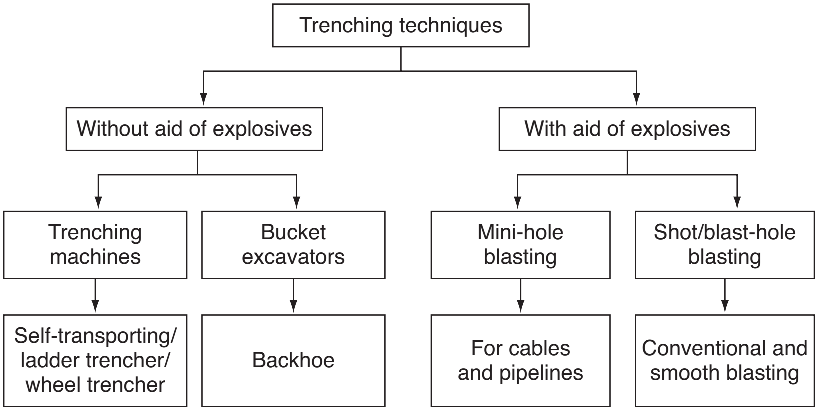


Figure 3.10 (a) A ladder trencher with other attachments. Interchangeable attachments increase the versatility and value of a unit. Attachments are available for trenching, vibratory ploughing, pavement and rock-sawing, and utility backhoe work. (b) A wheel trencher (courtesy of Ditch Witch Co.) (*Note*: Ditch Witch is a generic brand of commercial underground construction equipment built by The Charles Machine Works, Inc., Oklahoma, USA. However, the name is commonly used to describe the company's original product, a power trencher which was itself called the 'Ditch Witch'. The original Ditch Witch was the first mechanised, compact service-line trencher developed for digging long trenches for the purpose of laying underground water lines. Up to that time (1949), digging trenches was tedious and arduous as it was done manually using a pick and shovel. The company has grown its product line to include many other digging machines, such as drills, vacuum excavators, and the 'Zahn', a small machine that combines the functionality of a Ditch Witch, backhoe and excavator all in one package.)

(a)

(b)

Figure 3.11 Trenching applications

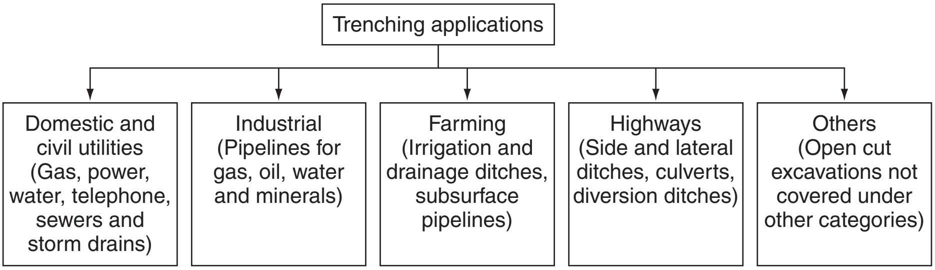
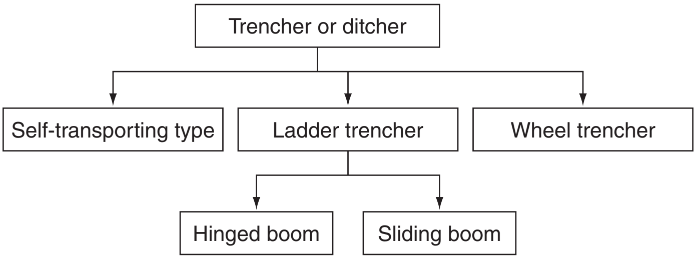


Figure 3.12 Classification of trenchers



Ladder- and wheel-type trenchers are used in alluvial and weathered rock/earth subsurface excavations up to 8.5 m deep and 1.8 m wide (Church, 1981); under favourable conditions, ladder trenchers can be equipped with longer booms, enabling them to reach deeper depths (Tables 3.5 and 3.6). The advantage of these trenchers over backhoe-type excavators for a similar type of task is they enable continuous operation of the equipment whereas backhoe operation is cyclical.

A *micro-trencher* is a small rockwheel specially designed for work in urban areas. It is fitted with a cutting wheel that cuts a micro-trench with smaller dimensions than can be achieved with conventional trench digging equipment. Micro-trench widths range from about 30 mm to 130 mm (1.2–5.1 in.) with depths of 500 mm (20 in.) or less. These machines are sometimes radio-controlled.

With a micro-trencher the structure of the road is maintained and there is no damage to the road from the operation itself. Owing to the reduced trench size, the volume of waste material excavated is also reduced. Micro-trenchers are used to minimise traffic or pedestrian disturbance during the laying of networks. A micro-trencher can be used on pavements or the narrow streets of cities, and can cut harder ground than a chain trencher, including cutting through solid stone. These machines are also used to cut pavement for road maintenance and to gain access to utilities under roads.

Table 3.5 Size of trenches for self-transporting trenching machines (Peurifoy and Oberlender, 1989)

Depth of trench: m	Width of trench: m	Type of soil	Soil factor, *C*
1	0.61	Sandstone	20
1.5	0.5	Hard clay	40
1.8	0.4	Firm clay	60
2.13	0.35	Soft clay	90
2.43	0.3 for soft soils		
2.43	0.25 for firm soils		
2.43	0.2 for hard soils		

Table 3.6 Data on the performance of trenching machines (Peurifoy and Oberlender, 1989)

Depth of trench: m	Width of trench: m	Digging speed: m/h
Wheel type		
0.6–1.2	0.4–0.5	45.7–68.5
	0.55–0.65	27.4–91.4
	0.7–0.75	18.3–54.9
1.6–1.8	0.4–0.5	12.2–36.6
	0.55–0.65	7.6–27.4
	0.7–0.75	4.6–12.2
Ladder type		
1.2–1.8	0.4, 0.5, 0.6	30.5–91.5
	0.55, 0.65, 0.75	22.9–61
	0.7, 0.8, 0.9	12.2–38.1
1.8–2.4	0.4, 0.5, 0.6	12.2–38.1
	0.55, 0.65, 0.75	9.1–6.8
	0.7, 0.8, 0.9	7.6–15.2
2.4–3.6	0.45, 0.6, 0.75	9.1–22.9
	0.75, 0.83, 0.9	4.6–12.2

Sewerage trenches can be made using the *backhoe-type excavator* (Fiat-Hitachi, 2000). The process involves a number of steps: preparatory work → sheathing → excavating → foundations for pipes → pipe laying → refilling. Similarly, during a road construction project, drainage at the roadside could involve the use of a backhoe excavator. Again the process would involve a number of steps: preparatory work → cutting → banking → retaining wall → drainage → structures.

The rate of trenching will depend on the type of soil, the width and depth of the trench and the power of the trencher. Equation 3.6 can be used to approximate the trenching rate:

$$S = \frac{C \times hp}{D \times W} \tag{3.6}$$

where S is the digging speed (ft/min), C is the soil factor (see Table 3.5), D is the trench depth (in.), W is the trench width (in.) and hp is the engine horse-power.

Equipment manufacturers produce different designs of trencher to suit various trenching tasks.

- *Pedestrian trencher* – used for residential and short-run commercial service line work including gas, water, sewerage, electric and communications lines. It trenches to a depth of 0.6–1.2 m (2–4 ft) and ploughs to a depth of 0.3–0.6 m (1–2 ft).

- *Compact trenchers and ploughs* – used for completing big jobs in small spaces. These small, manoeuvrable riding units are designed for residential utility installations and can trench to depths of 1.5–2 m (60–80 in.) depending on the boom length.
- *Heavy-duty trenchers* – designed for heavy-duty trenching, vibratory ploughing and pavement cutting. The large range of trenchers available feature power outputs of up to 185 hp (138 kW) and can dig up to 2.5 m (99 in.) and plough to depths of up to 1.2 m (48 in.) for the installation of mainline utilities.

3.3.4.1 Use of explosives for trenching

Trenches used for drainage, sewer systems and laying pipelines (water or gas) and/or electric cable are usually 0.8–3 m wide and 0.5–5 m deep. Guidelines, as shown in Table 3.7(a)–(e) and Figure 3.13, could be used to select the drilling diameter and the burden and spacing for the blast design.

Table 3.7(a) Design parameters for drilling patterns (Jimeno *et al.*, 1997; Matti, 1999)

Size of trench	Hole diameter, *D*: mm
Width $T_W < 1$ m; depth $T_D > 1.5$ m	32–45
Width $T_W > 1$ m; depth $T_D > 1.5$ m	50–65

Table 3.7(b) Design parameters: burden with respect to hole diameter (Jimeno *et al.*, 1997; Matti, 1999)

	Hole diameter, *D*: mm	
	<50	>50
Burden: m	26*D*	24*D*

Table 3.7(c) Design parameters: drilling pattern according to trench width (Jimeno *et al.*, 1997; Matti, 1999)

	Trench width, T_W: m		
	<0.75	0.75–1.5	1.5–3
Number of rows	2	3	4
	T_W	$T_W/2$	$T_W/2.6$*

* In contour blasts the hole spacing is reduced by 20%.

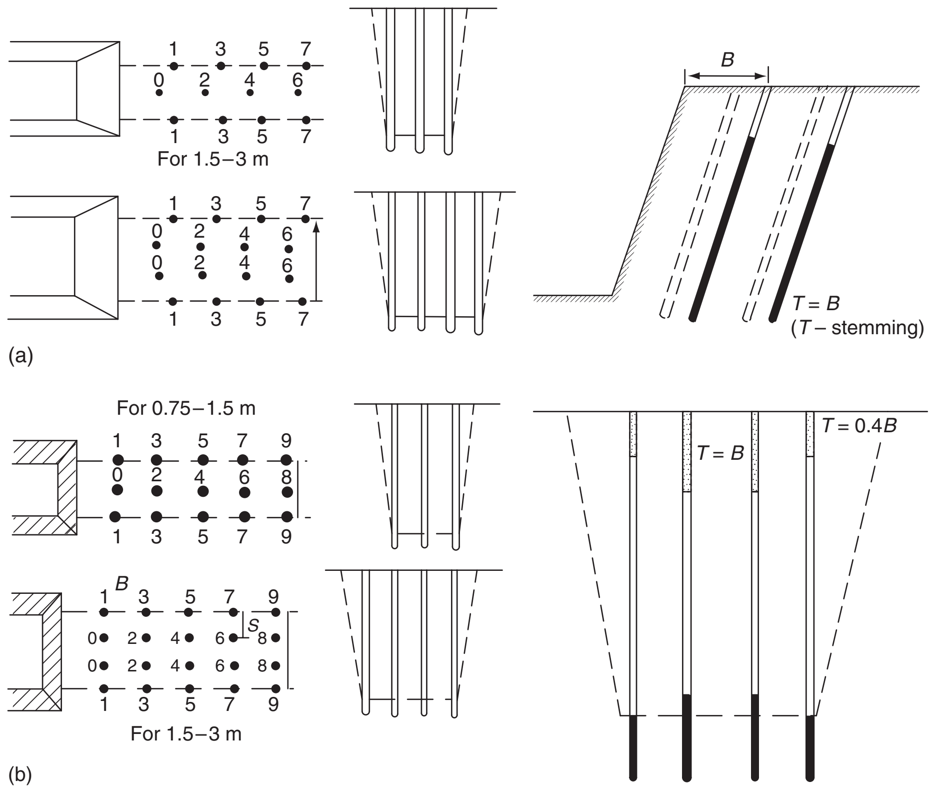
Table 3.7(d) Design parameters: length (m) of bottom charge (Jimeno *et al.*, 1997)

Conventional blasting	Smooth blasting
All holes: $0.4 + (T_D - 1)/5$	Central holes: $1.3[0.4 + (T_D - 1)/5]$ Contour holes: $0.7[0.4 + (T_D - 1)/5]$

Table 3.7(e) Blasting parameters for mini-hole trenching (Jimeno *et al.*, 1997)

Hole length = $T_D + 0.2$
Burden, $B = 0.018D$
Stemming length = burden
Explosive quantity, $Q_{exp} = 0.2 \times T_D$ (kg)

Figure 3.13 Patterns of holes for trenching by blasting. (a) Conventional blasting – central holes are placed in front of contour holes. (b) Smooth blasting – central holes are placed in line with the contour holes. Central holes have a higher explosive concentration than contour holes



3.3.4.2 Mini-hole blasting (excavations)

Due to restrictions on the amount of explosive that can be used, particularly in urban areas, a new technique has recently come to the fore. In this technique, holes of 22 mm diameter are drilled and charged with specially developed, high-density NG-based explosives (Jimeno *et al.*, 1997). A typical explosive of this type has some of the following features: density, 1.55 g/cm^3; weight strength relative to ANFO, 127%; detonation velocity, 6000 m/s; and high water-resistance. Charges of 80 g, 17 mm in diameter and 275 mm long are prepared in a plastic wrapping. Mini-hole blasting finds application in making narrow trenches for pipes and cables, and in pit excavations for erecting posts or poles.

Narrow trenches for pipes and cables. Blasting parameters for mini-hole trenching are given in Table 3.7(e). Typical patterns for narrow 0.4 m cable trenches and 1 m and 1.5 m pipe trenches are shown in Figure 3.14.

Pit excavations for erecting posts/poles. It is not very popular to use explosives to create pits (circular excavations) that are required for erection of poles, posts or beams. When

Figure 3.14 Pattern of holes for trenching by the application of mini-hole blasting. (a) Blasting pattern and blasting sequence using mini-holes for trenches for pipelines. (b) Blasting pattern and blasting sequence using mini-holes for trenches for cables. *B*, burden (m)

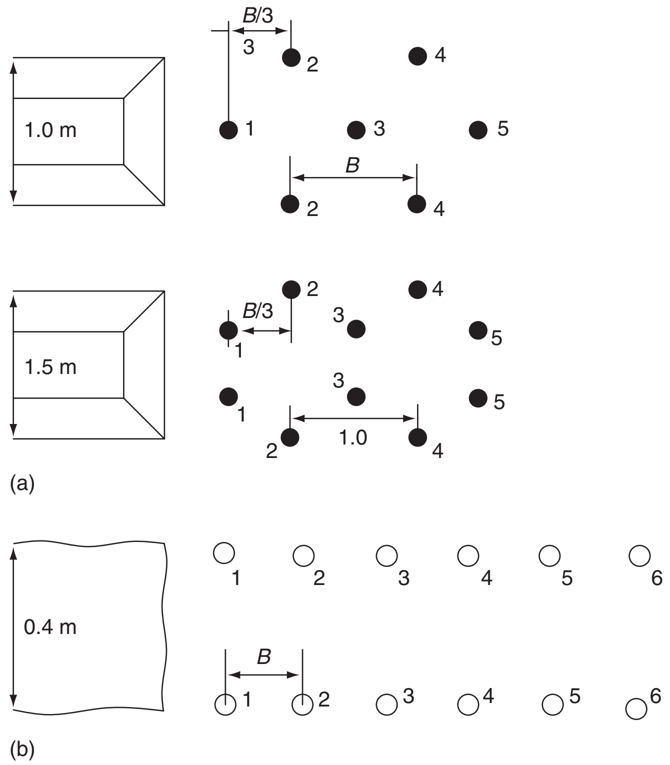
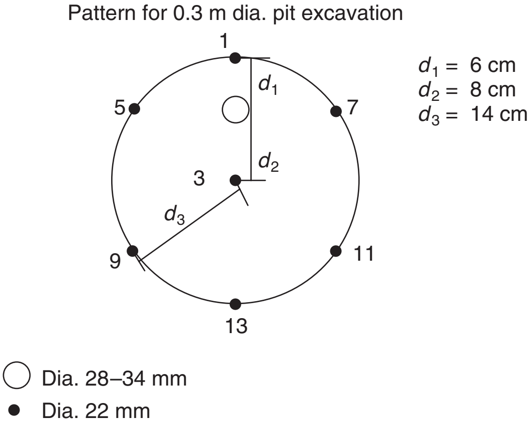


Figure 3.15 Pattern of holes used to create pits by the application of mini-hole blasting



such excavation has a diameter not exceeding 0.6 m, mini-holes of 22 mm diameter are drilled parallel and charged with special explosives. Relieving holes that should be left without charging are usually 28–34 mm in diameter. Figure 3.15 shows a typical pattern for a 0.3 m diameter circular pit.

3.3.5 Excavators

3.3.5.1 Wheel loaders/front-end loaders

These are available as articulated power steer (pivot steer), rigid frame (two-wheel steer) or two rigid frame (all-wheel steer) types and have multiple applications (Singh, 1993). The bucket itself could offer applications such as loading, bulldozing, soil stripping, clamping and clean-up of debris. The side-dump bucket feature allows use of this equipment in very narrow and tight areas. Such loaders can be used in side-dump, forward-dump or their combination mode. The selection of bucket depends on the type of work to be undertaken. For example: for heavy material – small bucket; light material – large bucket; highly abrasive material – bucket with hardened cutting edge; and consolidated material – toothed bucket. Long pipes, bars and tubular pieces require a fork. Speed and manoeuvrability are added advantages. This type of loader can be used for shifting machines and material and for miscellaneous jobs. Backhoe, fork-lift and lumber-fork attachments make it an ideal material handler, while an industrial sweeper attachment allows its use for general cleaning operations at roads and car parks.

3.3.5.2 Backhoes

This unit (see Figure 3.2(d,f)) is suitable for digging the surface (ground) and particularly finds application in hard and consolidated ground (Fiat-Hitachi, 2000). The material dug is dumped to the sides or to a transportation unit. The backhoe unit is ideal for coping with all the day-to-day site jobs (digging, loading, shifting, banking, lifting and handling materials) that need to be carried out by such multi-tasking equipment. Manufacturers supply backhoes with allied equipment. The attachments available can operate at the front as well as the rear. A hydraulically controlled quick disconnect plate allows the user to switch over from one attachment to another. The front attachments could include, for example, multi-purpose buckets, brushes, suction sweepers, snowploughs, dozer blades, log forks, etc., and the rear attachments could include trapezoidal ditching buckets, ditch-cleaning buckets, hydraulic hammers, augers, clamshell buckets, orange-peel buckets, etc. The unit can be used on roads, in built-up areas and at both rural and urban sites. The backhoe is an excavator that can be used to perform multiple tasks without interruptions to normal traffic.

3.3.5.3 Hydraulic excavator

This unit, which was introduced to the market during the 1970s, is also known as a hydraulic shovel (see Figure 3.2(c)) (Singh, 1993). It differs from a front-end loader (Blyth and Freitas, 1988) with respect to its mounting (a crawler rather than tyres), its greater digging force, its lower fuel cost per unit loading, and the more rugged structure of its main components. Compared with the dipper shovel it has greater mobility, higher travel speed, higher cutting force and improved steerability. It weighs half as much as a dipper shovel of the same power (capability). Hydraulic pumps and motors play an important role in the functioning of this unit, which can be diesel or electrically (AC) driven. Thus, its application lies at all those locales where wheel loaders or dipper shovels can be deployed, both at the surface as well as underground. The enormous development that has taken place in hydraulic excavators is evidenced by the four topmost excavators in the world, which are manufactured by different manufacturers, as detailed below (Mining-Technology, 2017).

The Bucyrus RH400 (Caterpillar) is the world's biggest hydraulic excavator. It is a front-shovel excavator weighing approximately 889 ton. The undercarriage is 8.6 m wide and the crawler is 10.98 m long. The shovel on the excavator has the capacity to hold 45 m^3 of rock in a single scoop.

The Hitachi EX8000-6 (launched by Hitachi Construction Machinery in 2012) is currently the second largest hydraulic excavator. It weighs 811 ton and is available with both shovel and backhoe attachments. The cab is 9.9 m high and 10.5 m long, and the undercarriage is 8.65 m wide. The excavator has a maximum digging reach of 20.5 m, a bucket capacity of 45 m^3 and a shovel capacity of 40 m^3. It can remove a 75 ton load in a single pass.

The excavator in third place is the Liebherr R9800 (built by Liebherr at its Colmar factory in France in 2008). This excavator is available with a shovel attachment, weighing 810 ton, or a backhoe attachment, weighing 800 ton. The cab height is 9.91 m and the undercarriage is 10.84 m long. Both the backhoe bucket capacity and the shovel have a capacity of 42 m^3.

With an operating weight of 744 ton, the Demag H740 OS excavator is the fourth biggest mining excavator. This is a front-shovel excavator with a wider car body and track pad than its predecessors. The shovel load capacity is 40 m and it has a breakout force of 2320 kN.

Hydraulic excavators are so versatile that they can be deployed to undertake the following six operations during a road construction project: excavating, loading, levelling, breaking/cutting, lifting and hauling (Brealey *et al.*, 1983). These units are equally useful for sewerage operations.

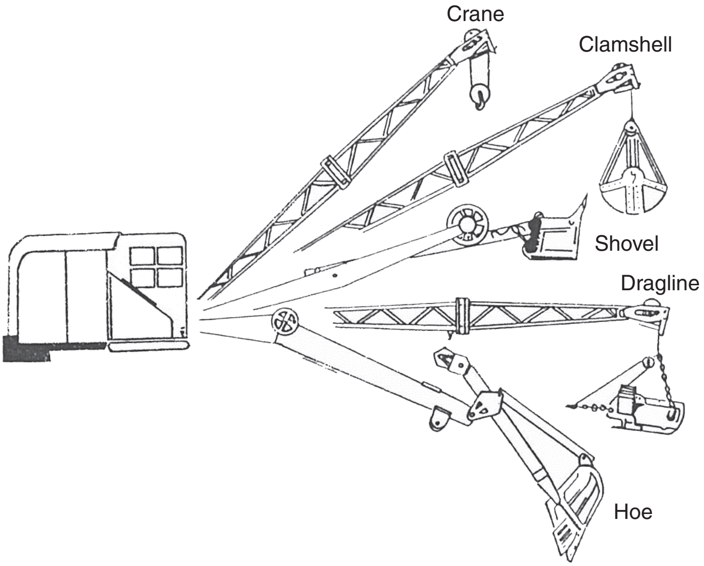
3.3.5.4 Shovels

Shovels are available with very small- to very large-capacity buckets, and are capable of excavating any type of muck or ground (Brealey *et al.*, 1983; Connel, 1973). The unit is known as a face, crowd or dipper shovel (see Figure 3.2(c,g)). The one with a large bucket capacity (usually more than 4 m^3) is known as a strip shovel, and is used for casting the ground in the adjacent area within its reach. This feature finds its application in opencast mines, where it strips the ore deposit (coal or other mineral) by removing the overburden and casting or backfilling it into the worked-out space, (i.e. the place from where the ore (useful mineral) has been removed). The cycle time of a strip shovel is shorter than that of a face shovel. A shovel of up to 4 m^3 (5 yd^3) bucket capacity is a multi-purpose unit which, with the aid of different attachments and accessories, can be used as a face shovel, crane, dragline, backhoe or clamshell (Figure 3.16).

In general, shovels can be divided into four size categories:

- small (0.5–2 m^3 bucket size), for small-scale earth-moving jobs in soft ground
- medium (>2–5 m^3 bucket size)
- large (>5–25 m^3 bucket size)
- very large (>25 m^3 bucket).

Figure 3.16 Shovel with various attachments



In the past, shovels were one of the most important excavators with a glorious past, but due to the availability of wheel loaders, hydraulic excavators and backhoes their utility, particularly in civil and construction projects, has diminished. However, for mining operations shovels are still one of the most useful pieces of equipment.

3.3.5.5 Draglines

A dragline is a single-bucket excavator (see Figure 3.2(i)) in which the bucket is pulled by a drag rope (hence the name 'dragline') over the face towards the equipment itself (Brealey *et al.*, 1983; Singh, 1993). It differs from the face shovel in that its bucket is not fixed rigidly to the boom but is hung from flexible ropes. The bucket is connected to the rope by lifting chains and their separating bar. These chains are joined together and are attached to a load line (drag rope). They are also attached to a dumping line, the other end of which is fixed to the front end of the bucket after passing over the bucket-hoisting block. This block is at the junction of the hoist line and the bucket chains.

A dragline stands on the bench that is to be dug, and travels on a caterpillar track or a walking mechanism. The usual inclination of the boom is in the range 20–25°. It can rotate through 360°. Draglines from as small as 0.6 m^3 to as large as 175 m^3 bucket capacity are available for use in soil and loose ground. The Bucyrus-Erie model 17 4250-W (Big Muskie), which weighs 12 000 ton is one of the biggest draglines. With a bucket capacity of 170 m^3 (220 yd^3) and bucket weight of 210 ton, a height of 67.8 m (222.5 ft.) and a boom length of 94 m (310 ft), it measures 148.6 m (487.5 ft).

The dragline is ideal for handling wet and soggy material, where other methods usually fail. Short-boom draglines are suitable for civil works, whereas long booms and large-sized bucket draglines are ideal for removing soft overburden at opencast mines. Draglines can be used in civil works to undertake some of followings tasks (Singh, 1993):

- excavating channels and canals
- excavating ditches and trenches
- excavating underwater soils
- stripping overburden
- shallow grading
- loading into hoppers
- sloping and grading.

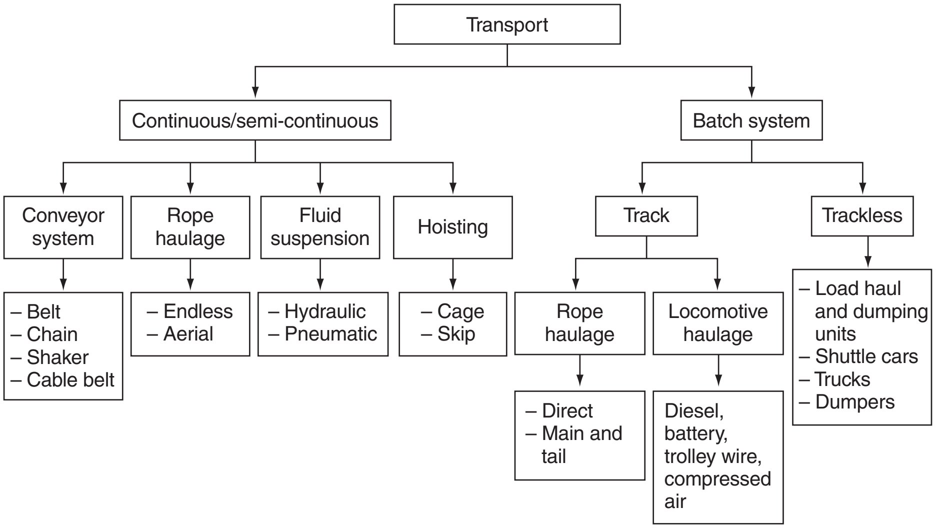
3.4. Haulage systems

'Haulage' means 'horizontal transportation', which is an essential link in the whole muck handling and disposal cycle. A number of options are available to suit a particular layout, situation or set of conditions. The different haulage systems available are classified in Figure 3.17.

3.4.1 Locomotive haulage

Rail transport finds its applications at surface as well as underground locales. Due to its flexibility and versatility, truck haulage is almost mandatory for muck disposal at civil and constructions sites (Brantner, 1973; Singh, 1993). Truck haulage also finds

Figure 3.17 Classification of systems of transportation



applications such as gathering and main haulage in underground mines and tunnels (see Chapter 4).

3.4.2 Automobiles – trackless or tyred haulage systems

- *LHD (load, haul and dumping unit)*: when used as a transporting vehicle, the hauling distance should not exceed 150 m. LHDs are suitable for underground applications (see Chapter 4).
- *Shuttle cars*: the limiting distance for these units is in the range 1–2 km.
- *Low-profile trucks/dumpers*: the use of these in underground mines and tunnels is dealt with in Chapter 4.
- *Rigid and articulated dump trucks and dumpers*: these units are available in normal (capacity 10, 20, 25, 35, 70 and 120 ton) and giant (capacity 135, 160, 180, 225, 270 and 315 ton) sizes.

Trucks/dumpers can be rear discharge, bottom discharge or side discharge types (Brealey *et al.*, 1983; Caterpillar, 2000; Connel, 1973; Komatusu Mining Systems, 2017). In mines, off-highway trucks capable of carrying heavy loads on abnormally uneven surfaces, with slow speeds and for a shorter hauling distance, are used. Their speed is limited to 80 km/h. Articulated trucks are extremely versatile hauling units that are growing in popularity around the world. As part of an earth-moving system they can haul a wide spectrum of material in a huge variety of applications and underfoot conditions. For these reasons, articulated trucks often provide the best return on investment (Buckeridge *et al.*, 1982).

Off-highway trucks, which have a mechanical power train, specifically work in mines, construction sites and quarries. Mechanical-drive trucks lug the engine under load rather than run at constant maximum power. This makes a mechanical power train efficient and productive in a wide variety of conditions. Off-highway trucks also are the best match with wheel loaders to speed up cycle times and maximise productivity.

3.4.3 Belt conveyors

Widely used in haulage conveyor systems, belt conveyors have applications in both surface and underground locales. A belt conveyor is basically an endless strap stretched between two drums. The belt carries the material and transmits the pull. A belt conveyor system essentially consists of a steel structure along its entire length. Mounted on this structure are carrying idlers (2–5 in number) and return idlers. The space between carrying idlers varies from 1.2 m to 2.1 m and the space between return idlers varies from 2.4 m to 6.1 m. In order to achieve a trough shape to accommodate more and more fragmented or loose material, the carrying idlers mounted on the sides are fixed at 20–35° to the horizontal. The belt is run by a driving unit that is installed at one of its ends and has a motor, gears, driving drum and other fittings to start and stop it. At the other end a take-up pulley is fitted to provide necessary tension to the system. At the discharge end a belt cleaner cleans any adhered material.

Belt conveyors can be classified as stationary, mobile or portable, based on their movability from one place to another. According to their their path they can be classified as horizontal, inclined or a combination of these. The inclination of a belt conveyor to the horizontal, β, depends on the friction between the belt surface and the material being conveyed, the manner in which the material is loaded onto the conveyor, and the static angle of repose of the material being conveyed. Although β can be up to 40° if belts of special design are used, an inclination up to 18° is more common.

3.5. Some developments

In addition to what has been described, some other features that are being incorporated in modern earth movers and excavators are outlined below (Singh, 1993).

- *Versatility*. The concept of one piece of equipment for one operation is no longer applicable. Manufacturers are producing machines that perform multiple functions. For example, a dipper shovel can be used as a dragline, crane, backhoe, clamshell, etc.
- *Hydraulics*. The application of hydraulic energy has brought about a revolution in the industry. Hydraulic pumps, producing pressures up to 250 bar or more, have made it possible to manufacture excavators of high capacities that were previously confined to cable or rope excavators. A hydraulic excavator has more breakout force than a cable excavator. Some of the designs have a slewing capability like that of a shovel.
- *Mini excavators*. Mini excavators gain momentum very quickly. They are available below 6 ton in weight, and can be easily transported and shifted. This type of excavator can dig up to 1.4 m in depth and 2.5 m in length.

The preceding paragraphs have shown the importance of earth movers and the demand for them in world markets. This demand has brought many equipment manufacturers into the arena; there is very tough competition between them, and this competition has given rise to many innovations and improvements in designs. New techniques and methods have been implemented to utilise these sets of equipment to the maximum. This has given rise to software programs that are available for the maintenance and operation of earth movers. Modular systems, remote control and automation are coming on stream at an increasing pace.

3.6. Equipment selection

When selecting any mucking or transportation unit, the following factors relating to production, productivity and overall cost of the operation should be considered:

- working range
- bucket capacity range
- hauling distance range (mobility)
- working cycle duration
- flexibility
- versatility
- weight range
- investment
- breakout force
- restrictions
- rough terrain and steep gradients
- digging power
- maintenance cost
- response to climate/weather
- utility.

3.6.1 Guidelines for selecting haulage and mucking units

Table 3.1 details the fleet of equipment that is required for earth-moving, and the scope, validity and range of applications for each of the vehicles (Fiat-Hitachi, 2000). Table 3.8 outlines the applications of various excavators to suit the ground/rock of different types that are encountered in civil and construction projects.

3.6.2 Environmental factors

The environmental factors that need to be considered in conjunction with excavation equipment are the degree of pollution the unit will produce in terms of noise, dust, vibrations, fog, exhaust gases and rise in the temperature of the surroundings (Table 3.9).

3.6.3 Accident factors

Accident factors include the possibility of accidents due to operating a unit at the work-face and the possibility of ground failure due to the use of the unit. The possibility of any accident to a third person should also be assessed. These interrelated factors can be rated as shown in Table 3.10.

Table 3.8 Applications of excavators (Fiat-Hitachi, 2000; courtesy of Hitachi)

Equipment type	Slippery conditions	Material/ground to be excavated from bank			
		Loose	Hard	Rippable, 1000 m/s	Unrippable, 3000 m/s
Drilling and blasting				– – – – –	✗✗✗✗✗✗✗✗✗✗✗✗✗✗
Crawler tractor + ripper			– – –	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗
Crawler dozer	– – – – – – ✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	– –
Wheel dozer	– –	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗	– –	
Crawler excavator	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗ with ripper bucket	✗✗✗ with breaker
Wheel excavator	✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗ with ripper bucket	✗✗✗ with breaker
Dragline	✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗	– – – – –		
Crawler loader	– – – –	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	– – –	
Wheel loader	✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗		
Towed scraper	✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗		
Conventional scraper	✗✗✗✗✗✗	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗✗✗		
Dual-load scraper	–	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗✗✗✗✗✗		
Elevating scraper	–	✗✗✗✗✗✗✗✗✗✗✗✗✗✗	✗		

✗, Normal application; –, extended application.

Table 3.9 Environmental degradation rating for the operation of equipment

Environmental factor*	Rating				
	0 Very good	1 Good	2 Fair	3 Bad	4 Very bad
Noise	Noiseless	Insignificant	Moderate	Strong	Very noisy
Vibrations	None	Insignificant	Moderate	Strong	Very strong
Exhaust gases	None	Electric	–	–	Diesel fumes
Dust	None	Small quantity	Moderate quantity	Large quantity	Very large quantity
Fog	None, clear	Slight	Moderate quantity	High	Very high
Temperature	Normal	Slight	Abnormal	High	Very high

* The important factors that need to be considered.

Table 3.10 Accident hazard rating for the operation of equipment

Accident element*	Rating				
	0 Very good	1 Good	2 Fair	3 Bad	4 Very bad
Vehicle	No risk	Small risk	Normal risk	High risk	Very high risk
Falling rock	No risk	Small risk	Normal risk	High risk	Very high risk
Danger to third person	No risk	Small risk	Normal risk	High risk	Very high risk

* The important elements that need to be considered.

3.6.4 Ergonomic factors

Ergonomic factors cover how much the equipment is liked (user-friendliness) by the workers who are going to operate and maintain it (Table 3.11), and the suitability of the equipment for the intended use in the given layout and environment.

3.6.5 Technical factors

Technical factors involve selecting the degree of fragmentation, including piling or aggregation, that will be most suitable for an efficient operation (Table 3.12). What dimensions of tunnels and drives will be required? And what are the requirements in terms of ventilation and illumination?

3.6.6 Economic factors

These include the costs of buying the equipment (capital cost), and the energy, maintenance and operating costs with respect to the output that can be yielded per unit time (Table 3.13).

Table 3.11 Ergonomic rating for the operation of equipment

Ergonomic element*	Rating				
	0 Very good	1 Good	2 Fair	3 Bad	4 Very bad
Ergonomic design	Very good	Good	Acceptable	Bad	Very bad
Possibilities for social contact	Very good	Good	Acceptable	Bad	Very bad
Working content	Independent work	Comparatively independent	Possible to influence	Almost impossible to influence	Strongly controlled (bound to the machine)

* The important elements that need to be considered.

Table 3.12 Rating of the technical aspects of the operation of equipment

Technical considerations*	Rating				
	0 Very good	1 Good	2 Fair	3 Bad	4 Very bad
Fragmentation	No demands	Low demands	Normal demands	High demands	Very high demands
Tunnel dimensions	No demands	Low demands	Normal demands	High demands	Very high demands
Ventilation	No demands	Low demands	Normal demands	High demands	Very high demands
Road condition	No demands	Low demands	Normal demands	High demands	Very high demands
Piling	No demands	Low demands	Normal demands	High demands	Very high demands
Illumination	No demands	Low demands	Normal demands	High demands	Very high demands

* The important factors that need to be considered.

Table 3.13 Rating of the overall economics of the operation of equipment

Economic element	Rating				
	0 Very good	1 Good	2 Fair	3 Bad	4 Very bad
Capital costs	Very low	Low	Moderate	High	Very high
Energy costs	Very low	Low	Moderate	High	Very high
Maintenance costs	Very low	Low	Moderate	High	Very high
Development costs	Very low	Low	Moderate	High	Very high
Wages	Very low	Low	Moderate	High	Very high
Capacity	Very high	High	Moderate	Low	Very low

* The important elements that need to be considered.

Case study 3.1

Selection of an LHD for use in a tunnel or drive

The parameters considered when selecting an electrically driven LHD (load, haul, dump unit) for use in a tunnel or drive, and the overall scenario that emerged are shown in Figure 3.18.

Dust generation, noise, vibration, ergonomic design aspects, social contacts, tunnel dimensions, road conditions and vehicle maintenance costs are given a negative grading, whereas the generation of no harmful gases, moderate ventilation requirements, high bucket capacity to handle coarse fragmented muck and working independently (working content) are some of the favourable aspects that give a positive grading. Apart from the consideration of all the parameters described above, effective utilisation of any such unit is the key to success.

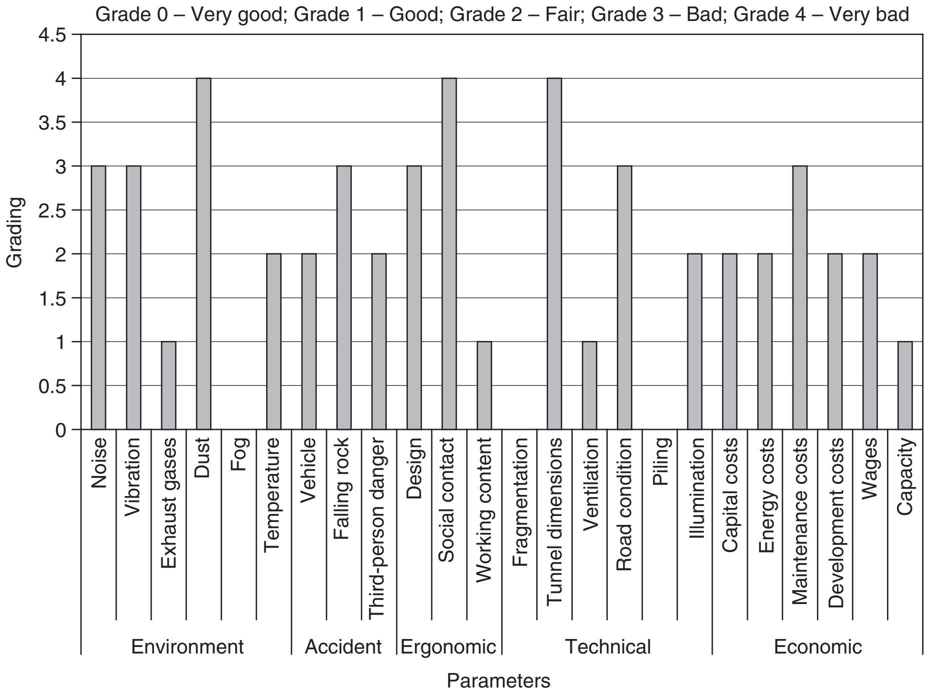
See Chapter 4 for further guidance on selecting loading and transportation units based on the parameters listed above.

3.7. Benching

The formation of slopes and benches over the hilly terrain that exists along roadsides is an important civil work. Benching is required during the following operations or types of civil and construction tasks:

- Road construction – to slope out sides while cutting a road through hilly terrain.
- Dam construction – to slope out the catchment area, especially if it happens to be a hilly terrain.
- While making large-sized tunnels and subsurface caverns and excavations. This also includes construction of hydro-electric power stations.

Figure 3.18 Selection of an electric LHD considering various parameters

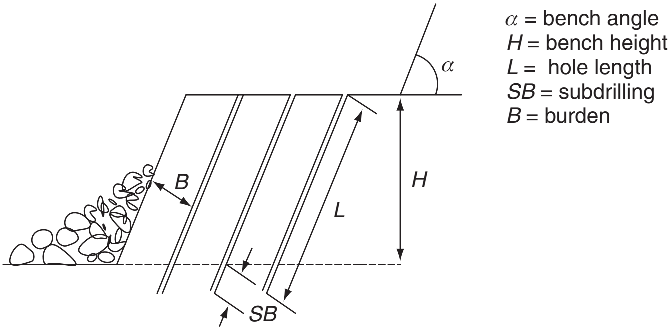


3.7.1 Bench design patterns

Bench height (Figure 3.19) is a function of the following factors (Agoshkov *et al.*, 1988; Hustralid and Kuchta, 1998; Matti, 1999):

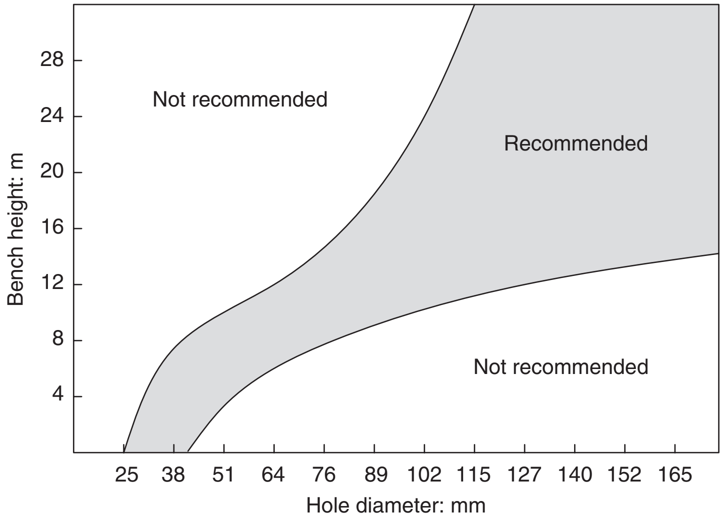
- *Ground competence*: that is, whether the ground is hard, compact, loose, friable, soft, consolidated, unconsolidated, etc. In strata such as gravel, sand, alluvial soil, clay, running sand or any other similar strata, the bench height should not exceed 3 m.

Figure 3.19 Bench blasting: nomenclature



α = bench angle
H = bench height
L = hole length
SB = subdrilling
B = burden

Figure 3.20 Selection of hole diameter based on bench height



- *Presence of water*: the ground or strata could be dry, wet, porous, non-porous, above or below the water-table, etc.
- *Presence of geological disturbances*: disturbances could be faults, folds, joints, cleavage or bedding planes, etc.
- *Height of the boom or cutting height* of the excavator to be deployed for loading, mucking or excavation tasks. In general, the maximum allowable bench height is

  $$\text{bench height} = \text{boom height of excavator} + 3\ \text{m} \qquad (3.7)$$

  A bench height more than this can prove unsafe.
- *Digging depth capability*: in the case of the dragline excavator, bench height will depend on its digging depth capabilities.

The graph in Figure 3.20 (Matti, 1999) shows the recommended bench heights based on blast-hole diameter, but ultimately it is the relevant safety regulations at the working site that will determine the bench height.

The bench angle or slope should be kept vertical but in practice this depends on the type of strata and is difficult to maintain. Usually, in practice, the angle is kept at 60–80° to the horizontal for working or active benches and at 45–60° for non-working benches.

Bench width is dependent on the following relationships:

$$\text{minimum bench width} = \text{working berm width} + \text{non-working berm width} \qquad (3.8a)$$

$$\text{working berm width} = 3 \times \text{the width of the truck/dumper to be operated on the bench} \qquad (3.8b)$$

$$\text{non-working berm width} = 3\ \text{m} \qquad (3.8c)$$

Thus,

$$\text{bench width} = 3 \times \text{truck width (or width of largest equipment operating)} + 3\text{ m} \qquad (3.8\text{d})$$

The *safety berm* is left when the bench reaches its *ultimate end*:

$$\text{Safety berm} = 0.2 \times \text{berm interval (i.e. bench height)}^{*} \qquad (3.9\text{a})$$

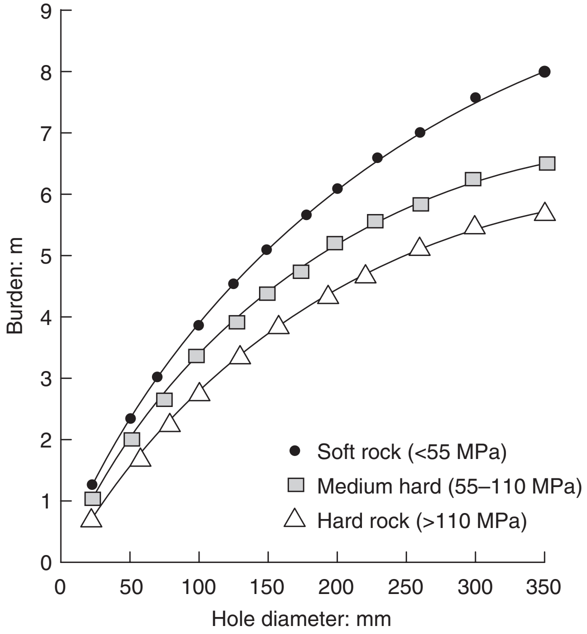
$$= \tfrac{1}{3} \times \text{berm interval (i.e. bench height)}^{**} \qquad (3.9\text{b})$$

*As per Russian practice (Agoshkov *et al.*, 1988). ** As per Matti (1999).

3.7.2 Bench blasting design parameters

The terms used to describe bench blasting are illustrated in Figure 3.19. Bench blasting is one of the most important operations. It is based on a number of parameters, and prominent among them are the type of rock (texture, structure and strength), hole diameter, terrain conditions, type of explosive and desired degree of fragmentation. In order to obtain proper fragmentation in order to achieve overall minimum cost, careful design of the drilling and blasting pattern is essential. In bench blast design, the most important parameters are burden and spacing. As the spacing is usually set either at equal to or at 1.25 times the burden (or even more under suitable conditions), it is necessary to determine the burden, which is the distance between the rows of holes running

Figure 3.21 Burden as a function of hole diameter and rock strength



parallel to the free vertical surface of the rock. If the burden is too small, part of the explosive energy is used to produce fine fragments and the rest will be lost in the form of noise, air-blast and throw. If the burden is too large, higher ground vibration and large fragments are generated. The optimum burden is the one that reduces the overall fragmentation cost, causes the least overbreak, reduces vibrations and produces proper fragmentation.

A number of empirical relationships have been proposed to design bench blasting, but this section is confined to giving a review of those formulae with which the burden can be calculated with respect to the blast-hole diameter (Atlas Copco, 2017; Hustralid and Kutchta, 1998; Jimeno *et al.*, 1997; Kou and Rustan, 1992; Matti, 1999; Tatiya and Ajmi, 2000).

3.7.2.1 Linear formulae

Langefors and co-workers proposed the relationship below for calculating the maximum burden for blast-hole diameters in the range 0.03–0.089 m (Kou and Rustan, 1992):

$$B_\mathrm{m} = 0.958d\sqrt{\frac{\rho_\mathrm{e}{}^{s}}{(S_\mathrm{b}/B_\mathrm{b})/c_0 f}} \tag{3.10}$$

where B_m is the maximum burden for good breakage (m), d is the blast-hole diameter (m), ρ_e is the explosive density (kg/m^3), s is the weight strength of the explosive, f is the confinement of the blast hole, S_b is the drilled spacing (m), B_b is the drilled burden (m) and c_0 is the corrected blastability factor (kg/m^3): $c_0 = c + 0.75$ for $B_\mathrm{m} = 1.4$–15 m and $c_0 = c + 0.07/B_\mathrm{b}$ for $B_\mathrm{m} \leq 1.4$ m.

3.7.2.2 Power formulae derived by statistical analysis

Rustan derived the following relationship for calculating the practical burden for open-pit mines with blast-hole diameters in the range 0.089–0.381 m (Kou and Rustan, 1992):

$$B_\mathrm{pl} = 3.1d^{0.689} \tag{3.11}$$

with a +52% expected maximum, a minimum value −37% and a correlation coefficient $R = 0.78$.

3.7.2.3 Tatiya and Ajmi's equation for burden with respect to blast-hole diameter

Atlas Copco, Sweden, based on its experience, has published curves for estimating the burden as a function of blast-hole diameter for different rock blastabilities, by keeping the spacing at 1.25 times the burden, and the bench height at more than 2 times the burden but not exceeding 20 m. However, these curves do not specify the range of rock strength for which each curve is applicable or the type of explosive that should be used. The equation (3.12) and curves (see Figure 3.21) proposed by Tatiya and Ajmi (2000) can be used to compute burden in relation to rock strength and hole diameter.

$$B = ad^2 + bd + c \tag{3.12}$$

where B is the burden (m), d is the hole diameter (m) and a, b and c are constants that depend on rock strength. If the uniaxial compressive strength σ_c of the rock is

$\sigma_c < 55$ MPa, then $a = -40$, $b = 35.9$, $c = 0.45$

σ_c from 55 to 110 MPa, then $a = -30$, $b = 29.4$, $c = 0.35$

$\sigma_c > 110$ MPa, then $a = -20$, $b = 24{:}1$, $c = 0.30$

The proposed empirical formula has the following features:

- It is easy to use as it is a function of hole diameter and the uniaxial compressive strength of rock, for mines using ANFO as the main explosive charge.
- Through the use of field trials, relevant blast designs for any mine may be checked.
- The model has been tried for limestone deposits but may be calibrated to any other deposit.

To use the model for any new deposit, using explosives other than ANFO, it will be necessary to change the various constants used in order to achieve the desired results.

3.7.2.4 Powder factor method

The method is described by Equations 3.13a–3.13h.

Sub-grade drilling: $J = 8d$ (m) (3.13a)

Stemming length: $T = 25d$ (m) (3.13b)

Calculate the length of charge in hole: $K = L + J - T$ (3.13c)

From a standard table or otherwise, calculate the explosive concentration, K (i.e. the charge in kg/m of hole length L).

Calculate total charge, Q: $Q = KL$ (kg) (3.13d)

Calculate volume of rock broken per hole, V_H: $V_H = \frac{Q}{P}(\text{m}^3)$ (3.13e)

Calculate volume of rock per metre of bench height V_1: $V_1 = \frac{V_H}{L} = \frac{Q}{PL}$ (3.13f)

Calculate the burden B for the desired spacing to burden ratio K_s:

$$B = \left(\frac{V_1}{K_s}\right)^{1/2} \tag{3.13g}$$

Calculate the spacing S: $S = K_sB$ (m) (3.13h)

In the above equations, d is the hole diameter (m), L is the hole length above the toe of the bench (i.e. bench height) (m) and P is the powder factor (kg/m^3).

3.7.3 Bench drilling and blasting operations

The selection of drills for construction and civil projects could be made as shown in Figures 2.2–2.4. The application of hydraulic energy to the drilling unit results in energy savings compared with the use of pneumatic energy. The selection of the proper hole diameter and bench height, and matching the explosive to perform a specific task and obtain the desired blasting results should be given due importance. Poor selection affects rock fragmentation and the profile (contour) of the excavation, and generates undue noise, vibration and flying rocks (Atlas Copco, 2017; Jimeno *et al*., 1997; Matti, 1999; Pradhan, 1996; Tatiya and Ajmi, 2000).

In some specific cases, controlled blasting is essential (see Section 2.5.3). In routine blasting, holes are not fully charged and the uncharged portion is filled with stemming material, which could be either a clay material, drill cuttings or even sand. Stemming plugs are also available. It may be necessary to use a lighter charge in some parts of a blast hole to achieve the desired powder factor. This is known as *deck charging* (Figure 3.22). Deck charging can be used for strata of varying rock strength within the same bench height (Pradhan, 1996). Use of this technique is almost mandatory when undertaking controlled blasting. Figure 3.23 illustrates charging schemes for holes of 50–75 mm and 150 mm diameter. Various types of explosives, spacers, detonating cords and other accessories are available and utilised in practice.

If the space between the stemming plug and explosive charge is left empty, it is known as an air deck pre-splitting (ADP) system, and is used in holes with diameters of 127–300 mm. The curves in Figure 2.13 could be used to determine the hole spacing for cushion or pre-splitting blasts. Specially manufactured low-density explosives, placed in long, small-diameter tubes, are used as the deck charge. In recent years, high core load (e.g. in Spain, 40, 60, 100 g of pentrite per metre) detonating cords, for hole diameters in the range 76–89 mm, have been used for contour blasting (Jimeno *et al*., 1997).

Figure 3.22 Deck charging – based on type of formation, with or without the presence of water

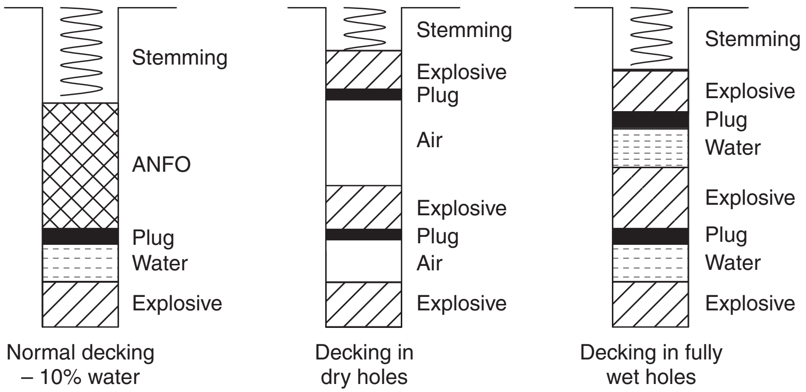
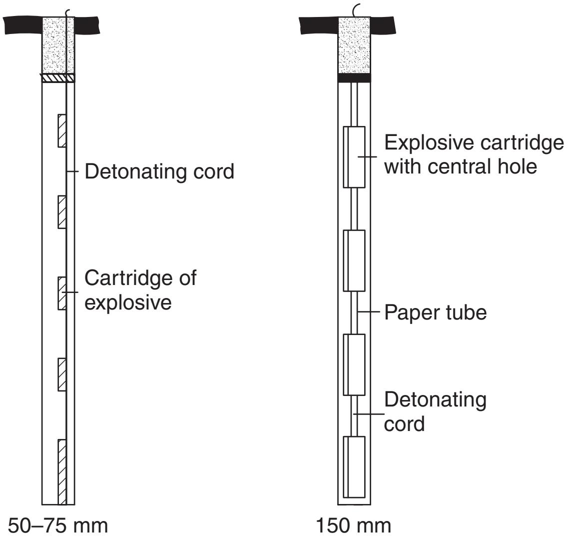


Figure 3.23 Charging contour holes – some practices (Komatusu Mining Systems, 2017)



3.8. Channelling/canal construction

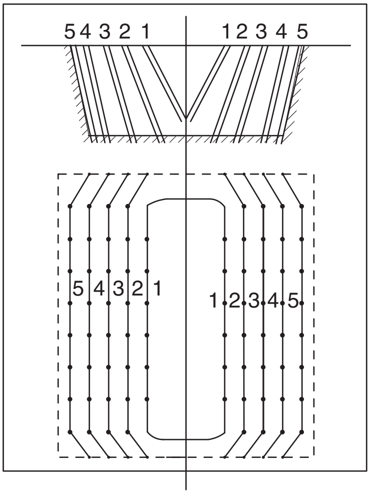
Excavation is sometimes required to pass through rocks when constructing channels and canals. As this type of excavation does not have more than one free face, it requires a special blasting technique. This can be accomplished by drilling 'V' or wedge-cut patterns vertically downward, as shown in Figure 3.24. The resultant shape is usually trapezoidal.

This excavation can be extended laterally by drilling the holes at the angle at which the side of the excavation needs to be sloped. In Figure 3.24, the holes drilled in row 5 could be extended further until the design width is reached. These box cuts provide an initial free face from which to enter lower areas. Using the box cut as the initial free face, the blast can also be extended longitudinally. This design can be used to make channels, canals, large trenches and an initial free face for making benches (Jimeno *et al*., 1997). This 'V' or wedge-cut pattern is the same as the one described in Section 4.4.3 and shown in Figure 4.4, except for the direction of drilling, which in the present case is in the downward direction (sinking). For the same set of conditions, a pyramid cut could be also applied.

3.9. Uprooting or blasting stumps

Sometimes tree stumps need to be uprooted, and this may not be easy to do using an excavator. In a scenario like this, blasting may be essential (Jimeno *et al*., 1997). This could be achieved either by drilling a shot hole (pop shooting) or by placing explosive appropriately and covering it with mud or plaster (plaster shooting). Care must be taken to use explosive judiciously to avoid undue flying rock, noise and vibrations at the blast site. An experienced crew should be deployed for such jobs.

Figure 3.24 Blast design for a box cut, or a cut to provide the initial free face for narrow excavations



3.10. Excavation for foundations

To undertake excavations for foundations, the use of ditchers, trenchers or backhoes is preferred, as such equipment disturbs the surrounding ground very little and the original strength of the walls of the foundations is preserved (Komatsu Mining Systems, 2017). However, in some circumstances, due to the limited size of the foundation configuration or some other technical consideration, it may not be possible to deploy such equipment. In such cases blasting could be a viable solution, but it must be done with due precautions to avoid overbreak. Precise drilling and blasting using the correct type and quantity of explosive should accomplish this.

3.11. Smooth blasting

In civil constructions it has become increasingly important that the rock wall remaining after the blast is of good quality in order to avoid or minimise rockfall, rockslides and excessive stabilisation work. Methods used to produce stable and smooth rock contours are described in Section 2.5.3.

3.12. Road construction and laying sewage lines

Figure 3.25 illustrates the operations involved in road construction and shows the fleet of equipment that should be deployed to achieve continuous progress. Material required for road construction is brought from the working mines where the rock can be obtained from benches (Kou and Rustan, 1992). Rock fragmentation at the benches could be carried out using drilling and blasting operations. Hydraulic breakers are deployed to fragment the rock in areas where blasting has some restrictions or where the rock does not require blasting.

Figure 3.26 illustrates the use of earth movers and transportation units for the type of excavation that needs to be undertaken for laying sewerage pipes or pipelines for other purposes.

Figure 3.25 Operations involved in and equipment deployed during road construction (courtesy of Tamrock)

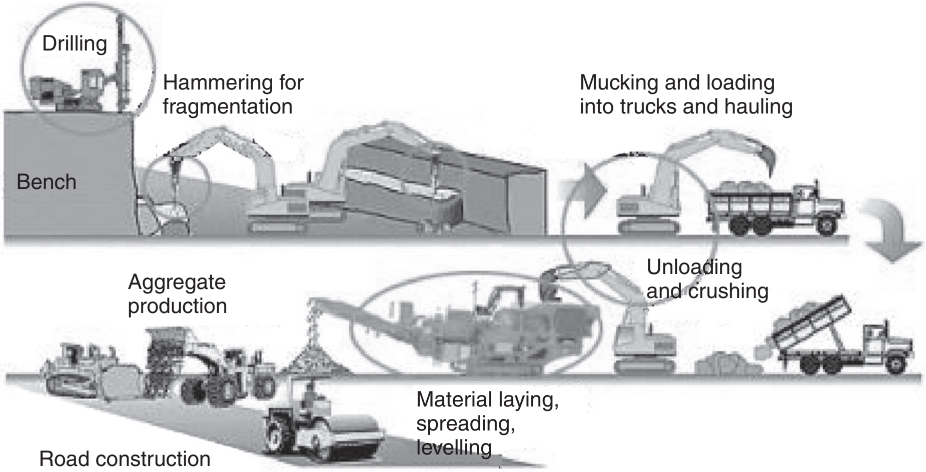
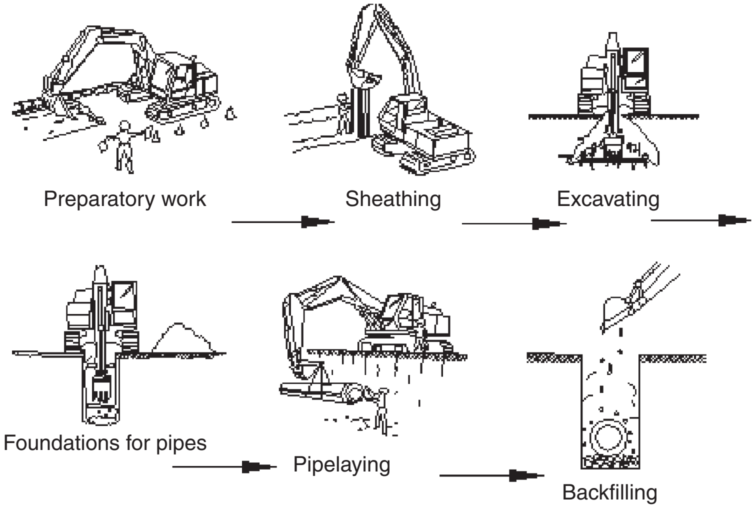


Figure 3.26 Operations involved and equipment deployed while laying sewerage lines and other pipelines (courtesy of Fiat-Hitachi)



3.13. Landfill

Table 3.1 gives useful guidelines for selecting different sets of equipment for various civil and construction operations. For sanitary landfills, for example, a number of options are available. The machines most commonly deployed are crawler dozers and loaders, wheel loaders and wheel-type refuse compactors. The methods used are (Fiat-Hitachi, 2000)

- area method – for handling >450 ton/day
- trench method – for handling <450 ton/day
- ramp method – a combination of the area and trench methods.

3.14. Concluding remarks

- Modern earth movers are versatile as they can perform multiple tasks. For example, a dipper shovel can be used as a dragline, crane, backhoe, clamshell etc.
- Advances in hydraulics have revolutionised the industry, and hydraulic pumps producing pressures of up to 250 bar or more have made it possible to manufacture excavators of high capacity (see Section 3.3.5.3).
- Mini excavators are used to undertake multiple tasks involved in day-to-day ground excavations operations and have gained in popularity very quickly. The demand for earth movers is rising, and this trend will continue.
- Strong competition in the sector has given rise to many innovations and improvements in designs. Software is now available for the maintenance and optimal operation of equipment. Modular systems, remote control and automation are coming on stream at an increasing pace.
- When selecting equipment, due weight should be given to environmental, safety, ergonomic, technical and economic factors.
- Bench blasting is one of the most important operations. It is based on a number of parameters such as rock type (texture, structure and strength), hole diameter, terrain conditions, type of explosive and desired degree of fragmentation.
- Careful design of the drilling and blasting pattern is essential to achieve proper fragmentation. The most important parameters in bench-blast design are burden and spacing. A number of empirical relationships are available to determine these factors.
- In civil constructions it is important that the rock wall remaining after the blast is of good quality in order to avoid or minimise rockfall, rockslides and excessive stabilisation work. Methods that produce stable and smooth rock contours should be selected.

3.15. Questions

1. Describe the scope of ‘civil excavations’ in current practice, and state why the excavation industry is booming. What do you understand by the term ‘earth mover’? What is seismic velocity range of rock at which this equipment gives the best results? How can a seismic velocity chart (as shown in Figure 3.6) be used to select an earth mover? List the sets of equipment that fall in the category of earth mover.
2. Define ‘muck’ and draw a line diagram to show the classification of muck-handling equipment.
3. Give a classification of bulldozers and dozing tools, and mention the application of each tool.

4 What do you understand by 'job condition correction factor' and 'operational efficiency factor'? Are these factors used to calculate the output of a dozer? Give the formula for calculating the output of a dozer.
5 Where can 'scrapers' be deployed? Give the formula for calculating the output of a wheeled scraper.
6 When a job requires excavations in several locations at the same time, which earth mover you would recommend?
7 When mass excavation is confined to one cut, which type of scraper would be preferred?
8 What is the function of ripping? Mention suitable conditions for its application. List the important factors for a successful ripping operation.
9 Give a classification of ripper/tractor units.
10 List the methods that are in vogue for estimating the production of ripping.
11 Classify trenchers. Briefly describe each one, including a micro-trencher.
12 Describe the mini-hole blasting technique. Where is this technique applied? Give the type of explosive suitable for mini-hole blasting.
13 Outline the guidelines used to select the drilling diameter, burden and spacing for a blast design for a trenching operation.
14 Suggest a pattern of mini-holes for making trenches for pipelines and cables and for creating pits for erecting poles.
15 Give the use of each of the following trenchers: heavy duty, compact and pedestrian. Describe a ladder trencher, including the various attachments used to accomplish different jobs.
16 How is a backhoe a piece of multi-tasking equipment? What are the front and rear attachments of a backhoe?
17 Compare a hydraulic excavator and dipper shovel. Mention the locales where these pieces of equipment find application. Describe the world's largest excavator, and note who it is manufactured by. This unit is so versatile that it can be used for six different operations. List those operations.
18 What is strip shovel and where does it find its applications? How does a strip shovel differ from a face shovel? How can a face shovel could be used to accomplish operations other than loading? Categorise strip shovels on the basis of bucket size. What makes the strip shovel one of the most popular pieces of equipment for use at surface mines?
19 What attachments can be added to a dipper shovel to enable it to perform different operations?
20 How does a dragline differ from a face shovel? Why is this equipment called a 'dragline'? How does a dragline work? Give the working range of this equipment in terms of bucket size, boom inclination and rotational angle. Where is the deployment of a dragline ideal to achieve optimum results?
21 What type of dragline is suitable for civil works? List the civil works where it could be deployed.
22 What is meant by batch and continuous systems of transportation? List the types of transport that fall in each of these systems. (*Note*: You can draw line diagram to answer this question.)

23 Classify belt conveyors considering different criteria. What outstanding features do the specially designed belt conveyors possess?

24 List the main characteristics of modern earth movers and muck-handling equipment.

25 Strong competition in the sector has given rise to many innovations and improvements in the design of mucking and haulage equipment. List these innovations and improvements.

26 List the factors related to production, productivity and overall cost that should be taken into account when selecting any mucking or transportation unit.

27 Draw up a table of the fleet of equipment that is required for earth-moving, and mention the scope, validity and range of applications of each piece of equipment.

28 Draw up a table of excavators and their suitability for use with the different types of ground and rock that are usually encountered in civil and construction projects.

29 List the factors that must be considered when selecting a mucking or transportation unit.

30 Give Tatiya and Adel's equation and draw their curves. Are these suitable for computing the burden in relation to rock strength and hole diameter?

31 How would you select the hole diameter based on bench height? Give the curve used to determine the hole diameter.

32 Describe the operations involved and the equipment deployed in road construction.

33 Use rock characteristic curves to design a surface mine blast or an open-cut excavation on a highway project using the following data: hole diameter, 100 mm; rock type, average; bench height, 11 m; rock density, 2.5 ton/m^3. Calculate the spacing, burden, subgrade drilling, rock broken/hole, and drilling length/hole.

34 The excavation for channels and canals can be accomplished using a special blasting technique. Name the technique and draw the drilling pattern used.

35 List the machines most commonly deployed for sanitary landfills.

36 Describe the operations involved and the earth movers and transportation units used to undertake a project for laying sewerage pipes or pipelines.

37 List the sets of equipment that could be deployed to undertake the excavation for laying foundations. Could this also be accomplished using explosives? If so, what precautions should be taken to achieve the best results?

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Chapter 4
Tunnelling by conventional methods

Tunnelling is opening up the future. It is narrowing gaps/distances by passing through the most difficult ground and hazardous conditions. Present technology can meet this challenge.

4.1. Introduction – function of drives and tunnels

A tunnel is an opening or passage of limited cross-section driven through the rock mass or ground and having at both its ends an entry point (or portal), as well as a terminal, exposed to the atmosphere. The term ‘tunnel’ is also often loosely used to designate similar openings that do not have both ends exposed to the atmosphere. Tunnels are driven to provide passage for rails, roads, navigation, pedestrians, etc., and also for conveyance of water and sewage.

4.2. Prior to driving civil tunnels

4.2.1 Site investigations

The success of any tunnelling project relies on a reliable investigation of the soil, rock, groundwater and ground stress conditions (see Chapter 1). If this is not done, even the most up-to-date methods and designs may be of little use. The project may run into unexpected problems, and there may be disputes with contractors or other agencies, cost overruns and delays in completing the tunnelling programme. If adverse geological features remain undetected during the design and construction phases, the potential for failure during operations remains. Establishing viable data sets (information) on the proposed site prior to starting tunnelling operations is, therefore, necessary.

4.2.2 Location of tunnels

The location of a tunnel can be altered to a great extent in favour of the benefits that may be available if a particular route is followed. The location could be mountainous or hilly terrain or below water-bodies, or may pass through urban areas. When driving through mountainous or hilly terrain tough rocks are usually encountered, and these may be self-supporting, in comparison with those requiring some support. When driving below water-bodies, the provision of prefabricated support is necessary as the strata are usually subaqueous. In urban areas, soft ground is usually encountered, as most cities are located near rivers and away from hilly terrain.

Another consideration with regard to a tunnel’s location is its datum; that is, whether it is going to be below the valley level or above it. Keeping the tunnel’s portal at least 5 m above the highest flood level in the area will prevent water inflow into the tunnel during the rainy season.

The location with respect to depth is also an important consideration. In the case of urban tunnels, a minimum capping or overburden is necessary for stability; otherwise, a cut-and-cover method (Section 7.8) should be adopted, which allows tunnels to be positioned at shallow depths.

4.2.3 Rocks and ground characterisation

Useful guidelines in this regard are given in Section 1.3.

4.2.4 Size, shape, length and orientation (route) of tunnels

The size of a tunnel depends on its purpose, as shown in Figure 1.1. During the design stage, consideration should be given to the vehicles or equipment of largest dimension, the clearance on either side and to the roof, and the thickness of the support work. Allowance for space for pedestrians, drainage and other facilities should also be taken into consideration. The cross-sectional area should be verified by the ventilation requirements in terms of adequate (quantity) circulation of fresh air that should flow through a tunnel, within the allowable velocity range, based on local environmental laws. The stability of the tunnel depends on its shape. In order of highest to lowest stability, the various shapes are trapezoidal, rectangular, semi-circular (wide arch, narrow arch), circular, hexagonal with vertical apex and pearl/pentagon.

The ratio between the whole cross-sectional area and useful cross-section is

- rectangular 1 : 1
- arched on both sides 1.22 : 1
- elliptical 1.27 : 1
- circular 1.30 : 1.

In borer-driven tunnels, circular or elliptical shapes cannot be avoided. While these shapes have disadvantages in terms of the effective utilisation of space, they offer better stability for tunnels. The length of a tunnel could be from a few metres to 50 km or more. The tunnel length dictates the selection of the equipment: short tunnels are mostly driven using conventional methods, while for longer tunnels the use of borers and modern technology has proved advantageous.

The orientation of a tunnel or the route through which it should pass is an important consideration, and this is often dictated by the characteristics of the ground through which the tunnel is to be driven. Sometimes, passing through difficult ground conditions can jeopardise a tunnel, not only during the construction phase but also later on during its regular use. The shortest route with minimum support work is the ideal solution.

4.2.5 Preparatory work required

Apart from proper design details with regard to location, orientation, gradient (inclination), size, shape, support types and position of tunnel portals, there are many other facilities that need to be established. Prominent among these are access roads, warehouses, stack yards; shunting yards, power, potable water, telephone, maintenance facilities, first aid, waste disposal, offices, canteen, lamp room, rest shelter, magazine, hoist room, compressed air, drilling water, waste-disposal arrangements, etc. Most of these installations are temporary and can be removed after the completion of the tunnelling operation.

Tunnelling appliances, equipment and services. Some of the equipment and appliances can be hired, and if the tunnelling task is subcontracted the contractor provides the equipment. Special items needed for the purpose are haulage equipment; tunnel surveying devices; tunnel ventilators, with rigid and flexible ducting; face and main pumps, with suction and delivery pipe ranges; compressed air and water pipelines; portable pneumatic lights; concrete mixers and delivery range; blasting cables; winches; and a few others. The services to be provided include power supply, water supply, transport, stores, repairs, refreshment, housing, social facilities, etc.

4.3. Tunnelling techniques

The term *drivage* refers to constructing, driving or making a tunnel through ground, which could consist of any formation from soft to hard rocks, soils to consolidated ground. The ground could be with or without discontinuities, water, gases or a combination of more than one of these parameters. Thus, the same method or technique cannot be applied in every scenario or situation. Rather, driving a tunnel is a very challenging task that requires skilled engineers, supervisors and work crews.

Earlier methods and techniques were very tedious, slow, arduous and unsafe but there has been a consistent improvement in this regard. More progress has been achieved with regard to developments in techniques, methods and equipment during the past six decades or so than was achieved during many earlier centuries.

The choice of a particular process (i.e. technique, method and equipment) depends on the types of ground environment through which the tunnel is to be driven; the tunnel's size, shape, inclination, disposition with respect to a particular reference point; the speed of drivage; and the availability of resources in terms of capital.

Figure 4.1 classifies the various techniques available to drive tunnels for civil works. The conventional tunnelling procedure is cyclic, as shown in Figure 4.2. It consists of the following operations:

- survey and alignment, including hooking up the machines and services
- drilling
- charging, blasting and fume clearance
- scaling
- muck disposal – loading and transportation
- face support and extension of services
- repeating the cycle.

Figure 4.1 A detailed breakdown of driving techniques used for mine openings and tunnels

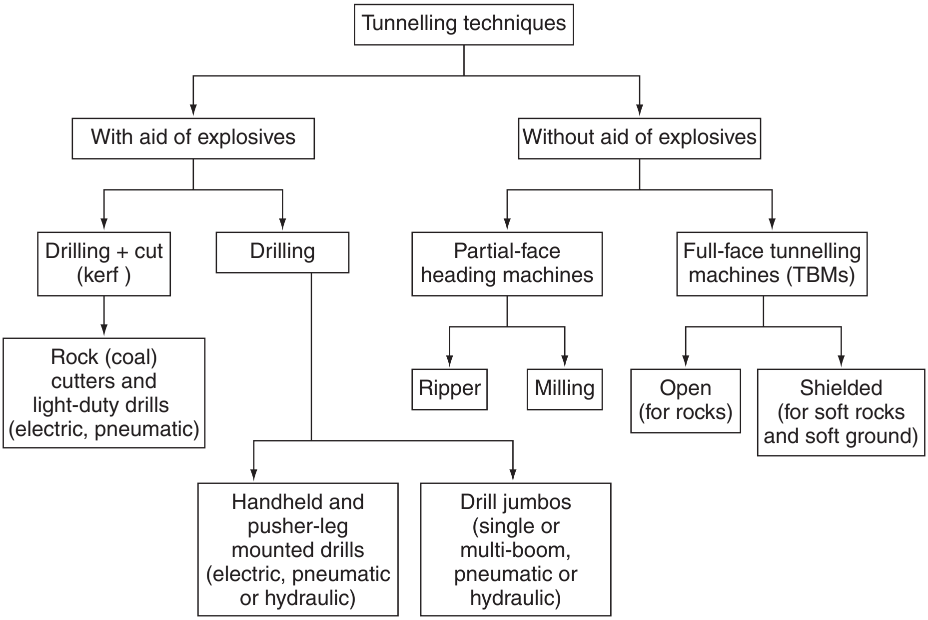
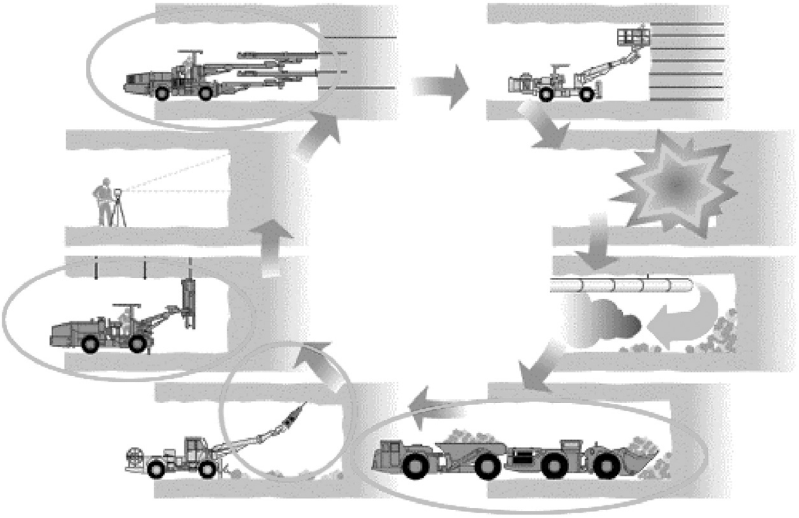


Figure 4.2 Cycle of operations during conventional mechanised tunnelling using explosives (Matti, 1999). The operations shown are drilling, charging, blasting, fume clearance and scaling, mucking, re-scaling, rock bolting (face support), extension of services including face alignment by surveying, and then resuming drilling after hooking up the drills (courtesy of Sandvik-Tamrock)



In tunnelling operations, rock fragmentation (primary breaking) is the first stage and can be carried out with or without the aid of explosives. Fragmentation using explosive requires drilling and blasting, but if it is to be carried out without explosives then rock-cutting machines, which are known as roadheaders and partial and full-face borers (see Chapter 5) are used. Figure 4.2 depicts the operations necessary when carrying out tunnelling tasks using explosives. The tasks include those listed above. When cutting machines are used to fragment the rock in tunnels, all operations except drilling and blasting are necessary. In this situation work can go smoothly, and almost continuously, without disturbing workers or the surrounding strata.

4.4. Drilling – drivage techniques that use explosives

In tunnelling operations, the rock-drill jackhammer with a pusher-leg, which came onto the market some 60 years ago, still finds applications in face drilling, particularly in small-sized tunnelling projects having a limited amount of work and capital available. In a tunnel face, up to three sets of jackleg machines can be deployed but more machines than this makes the face crowded and difficult to manage. Drilling takes a considerable portion of the total cycle time. A round longer than 2.4 m often results in the deviation of the drill holes. In soft formations, rotary electric drills that are lightweight and hand-held sometimes find application. To improve productivity and achieve faster penetration rates and a shorter duration of overall drilling operation and accuracy, the boom-mounted pneumatic drifter, which is more powerful than a jackhammer, was brought into operation during the 1960s. Multi-boom jumbos were commonly used. The 1970s saw the introduction hydraulic drifters, and this brought a revolution in drilling technology. These drifters were faster and more environmentally friendly than pneumatic multi-boom jumbos due to reduced noise levels and longer accessory life. Today, hydraulic jumbos that are fully automatic and capable of achieving drilling rates up to 300 m/h (see Figure 2.5(a)) are in use for large tunnelling and mining projects. The choice of a particular set of machines depends on the size of the project, the capital available, the desired progress rates and matching to the equipment deployed for muck handling and disposal (Atlas Copco, 2017; Stig and Olsson, 1998).

4.4.1 Pattern of holes

The placement of holes in tunnels in a systematic manner is of utmost importance. The term ‘pattern of holes’ is used to designate a suitable design for the placement of holes for charging with the chosen explosive. The selection of a suitable pattern of holes can accomplish the following:

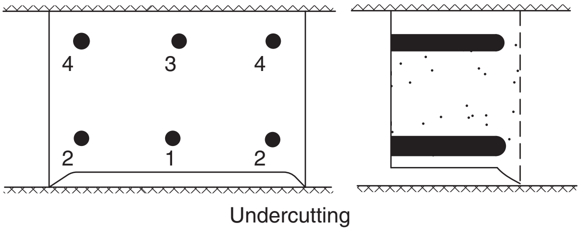
- the desired shape, size, orientation and gradient of the tunnel
- reduced overbreak/underbreak, thereby achieving a smooth configuration
- compact heaping of the blasted muck after blasting at the working face.

Depending on the ground conditions, the following two types of drilling pattern could be used.

4.4.1.1 Mechanised cutting of a kerf

In this technique, the use of a rock-cutting machine is made to cut a kerf (a cut or cavity) (Figure 4.3), at the bottom, middle, top or any other desirable position of an opening or

Figure 4.3 Application of cutting machines to cut a kerf in the rock to provide an initial free face. 1–4, Shot holes to be charged with explosive; the number indicates the delay order (figure not to scale)



tunnel face (Hartwig and Nord, 1998; Pradhan, 1996). This acts as an initial free face towards which blasting of the holes drilled in the face is directed. This free face reduces considerably the amount of drilling and explosives needed, but the cutting of a kerf is practicable only in soft and medium hard rocks such as coal, salt, potash, etc. Hence, its use is usually restricted to mines where such formations are encountered. A similar concept, which is used in civil tunnels, is to saw a small slit (or slot; 15–20 cm thick, 3–4 m long) along the outer line of the section to be excavated (see Section 7.4.1). This slit is then shotcreted. Rock-cutting machines, together with their accessories and power packs, are thus, additional items required, compared with the technique of blasting off the solid, as described below.

4.4.1.2 Blasting off the solid

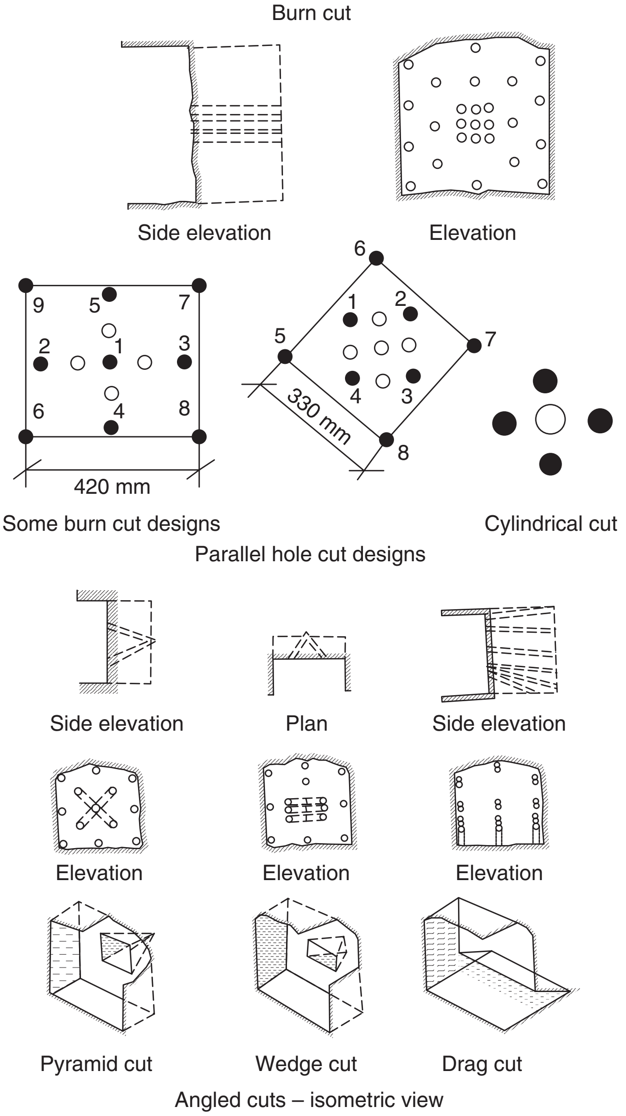
When the tunnel face is drilled and blasted without cutting a kerf at the tunnel face the technique is known as ‘blasting off the solid’. This technique involves the creation of a ‘cut’ by drilling holes at right angles or parallel to the direction of the tunnel; these are known as *parallel hole cuts*. The cuts can also be made at an angle to the axis of the tunnel, in which case they are known as *angled cuts*. Holes within the cut area are known as *breaking-in holes*. A *cut* is that area within the tunnel face where an initial free face (a small opening) is created. The holes surrounding this initial opening are charged with explosives and delay detonators. Delays to these holes are allocated in an increasing order (from this initial free face or opening) until the contour or peripheral holes (also known as *round holes*) of the tunnel face are reached. Blasting of these holes enlarges the cut area in a sequential manner until it the planned contour/configuration of the tunnel is achieved.

4.4.2 Parallel hole cuts

Burn cuts, cylindrical cuts and coromant cuts fall in this category (see Table 4.3, Figure 4.4). For a given rock there is a specific geometrical relationship between the diameter of empty holes and the spacing between the empty and charged holes which gives optimum breakage conditions. Success in blasting a round using a parallel hole cut pattern lies in the proper design of the cut area. The design includes selection of

- the empty hole diameter
- the distance from the blast hole (shot hole)

Figure 4.4 Conceptual diagrams of drilling patterns – angled and parallel hole cuts (Gregory, 1984)



- the charge concentration in the shot hole
- the drilling accuracy required and precautions necessary when charging the holes.

4.4.2.1 Cut design

Based on the literature (Jimeno *et al.*, 1997; Langefors, 1966; Matti, 1999; Olofsson, 1997; Pokrovsky, 1988) and the practices that are followed, it should be mentioned that the distance (measured centre to centre) between the shot hole and the empty hole (also known as the *relief hole*) should not be larger than 1.5 times the diameter of the empty hole; a higher burden than this could cause rock breakage, known as *plastic deformation*. When this occurs, the penetration may not reach the full depth of the round and the blast may not give the desired results. A burden within 1.5 diameters of the empty hole allows clean-cut breakage, which means creating an initial clear-cut slot or opening up to the full depth of the round. This would mean achieving optimum utilisation of the resources used. Slight deviation in drilling can jeopardise the whole blast.

4.4.2.2 Cut-hole area of cylindrical pattern

There are variations in the cut-hole patterns: some designs employ large-diameter relief holes (the cylindrical cut pattern), while in others the shot holes are uncharged (the burn-cut pattern). The patterns employed are shown in Figure 4.4. Where several empty holes are used, a fictitious diameter D can be calculated using the following relationship:

$$D = \Phi\sqrt{n} \tag{4.1a}$$

where Φ is the diameter of an empty hole (relief hole) and n is the number of holes.

The fictitious diameter D is used to calculate the side of the first square in the cut area.

$$a = 1.5\Phi \tag{4.1b}$$

where a is the centre-to-centre distance between the large hole and the shot hole. In the case of several large holes:

$$a = 1.5D \tag{4.1c}$$

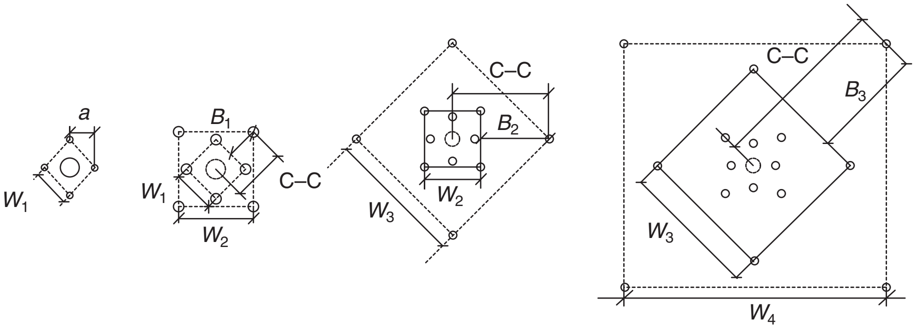
The number of squares in the cut area is limited by the fact that the burden in the last square must not exceed the burden of the stoping holes for a given charge concentration in the hole. The cut holes occupy approximately 2 m^2 (in fact for small tunnels only cut holes and contour holes are used). Calculation of the width of the resultant squares in the cut area can be done as shown in Table 4.1. The resultant squares are shown in Figure 4.5.

Table 4.1 Calculation of the dimensions of the cut section of a tunnel round in the parallel hole cut pattern

Section of the cut	Burden value (centre to centre)	Side of the section (i.e. square)
First square	$a = 1.5\Phi$	$W_1 = a\sqrt{2}$
Second square	$B_1 = 1.5W_1$	$W_2 = B_1\sqrt{2}$
Third square*	$B_2 = 1.5W_2$	$W_3 = B_2\sqrt{2}$
Fourth square*	$B_3 = 1.5W_3$	$W_4 = B_3\sqrt{2}$

* Stop calculations if the burden value exceeds the burden of the stoping holes B (see Table 4.2).

Figure 4.5 Calculation of the width of the resultant squares/rectangles in a cylindrical cut pattern



The next calculation is the estimation of the charge concentration (kg/m) in the holes to be charged in the initial holes in the cut area. Figure 4.6(a) could be used to determine this. Blasting would result in a first square (opening).

Charging the holes in the first square. The holes closest to the empty hole must be charged very carefully. Too low a concentration of charge may not break the rock, while too high a concentration may re-compact the rock (usually known as *freezing*) and thereby not allow the rock to blow out through the large hole. The charge concentration can be found using the graph given in Figure 4.6(a).

Calculation the remaining squares of the cut. The method for calculating the remaining squares is the same as for the first square except that the breakage is towards a rectangular opening instead of a circular one (Jimeno *et al.*,1997; Olofsson, 1997). Normally, the burden B for the remaining squares of the cut is equal to the width W of the opening:

$$B = W$$

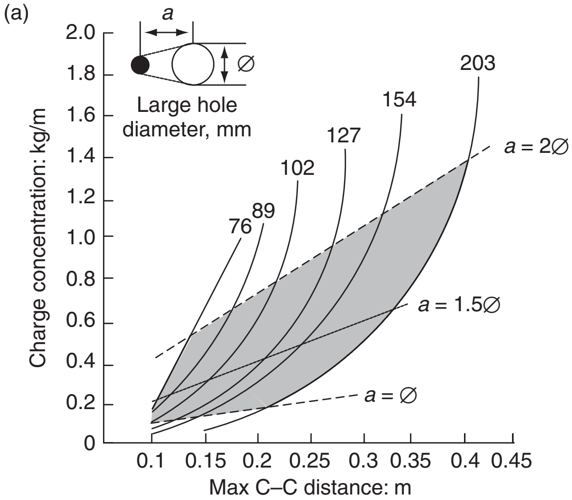
The charge concentration (kg/m of hole) can be obtained for the calculated burden from Figure 4.6(b).

After calculating the cut area, details of the rest of the tunnel round may be worked out. For this purpose, the rest of the area of the tunnel, other than the cut holes, is divided into the following zones:

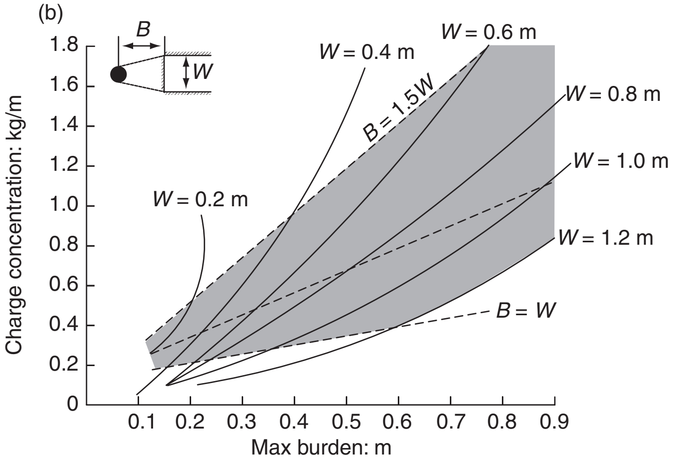
- floor holes
- wall holes
- roof holes
- stoping – upwards and horizontal holes
- stoping – downwards holes.

The graph in Figure 4.6(c) may be used to calculate the burden, spacing and charge concentration. This graph shows the use of explosives such as Emulite-150 in paper

Figure 4.6 (a) Graph for determining the charge concentration in the cut holes to be charged with explosive. Diameters 76–203 mm are the relieving/empty shot-hole diameters. (b) Determination of charge concentration based on the width of openings (square/rectangles) after blasting the cut holes. (c) Graph for calculating the burden, spacing and charge concentration for different types of explosive



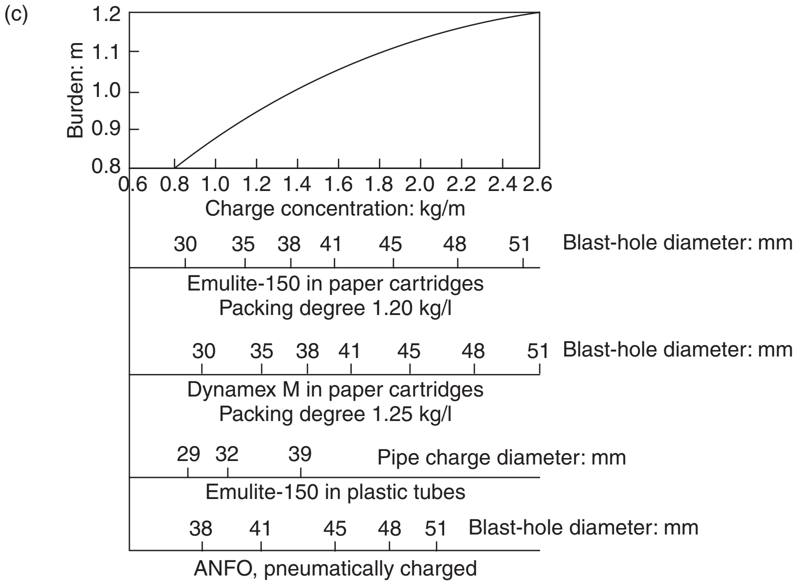
The minimum required charge concentration (kg/m) and maximum C–C distance of large hole diameter holes



The required minimum charge concentration (kg/m) and maximum burden (m) for different widths of opening

cartridges; Dynamex M in paper cartridges; Emulite-150 in plastic tubes and pneumatically charged ammonium nitrate–fuel oil mixture (ANFO). By projecting the cartridge diameter of any of the explosives mentioned above, the burden *B* of the floor holes and the charge concentration (kg/m) can be obtained. The charging pattern can then be assessed using Table 4.2 (Jimeno *et al.*, 1997; Olofsson, 1997).

Figure 4.6 Continued



For lifters:

$$B = 0.9\sqrt{\frac{q_1 + PRP_{\mathrm{ANFO}}}{(S/B)c_0 f}} \tag{4.2}$$

where B is the burden of the lifters (m), q_1 is the linear charge concentration of the explosive (kg/m), PRP_{ANFO} is the relative weight strength of the explosive with respect to

Table 4.2 Design of drilling and blasting patterns in tunnels and mine drives*

Part of round	Burden, B: m	Spacing: m	Length of bottom charge: m	Charge concentration		Stemming: m
				Bottom: kg/m	Column: kg/m	
Floor (lifters)	B	$1.1B$	$L/3$	l_b	l_b	$0.2B$
Wall*	$0.9B$	$1.1B$	$L/6$	l_b	$0.4l_b$	$0.5B$
Roof*	$0.9B$	$1.1B$	$L/6$	l_b	$0.36l_b$	$0.5B$
Stoping						
Upwards and horizontal	B	$1.1B$	$L/3$	l_b	$0.5l_b$	$0.5B$
Downwards	B	$1.2B$	$L/3$	l_b	$0.5l_b$	$0.5B$

l_b, Charge concentration in the bottom of the hole $= 7.85 \times 10^{-4} d^2 \rho$; d, cartridge diameter (mm); ρ, explosive density (g/cm^3); B, burden in the stoping area $= 0.88 l_b^{0.35}$; L, hole depth in the round.

* In some cases smooth blasting is essential and these relationships are not applicable.

ANFO, f is the fixation factor (generally taken as 1.45, this accounts for the gravitational effect and delay timing between blast holes), S/B is the spacing/burden ratio (usually 1), c_0 is the corrected blastability factor (kg/m^3), $c_0 = c + 0.05$ for $B \geq 1.4$–1.5 m and $c_0 = c + 0.07/B$ for $B < 1.4$ m (c is the rock constant, the values of which vary from 0.2 to 0.4 depending on the type of rock (Roger, 1982); for brittle rocks 0.2, and for all other rocks 0.3–0.4).

The number of blast holes (lifters) is given by (Jimeno *et al.*, 1997):

$$NB = \text{integer of}\left(\frac{AT + 2L \times \sin\gamma}{B} + 2\right) \tag{4.3}$$

where AT is the tunnel width, L is the hole depth and γ is the lock-out angle.

Table 4.2 should be referred to for the rest of the calculation. The burden should comply with the condition (Jimeno *et al.*, 1997)

$B \leq 0{:}6L;$ i.e. the burden should not exceed 60% of the hole depth.

With regard to the bottom and column charges, the column charge could be up to 70% of the bottom charge but, in practice, it is difficult to obey such rules. Usually the same concentration is used at both sections. The stemming depth is usually 10 times the hole diameter.

Apart from the calculations discussed above, some of the relationships based on experience that could be applied to determine the number of holes in the round are mentioned below.

$$\text{Swedish relation: } N = (30.9 + W \times H)\frac{44}{d} \quad \text{or} \quad N = (30.9 + S)\frac{44}{d} \tag{4.4}$$

where N is the number of holes, W is the width of the drive (m), H is the height of drive (m), d is the hole diameter (mm) and S is the cross-sectional area (m^2). In actual practice this figure could be $\pm 10\%$.

Wilber (1982) gave the following equations for tunnelling work in the USA:

$$\text{Soft or highly fractured rocks: } N = 0.124A + 10 \tag{4.5a}$$

$$\text{Hard or massive rocks: } N = 0.158A + 28 \tag{4.5b}$$

where A is the cross-sectional area (ft^2).

4.4.3 *Angled cuts*

If breaking-in holes are put at an angle to the axis of the working face (drive or tunnel), the pattern of holes is known as an *angled cut*. The tunnel face is used as a free face towards which the initial blasting power is directed. This results in a cavity, towards which the subsequent blasting is directed. In an angled cut, use is made of the orientation of the rock beds, available joints and cracks, jointing pattern, lamination, etc. However, these patterns are also drilled in hard and tough rocks. These patterns result in flying rocks and a high consumption of explosives. Common parallel hole cut and angled cut patterns are described in Table 4.3.

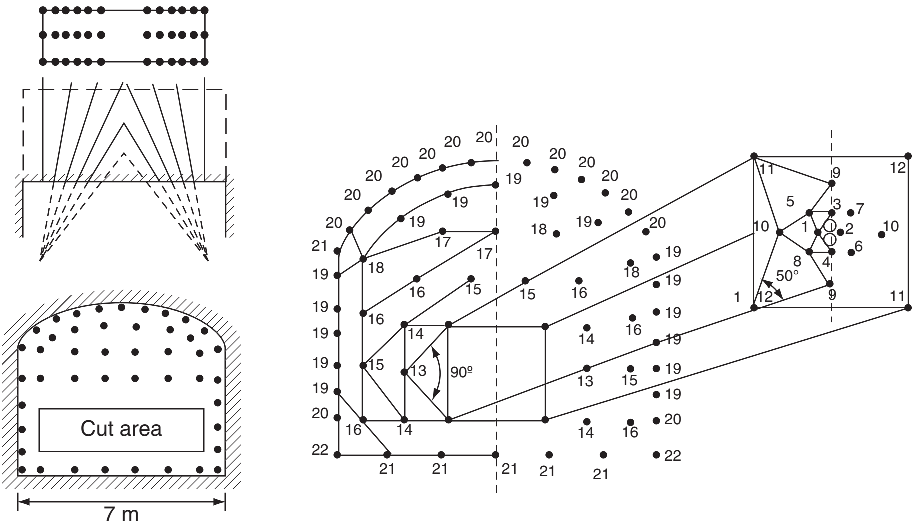
4.5. Blasting – charging and firing rounds

Explosives of different kinds are described in Chapter 2. The selection of explosive depends on the type of rock, the diameter of the holes, the desired degree of fragmentation and the face conditions in terms of presence of water and gases. Cartridges of 25–28 mm or 30–34 mm diameter are used in small-diameter holes, whereas for large-diameter holes either ANFO, slurry explosives or cartridges of large diameter should be used. The use of large-sized holes should be practised in large-sized drives and tunnels in order to reduce the number of holes required and so the time taken for drilling and face blasting (Figure 4.7) (Atlas Copco, 2017).

4.5.1 Placement of primer

Blast holes (or shot holes) are usually charged with a continuous column of explosive cartridges. The effectiveness of the blast in this practice is greatly affected by the location of the primer and the material and size of the stemming. The primer can be placed at the blast-hole collar (*direct initiation*) or at the blast-hole bottom (*inverse (indirect) initiation*). In inverse initiation the blast energy is utilised to a greater extent than in direct initiation due to prolonged action of the explosion product on the enclosing rock. The effects of inverse initiation increase with increasing hole depth.

Figure 4.7 (a) Different views of an angled cut; (b) firing sequence and pictorial view of a parallel hole cut pattern. Numbers indicate the firing order. Details of the cut area are shown separately



V cut

(a)

Firing sequence for tunnel in numerical order

(b)

Table 4.3 A comparison and brief description of patterns of hole cuts

Pattern	Concept and description	Application and remarks
Parallel hole cuts		
Burn cut	A cluster of parallel shot holes is drilled at right angles to the face in order to blast off a cavity in the centre of the heading. Some of the holes are charged, while others are kept empty. When the shock waves are reflected at the empty holes the rock is shattered and subsequently blown out by the escaping gases. In burn cut, the holes (5, 7 or 9) are of the same diameter (32–38 mm).	Small-sized tunnels Harder formations
Cylindrical cut	Same as burn cut but one large-sized hole, which is not charged, is drilled in the centre. In large-sized tunnels more than one large hole could be drilled.	Medium to large-sized tunnels Hard and tough formations
Coromant cut, spiral burn cut	In coromant cut, a template is used to drill two large-sized (55–57 mm diameter) holes to form a *figure of eight* at the centre of the cut area. In spiral cut, a central hole (75–200 mm diameter) is drilled, and this is surrounded by smaller holes with increasing spacing between them to form a spiral. This is unlike the cylindrical cut, where holes surrounding the large central holes are equidistant. In coromant and spiral cuts the holes surrounding the cut hole are given separate detonation delays in increasing order.	Medium to large-sized tunnels Hard and tough formations Skilled drilling crew is essential
Angled cuts		
Fan cut	Holes are drilled in a fan-like fashion at a horizon (1–1.5 m above the floor). The holes are set at different angles in an increasing order of inclination, starting from one side of the face, so that the last hole (at the other side of the face) is at 90–95°. Sometimes a second fan is drilled at another horizon within 0.3 m above or below the first horizon. Holes are fired in sequential order starting from the first hole (the hole at the least angle at one side of the face). This results in an initial kerf towards which the blasting of the rest of the holes of the round can be directed by the use of delay detonators.	Suitable for soft to medium-hard formations Use a hole director (template) to achieve best results

Table 4.3 Continued

Pattern	Concept and description	Application and remarks
Drag cut	Holes are drilled as in a fan cut pattern but in a vertical plane (see Figure 4.4). When these breaking-in holes (i.e. cut holes) are blasted an undercut (slot or ditch) at the face is created. The drilling and blasting for the rest of the holes are directed towards this cavity.	For soft to medium-hard formations
'V'/wedge cut	In 'V' cut, two holes are drilled at a horizon (1–1.5 m above the floor) almost at the centre of the face (width-wise). Ideally, both holes should meet at their apex, but in practice this is difficult to achieve and instead of a 'V' a wedge results. Hence the name 'wedge cut' (see Figure 4.4). The angles of the subsequent holes drilled at the same horizon are increased in such a way that the round holes (at the sides) are at 90–95° to the face. In harder strata (formations), a double or triple 'V' or wedge can be drilled. When blasting, the 'V' holes have the initial delay detonator and subsequent delays are placed in sequential order in the subsequent holes. Thus, a wedge of rock is pulled out first and this then ultimately becomes a kerf that has been generated by blasting. The rest of the holes in the pattern are drilled parallel to the axis of the drive or tunnel and blasted in sequential order using delay detonators and taking advantage of the initial free face created.	This pattern is suitable for medium-hard to hard strata. The following guidelines for 'V' cuts could be used (Pokrovsky, 1988): ■ An advance of 45–50% of the tunnel width is achievable. ■ The angle of cut should not be too acute and should not be less than 60°. More acute angles require higher charge concentrations in the holes. The cut usually consists of two Vs, but for deeper rounds three or four Vs may be required. ■ Holes within each V should be given the same delay number and there should be a delay interval of 50 ms between consecutive Vs to allow time for broken rock displacement and swelling.
Pyramid cut	This pattern (see Figure 4.4) can be drilled for any drivage work – horizontal, upward or downward. A cluster of holes (4–6 holes) is drilled in the centre of the face. The hoes are directed towards a common apex so that a pyramid is formed after blasting. The angles of subsequent holes drilled around the cut holes are increased in such a way that the round holes (at the sides) are at 90–95° to the face.	This pattern is popular during shaft sinking and raising operations and is suitable for all types of strata.

4.5.2 Stemming

The amount of *stemming material* is specified by the safety regulations in some countries. In practice, it is usually in the range 0.6–0.8 m for drift/tunnel blasting. Usually, a mixture of clay and sand in the ratio 1 : 4 is used. Water stemming (polyethylene tubes filled with water) contributes to adsorption of toxic gases and suppression of dust (Pradhan, 1996).

4.5.3 Depth of round/hole

There is no empirical formula as such for determining the depth of a round, but as a guideline (Pokrovsky, 1988), particularly in workings of limited cross-section, the depth of the hole is $0.5\sqrt{S}$ for angled cuts and $0.75\sqrt{S}$ for parallel hole cuts (where S is the cross-sectional area of the drive).

4.5.4 Charge density in cut holes and rest of the face area

(Jimeno *et al.*, 1997; Langefors, 1966; Matti, 1999; Olofsson, 1997; Pokrovsky, 1988; Pradhan, 1996; Roger, 1982; Sig and Olsson, 1998)

The charge concentration (density) required in a cut and in the rest of the tunnel face can be assessed as described in the preceding sections. As noted there, the charge density (i.e. the amount of explosive per metre length in the cut-hole area) is a function of the diameter of the empty hole, its distance from the charge hole and the explosive density. However, as the distance between the cut holes is so short and as the volume of rock likely to be blasted by the cluster of holes (i.e. in the cut-hole area) is small, the required charge concentration per metre length should be low. This means that either explosives of low density or higher density explosives with loose confinement, or with the use of some inert material such as wood as spacers, should be used. Except for ammonium nitrate-based explosives, all commercial explosives have a relatively high density (in the range 1.2–1.7 g/cm^3). Hence, the explosive cartridges must be just pushed into the cut holes without any tight or hard tamping. The blast creates a sufficient void in the cut area. However, the rest of the holes, which are drilled at an increased burden and spacing, and ultimately yield a sufficient amount of rock, should be charged thoroughly with tight tamping. At the line holes (peripheral holes) the spacing between the holes should be reduced; the charge concentration should also be reduced, by the use of either low-density explosive or higher-density explosive with spacers, to obtain a smooth face profile with minimum overbreak.

4.5.5 Smooth blasting

In practice, blasting a round results in overbreak along the planned shape, contour or configuration. This can lead to higher costs for supports, more mucking, dilution and the generation of cracks and, exceptionally, roof falls. To obtain a better correlation between the actual cross-section and the designed one, a technique known as *smooth blasting* is used. In this technique extra care is taken while drilling and blasting the line (peripheral holes). Increasing the number of line holes and reducing the spacing between them could achieve this. Practically, the spacing of line holes for a burden of 0.7–0.9 m is taken as 0.5–0.6 m (Pradhan, 1996). The line holes should be located as close to the working as the drill machine permits. In smooth blasting, drilling in the outer profile must be increased to about 1.5 times the normal. The drilling quality achieved using hand-held machines is usually poor as far as accuracy is concerned, whereas drill jumbos can provide accurate drilling (Jimeno *et al*., 1997; Matti, 1999; Olofsson, 1997; Pokrovsky, 1988; Pradhan, 1996; Roger, 1982).

Special explosive is used to charge the line holes in different countries. For example, Gurit is a special explosive manufactured for this purpose by Nitro Nobel, Sweden. It is supplied in the form of small-diameter rigid plastic pipes. In Italy, Profile-X, available in cartridges of 17–25 mm diameter and with special centring devices to provide air cushions, are used. In Australia, ANFO and polystyrene beads have been used for this purpose since 1975. In Germany, detonating cords of varying strengths such as 40, 80 or 100 g/m are used for stone drifting (Pradhan, 1996).

Smooth blasting is most effective in large drives and tunnels, and its importance has been realised for working large cross-sections. The interrelationships between important drilling and blasting parameters during contour/smooth blasting are shown in Table 2.6. Smooth blasting decreases the consumption of concrete for linings and promotes a wider use of shotcrete lining, which reduces the roughness of tunnel surfaces – a desirable property from the ventilation point of view in mines and the water flow point of view in hydraulic tunnels.

Another technique that is popular in large tunnels is pre-splitting. This method consists of drilling as accurately as possible, with respect to the contour of the tunnel, a set of blast holes arranged in a single plane or in line. The technique is popular during bench blasting at civil and construction sites (see Figure 2.14) and in open-pit and opencast mining operations to reduce vibrations.

4.5.6 Charging and blasting procedure

- Before charging, prepare the primers and get ready the required quantity of explosive and detonators.
- Keep ready and in proper condition the necessary blasting and charging tools such as scraper, stemming rod, circuit tester, connecting wires, blasting cable, warning display boards, explosive charging device (if any), exploder, etc.
- Check for the correct number, disposition and length of the shot holes to be charged.
- Clean the shot holes by blowing into them so that sludge and water, if any, are flushed out.
- For charging, follow the standard procedure for charging shot holes. In large tunnels this could be done using a cartridge loader.
- Tamp the explosive cartridges as required, based on the location of the shot holes with respect to the cut.
- Make tight and neat connections of the lead wires.
- Properly earth the charging equipment if charging is to be carried out pneumatically.
- Before blasting, lay out the blasting cables properly and test the circuit for its correctness.

- Post guards at appropriate locations. Display warning display boards, if required. Sounding sirens or hooters can perform this task.
- Take shelter at right angles from the blasting face, wherever practicable.
- Reverse the ventilating current so that it acts as an exhaust, if so planned.
- Make sure that all the required precautions have been taken prior to turning the key of the exploder.
- After blasting, allow sufficient time before approaching the face. Check for misfires, if any.
- Follow the standard procedure to deal with misfired shots.

4.5.7 Application of ANFO in tunnels

According to studies conducted by the United States Bureau of Mines, holes of less than 40 mm diameter charged with ANFO may not give proper blasting results, but when the hole diameter exceeds 40 mm the use of ANFO works out to be cheaper and more productive. ANFO is charged pneumatically using ejector or pressure-type loaders and antistatic detonators such as Anodets, Nonel, etc., to avoid the risk of static charge that is produced during pneumatic charging. Today, more than 85% of consumers in Scandinavia use non-electric detonators, and ANFO is used in bulk quantity in mines and tunnels.

4.6. Muck handling and disposal at the subsurface locale

4.6.1 Underground mucking units

For mucking from underground openings, including tunnels, several types of equipment are available. Some of the prominent sets of equipment are described below:

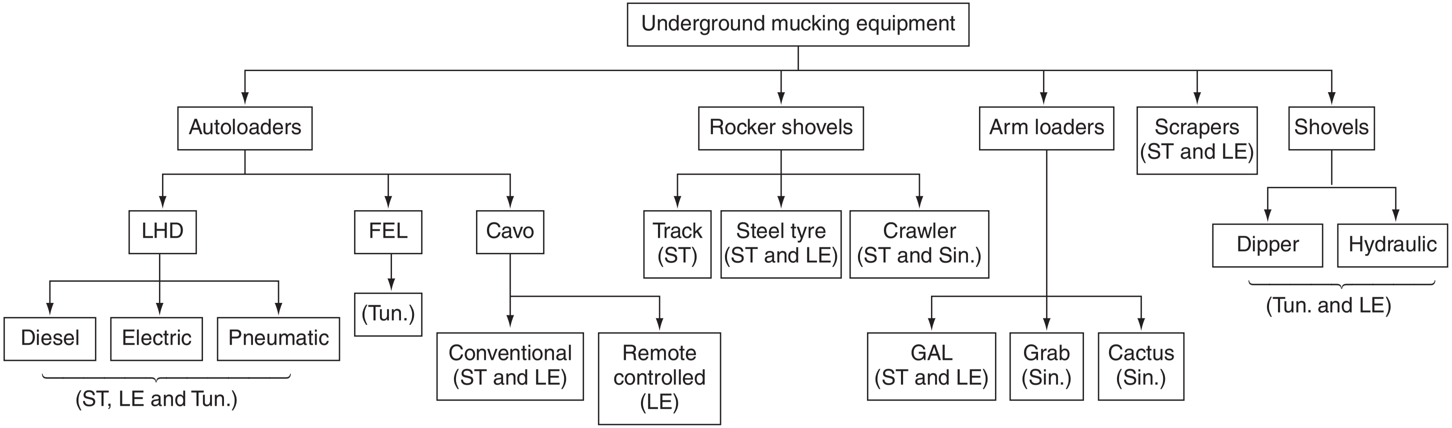
- overshot loaders – rocker shovel
- autoloaders – hopper loaders and load, haul and dump units (LHDs)
- arm loaders
- scrapers
- dipper shovels and hydraulic excavators (shovels).

The classification of these loaders is shown in Figure 4.8. A suitable match of loading and transportation units is depicted in Figures 4.9 and 4.10.

4.6.1.1 Overshot loaders

Overshot loaders pick up the muck from the face and discharge it to the rear (without turning), either into Granby cars or sinking buckets that are deployed and replaced when filled. These machines are simple in design and require minimum maintenance. Track- or tyre-mounted loaders find their application in faces having a cross-sectional area of less than 8 m^2 or so, whereas crawler-mounted loaders, such Eimco-630, are suitable for mucking from sinking shafts and drives with undulating and rough floors. In general, these loaders are not efficient for use in larger-sized openings and tunnels, as the productivity is low due to the operator becoming fatigued very quickly because of the continuous jogging and jarring. The performance of these machines also depends on the bucket capacity (Atlas Copco, 2017), which ranges from 0.2 m^3 to 0.6 m^3. In addition, side discharging loaders with lateral unloading buckets are also available.

Figure 4.8 Classification of mucking equipment together with their applications for underground excavation and tunnelling operations



GAL – gather arm loader
LHD – load, haul and dump unit
FEL – front-end loader
( ) – application for the type of operation
ST – small-sized tunnels or openings
Tun. – large-sized tunnels
LE – large underground excavations such as chambers, caverns, etc.
Sin. – shaft sinking

Figure 4.9 Low-profile trucks entering into a tunnel – a trackless system layout (courtesy of GIA Industri AB)

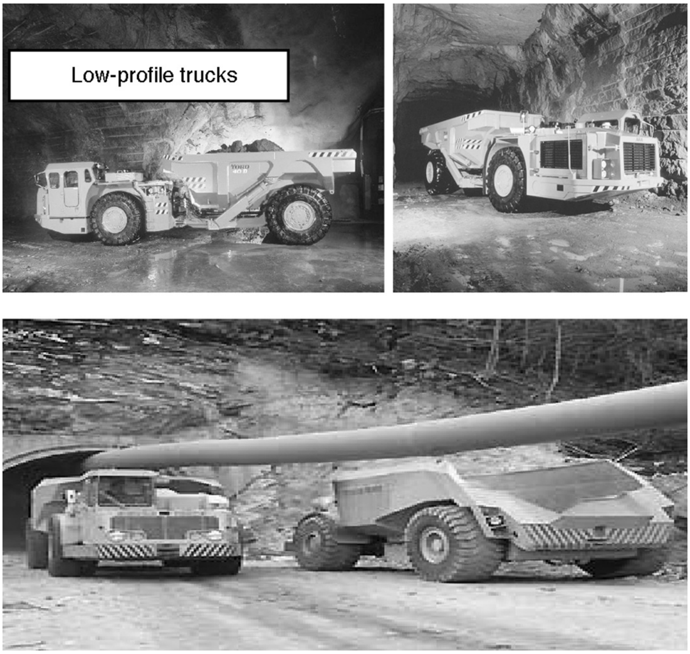
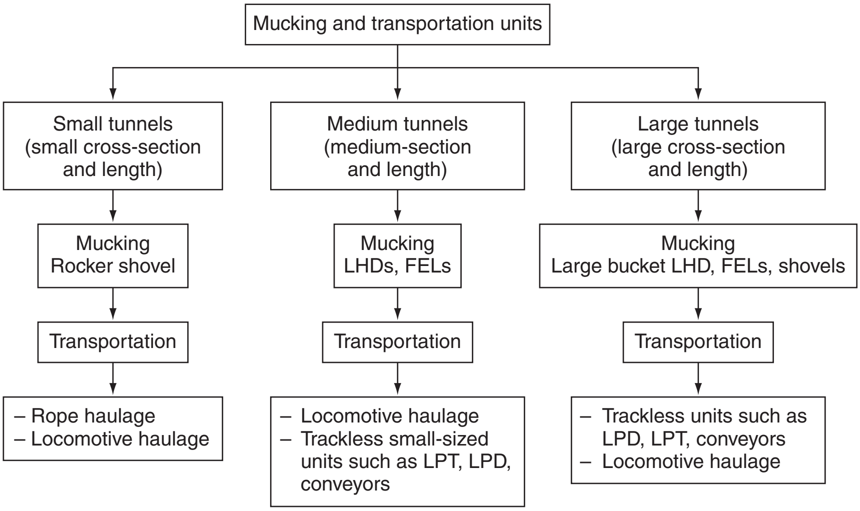


Figure 4.10 Selection of mucking and transportation units used in underground mines and tunnels



LHDs – load, haul and dump units; LPD – low-profile dumpers; LPT – low-profile trucks;
FELs – Front-end loaders
Shovels include hydraulic excavators and dipper shovels

These types of loader are used for horizontal workings of low height and are particularly suitable for workings equipped with conveyors.

4.6.1.2 Arm loaders

These machines find applications during sinking operations and are dealt with in Chapter 9.

4.6.1.3 Autoloaders – mucking and delivering

This category of loader does all three operations – loading, hauling and dumping. One type of these loaders is the hopper loader, which has an overshot bucket that loads into the hopper mounted on the same machine. When this hopper is full, the loader travels up to the discharge end, which could be a waste pass, ore pass or mill hole, to discharge the muck. Examples of this kind of loader are Cavo loaders, which are pneumatically operated, wheel-mounted loaders with the body or hoppers available in two sizes (1 m^3 or 2.2 m^3). The performance of these loaders is a matter of body capacity and the travel distance from the mucking face to the discharge end. Remote-controlled Cavo units are the latest versions of these loaders.

4.6.1.4 Load, haul and dump units (LHDs)

An LHD is similar in appearance to a conventional front-end loader (described in Section 4.6.3.1). Although an LHD does not offer top travel speeds, it has 50% greater bucket capacity, a slightly smaller engine and, generally, better exhaust emission characteristics than a front loader (Atlas Copco, 2017; Matti, 1999). These units are so popular that more than 75% of the world's underground metal mines use them to drive small and large tunnels, chambers and wide excavations (stopes). Although some of the smaller LHDs are available with electric motors, mostly they have diesel engines of power varying from 78 hp (for small models) to 145 hp or more. LHDs are available with buckets of various sizes (i.e. payload) ranging from 0.8 m^3 to 10 m^3 with a payload of from 1.5 ton to about 17 ton (Table 4.4), but the general trend is for 1.53 m^3 and 3.83 m^3 LHDs. At most mines and tunnels LHDs operate on gradients of between 10% and 20%, but operating them on a flat surface will improve the machine's life and reduce operating costs. The higher capacity and longer tramming distance units are fitted with diesel engines.

Table 4.4 Details of LHD buckets with payload and power rating (applicable to both diesel and electric power versions)

Payload: t	Capacity: m^3	Power: kW
3.5	1.5	63
3.5	1.6	63
4	2	63
6	3	102
8	4.5	170
9.5	5	170
14	6	204
17	8.5	240

These need extra ventilation arrangements and efficient exhaust-treatment devices. Every country has its own safety laws (i.e. regulations) for operating LHDs, particularly with regard to ventilation standards.

4.6.2 Transportation units

4.6.2.1 Underground trucks

The use of underground trucks began in the early 1970s in subsurface horizons (underground mines and tunnels). Both two-wheel drive and four-wheel drive trucks are in use. Two-wheel drive trucks are used on 0–12% gradients in mine roadways. The road should have a hard surface, it should not be very slippery or soft. Four-wheel drive trucks can be used for rough, slippery conditions and even at gradients steeper than 12%. Trucks can be classified into three types: tip dumpers, telescopic dumpers and push-plate dumpers.

Tip dumpers have the feature that the rear body can be lifted for unloading. The muck is discharged by gravity from the dumper to grizzlies, ore passes, waste passes or any other dumping point. The capacity range of these trucks is 5–40 ton.

Telescopic dumpers are designed to accommodate maximum payloads within the space available and are compact to negotiate low back heights. While discharging the muck, the telescopic bed is moved towards rear, thereby unloading half the muck while the remaining half is ejected out of the truck by a push plate. The usual capacity is in the range 10–25 ton.

Push-plate dumpers are similar to telescopic dumpers, but in place of two stages of pushing to discharge the muck, discharge is accomplished in a single motion. These trucks are usually available with capacities of 10–25 ton.

Kiruna, Wagnor, Eimco, Mormet, Kelbl, Caterpillar and a few other companies manufacture low-profile dumpers having a capacity of up to 50 ton. Kiruna's low-profile diesel and electric trucks are shown in Figure 4.9. Electric and diesel trucks are successfully working in mines in Australia, Canada, Sweden, Spain, China, India, Chile and many other countries. Electric trucks are environmentally friendly as they are less noisy and do not produce exhaust fumes.

4.6.2.2 Locomotive haulage

Rail transport is used as gathering and main haulage in underground mines and tunnels (Brantner, 1973; Atlas Copco, 2017). Rope haulage systems work on tracks, while locomotive haulage systems can work on tracks or rails. Locomotive haulage (Figure 4.11) is best suited to long-distance haulage at gradients in the range of 1 : 200 to 1 : 300, but gradients up to 1 : 30 can also be negotiated for a short distance. Locomotive systems are more flexible than rope and belt conveyor systems. Good roads, efficient maintenance, large output and adequate ventilation are the basic requirements for the success of a locomotive system. A good road is well drained, properly graded and has minimum turns with smooth curves. Laying rails of suitable size (i.e. weight per metre or yard) with proper fittings and alignment is the key to the success of railed systems. The weight of

Figure 4.11 Diesel locomotive with ventilation arrangement at the portal of a tunnel – a track system layout (courtesy of GIA Industri AB)

rails varies according to the weight of the locomotive and the number of wheels it has (which could be four or six). For locomotives weighing 5–100 ton the rail size is in the range 15–50 kg/m.

Locomotives for underground use are either diesel or electrically powered. Electrically powered systems include battery, trolley wire and combined trolley–battery power. Elaborate ventilation requirements in underground gassy tunnels restrict the use of diesel locomotives. Similarly, the use of trolley wire locomotives is also restricted in such areas due to the risk of fire and explosion that can be caused by the bare trolley wire and electric sparks. The battery locomotive is, therefore, a better choice for all types of mines and tunnels, particularly when it is used for gathering haulage. Trolley wire and diesel locomotives find their applications in main roads in mines and in civil tunnels.

4.6.3 Muck disposal

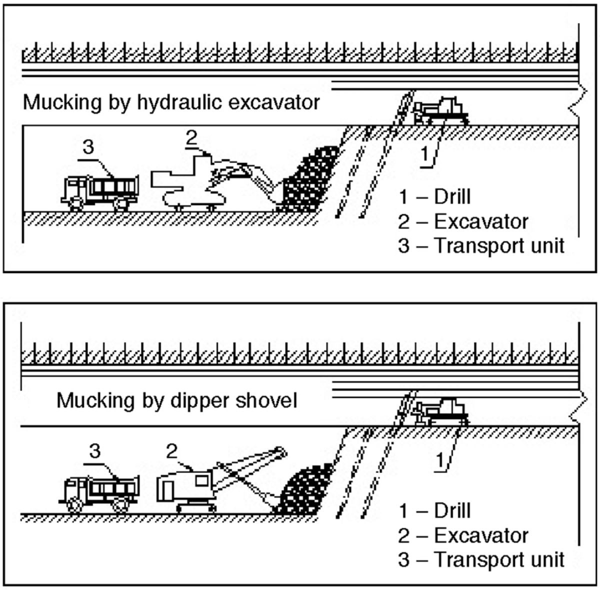
4.6.3.1 Mucking

Mucking and transportation units for operations at surface locales are described in Chapter 3.

In underground situations, after blasting, once the fumes are cleared, the face is inspected by the supervisor and the blaster, and declared free from any misfires. Water spraying then follows to suppress the dust. Once the face has been loose-dressed (scaled) it is ready for mucking. The selection of mucking and transportation units differs from one tunnel to another. Figure 4.10 can provide a useful guide.

Spoil (muck) handling in tunnels can be achieved by the use of any of the loading equipment described in the previous sections if the size of tunnel is up to 30 m^2. However, for tunnels having larger cross-sectional areas, particularly for civil works, other sets of equipment are deployed for the purpose of mucking. Prominent among these are

Figure 4.12 Application of hydraulic excavators and a dipper shovel in large caverns and tunnels



front-end loaders, hydraulic excavators and wheel loaders. These large-capacity units dig into the muck pile, load the bucket and discharge the muck into trucks, which then carry it out of the tunnel for disposal. This system is flexible and suitable for a distance range of 300–1500 m and gradient of up to 27% (Pokrovsky, 1988), but it requires efficient ventilation and pollution control measures to combat the heat, dust, noise and harmful gases generated by the transportation equipment. A dozer is also required to push the muck towards the face.

Basically, shovels are used at the surface locale, as described in Chapter 3, but their proven productivity tempted tunnel engineers to take them below ground for mucking in large tunnels and openings. Figure 4.12 (Pokrovsky, 1988) shows the use of a shovel for mucking in a Russian tunnel.

4.6.3.2 Transportation

Proper selection of transportation units for muck disposal from tunnels and drives can avoid delays and waiting time, and a good decision at the time of purchasing the units will mean that money is spent judiciously. The next important consideration is the type of layout to be used to load the muck from the face and transfer it to the transporting units (unloading). Various schemes are available for track and trackless systems. For a single-track system, the arrangement includes

- superimposed parting
- bypass system
- transverse system.

With double-track systems some of the layouts include the use of

- a portable switch
- shunting locomotives.

For a large output and to achieve almost continuous mucking from the face, shunting locomotives can be used in medium to large mines and tunnels. The selection of the type of system to be used depends on the local conditions, which can differ from mine to mine or from one tunnel to another.

When driving blind headings or tunnels, muck disposal arrangements in a trackless system require some space for turning the loading and transportation units, and such space should be provided at regular intervals on the intended haulage route. At the muck discharging (unloading) point of the mucking unit or muck receiving point of the transportation unit, a height of more than that of the tunnel is required to facilitate the muck unloading operation. To achieve smooth operation at least 0.3–0.5 m clearance from the roof or back should be allowed.

4.7. Ventilation

Fans for ventilation in tunnels are installed at the portal (Figures 4.11 and 4.13). Usually a fan drift, or an adit, is put within 30 m of the portal to deliver an air current to the tunnel. Depending on the length of a tunnel, one of the schemes shown in Figure 4.13 can be adopted. Figure 4.13(a) shows a blowing or forcing system for tunnel lengths up to 1 km. The distance of metallic ducting from the face can be kept to 50–80 m. If the need arises, flexible ducting can be added to make the air current more effective. For tunnels up to 1.5 km long, a single fan using two ducting pipes – metallic (1.2 m diameter) and flexible (1 m diameter) – can be used to supply air (see Figure 4.13(b)). The flexible ducting can lead ahead of the metallic one by a distance of up to 300 m. Provision for a second duct allows better ventilation to the spots where most of the equipment and work is located. The supply of fresh air can be made uniform along the tunnel by providing ports in the air duct every 80–100 m and regulating the discharge through them by dampers. For tunnels up to 2.5 km in length two fans and three air ducts can be used (see Figure 4.13(c)). In very long tunnels, a number of fans can be installed at regular intervals in the metallic ducting. Figure 4.13(d) shows a combination of exhaust and forcing fans, and to avoid mixing of foul and fresh air a barrier (sometimes created by mist generators or ventilation doors) may be installed (Atlas Copco, 2017; Pokrovsky, 1988; Vergne, 2000).

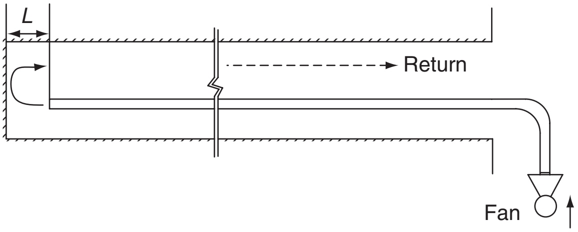
Table 4.5 shows ducts of different types and their important features. These ducts are used in mines and tunnels to carry the ventilation current.

4.8. Driving large-sized drives/tunnels in tough rocks

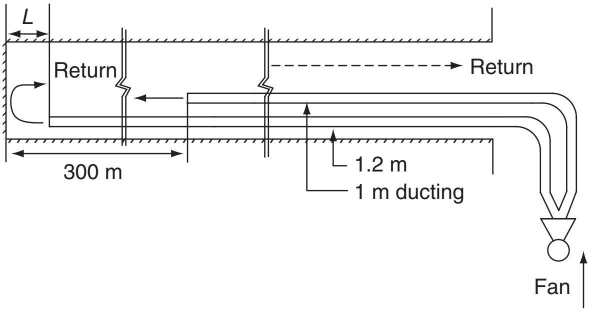
4.8.1. Large-sized drives/tunnels

The usual procedure that is followed in the construction of tunnels and mine openings of small to normal sizes has been described in the preceding sections. When openings of

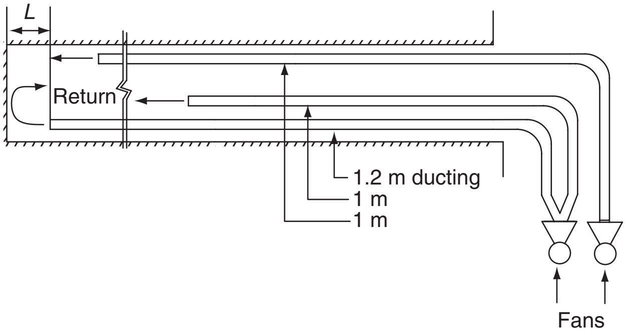
Figure 4.13 Ventilation schemes for tunnels



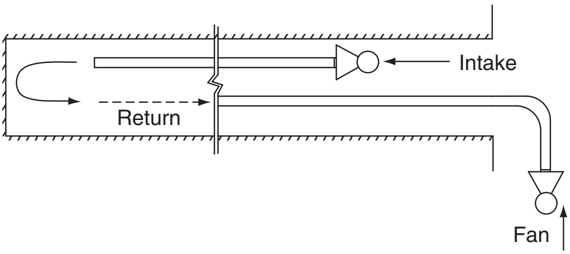
(a) Forcing system with single ducting for tunnel lengths up to 1 km



(b) Forcing system with double ducting for tunnel lengths up to 1.5 km



(c) Forcing system with double fans and ducting for tunnel lengths up to 2.5 km



(d) Combined system (forcing and exhaust) for long tunnels

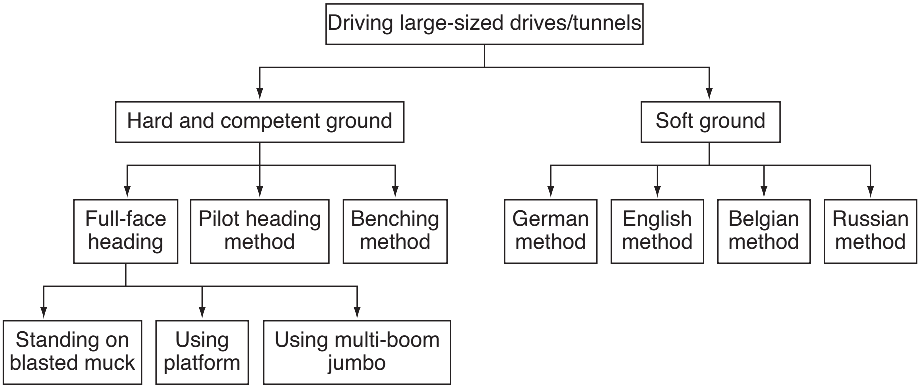
Table 4.5 Ventilation ducts with their important features (Vergne, 2000)

	Hard line (plastic/fibreglass)	Hard line (metal)	Smooth bag (plastic fabric)	Spiral bag (plastic fabric)
Typical resistance (K factor) $\times 10^{-10}$	13	15	20	60
Max. design velocity: ft/min (m/min)	4000 (1292)	3750 (1143)	3350 (1021)	2250 (686)
Air flow: ft^3/min (m^3/min)	Maximum duct diameter: in. (m) Standard sizes: 18 (0.45), 24 (0.60), 30 (0.75), 36 (0.90), 48 (1.2), 60 (1.5), 72 (1.8)			
5 000 (142)	15 (0.38)	16 (0.40)	17 (0.43)	20 (0.50)
10 000 (283)	21 (0.53)	22 (0.55)	23 (0.58)	28 (0.70)
15 000 (426)	26 (0.65)	27 (0.68)	29 (0.73)	34 (0.85)
20 000 (566)	30 (0.75)	31 (0.78)	33 (0.83)	40 (1.0)
40 000 (1132)	43 (1.08)	44 (1.10)	47 (1.19)	56 (1.42)
50 000 (1415)	48 (1.21)	49 (1.25)	52 (1.32)	62 (1.57)
75 000 (2123)	59 (1.50)	61 (1.52)	64 (1.62)	78 (1.98)
100 000 (2830)	68 (1.73)	70 (1.78)	74 (1.88)	90 (2.29)

large size need to be driven, some of the special techniques available are (Figure 4.14) (Jimeno *et al.*, 1997; Matti, 1999; Olofsson, 1997; Whittaker and Frith, 1990):

- full-face driving/tunnelling
- heading and benching
- pilot heading.

Figure 4.14 Methods of driving large drives/tunnels underground



4.8.1.1 Full-face driving/tunnelling

It is feasible to drive the full face of large-sized tunnels/openings in tough rocks without the use of any temporary supports. However, the use of permanent supports can be made as the face advances. The technique involves carrying out all the unit operations in their sequential order for the full face (see Figure 4.2). If the height of the working exceeds 2.5 m and a pusher-leg-mounted jackhammer is used for drilling, then it is essential to drill the upper portion of the face either by standing on the blasted muck of the previous blast or by erecting a platform. This practice has been mostly replaced by the advent of multi-boom jumbos that can cope with faces having a cross-section of 15 m^2 up to 110 m^2. The arrangement required is shown in Figure 4.15.

The large face size enables the use of high-capacity equipment to carry out drilling, blasting, mucking and transportation. This, in turn, results in faster work rates and productivity for the operation. The shortcomings of the method include the high capital cost of the equipment, difficulty in trimming the roof and sides, and the problem of the erection of supports.

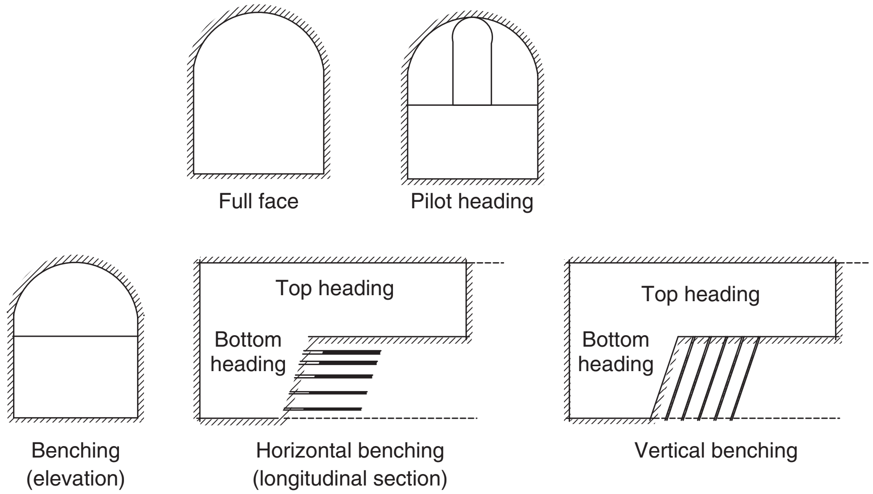
4.8.1.2 Pilot heading technique

There are two ways to carry out the driving operation using this technique (Pokrovsky, 1988):

- pilot heading in the bottom part of the drive/tunnel
- pilot heading in the centre of the drive (see Figure 4.15).

In the first method, a heading equal to 0.35–0.4 times the cross-section of the drive/tunnel is driven through the full length as it is being cut. The method has proved useful

Figure 4.15 Driving techniques in competent ground for large-sized tunnels. Top: heading (full and pilot). Bottom: benching



for drives and tunnels having a cross-sectional area up to $50\,\text{m}^2$ (Pradhan, 1996). Advance information regarding the type of rock to be encountered can be obtained using this method. The shortcomings of the method include the slow rate of driving the pilot heading and its subsequent widening. This technique is widely used.

In the second technique, a central heading is driven first, and this is then widened by radial drilling. The absence of proper drilling and blasting can result in an uneven profile of the tunnel/drive, including at its floor.

4.8.1.2 Heading and bench method

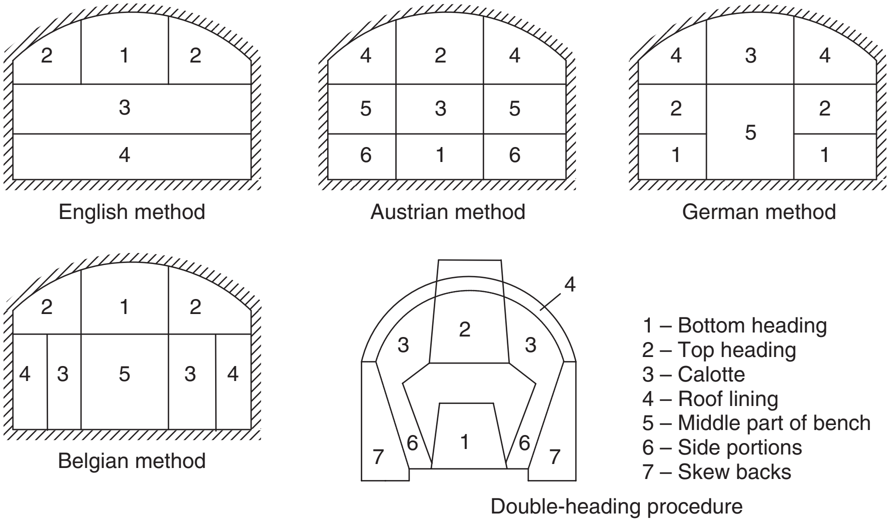
In this method, the face is divided into two parts – top and bottom (Pokrovsky, 1988). The top portion can be driven first and the bottom afterwards, or vice versa. The type of rock, the total cross-sectional area and the type of equipment available govern the ratio of top to bottom excavation, which varies between 0.75 and 1. The top bench is driven in a similar manner to the full-face method. If support is required, it is erected simultaneously. The bottom bench is excavated under the protection of a previously placed permanent lining of the top bench. This bench has two free faces, which gives better drilling and blasting performance. In this technique, due to the smaller size of the top heading, the design and erection of temporary and permanent supports are simplified. High productivity can be achieved while driving the bottom bench. The shortcomings include longer overall time to complete the total drivage operation due to the sequential working. If the rock is very stable, then the reverse process (i.e. driving the bottom heading first and then heightening it) can be followed. Figure 4.15 illustrates two schemes: one with benching by drilling vertical holes, and the other with benching by putting in horizontal holes.

Of the various techniques outlined in the preceding sections, the practice of full-face driving is widely used due to its economy of operation. The next most commonly used is the heading and bench method. In mines and tunnels where jumbos are not available the pilot heading method can provide better results.

4.9. Tunnelling through soft ground and rocks – conventional methods

Driving through soft rocks or ground is not an easy task, and the main concern is to avoid collapse and subsidence of the overlying strata. Soft ground or rocks can be described as ground which when dug is not self-supporting and which cannot stand without support beyond a very short period (from a few minutes to several hours or days). In some circumstances, advance timbering by the method known as *fore-polling* is necessary. In such an area, explosive is of little practical use to fragment the ground, and conventional tools and appliances such as picks, spades, wedges, chisels, shovels and rippers or their equivalents, which are meant for ground dislodging, digging and excavation, are used. The ground needs to be excavated in a sequence and the setting up of the temporary supports is done at the same time. Once the muck has been disposed of, the temporary support is replaced by the permanent one. The presence of water may pose additional problems. It may result in mud and other unconsolidated material inflow conditions, which require additional arrangements (Pokrovsky, 1988; Whittaker and

Figure 4.16 Techniques for driving large-sized tunnels in soft ground, as per the practices followed in different countries



Frith, 1990). Different ways or sequences of excavating the ground are used in different countries, such as Germany, Belgium, England and Austria etc., as shown in Figure 4.16. The numbers in the figure indicate the sequence of excavation.

The main problem in tunnelling through soft ground is that it weakens and tends to sink into the opening – a phenomenon called *decompression*. New and more advanced methods involve techniques to overcome the problem of such decompression or ground fall. The techniques applied are

- advance timbering or fore-polling using steel or concrete piles
- ground improvement or consolidation (see Section 7.6)
- use of shields (see Chapter 6).

4.10. Supports for tunnels

When considering the requirements of supports for mine openings and tunnels, it is important to understand the basic difference between these two structures. Tunnels for traffic and transport purposes have large dimensions. A tunnel's service life is practically unlimited and can exceed 100 years in many cases. A tunnel is used around the clock and, as such, repairs of any kind, if not impossible, are impracticable, and can cause great disturbance to users. Its supporting system should be waterproof (no seepage of water) and smooth, with an even surface and aesthetic finish. The primary requirement of the support is that it should be strong enough to sustain the calculated load, with a factor of safety not less than 2. The supports used in mines could be temporary, or in place for the period during which the minerals are exploited (mined out).

4.10.1 Classification

The supports used for mines and tunnels can be classified as

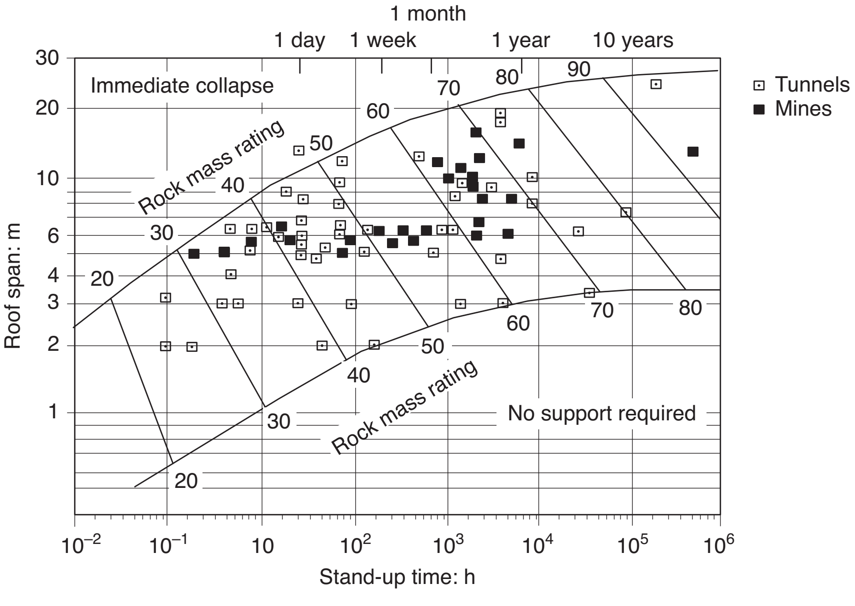
1. temporary
2. permanent or primary lining
3. secondary lining.

In some situations, when driving tunnels, the lack of a support even for a few minutes to a few hours can cause their collapse and, as such, the use of temporary support is essential. In some circumstances, even in advance or before digging the ground ahead, tunnel support is essential. Support is provided either by the method known as fore-polling, with the use of timber or steel piles, or by the use of shield supports. Wooden props, bars and sets, and rock bolting are used to support the site temporarily.

Permanent support or lining by some artificial means is mandatory in soft ground and in rocks, which can be soft to medium hard. Even a hard and competent ground needs support, depending on the life of the tunnel. The time gap and the span of the unsupported or temporarily supported ground differ from place to place, and the time gap could be from a few hours to a few days (Figure 4.17). Different types of support which are in vogue are

- natural (self-support)
- rock reinforcement using rock bolts, rock dowels and rock anchors

Figure 4.17 Roof span and stand-up time, based on the rock mass rating given by Bieniawski (1984, 1992). The plotted data points represent the roof fall studied. The contour lines are the limits of applicability



- segmental supports (tubing made of cast iron, steel or reinforced concrete)
- steel sets or rolled-steel joist (RSJ) supports
- concrete supports: monolithic (cast-in-place), prefabricated segments or blocks, shotcrete
- wooden supports.

4.10.2 Selection of supports

Deere *et al*. (1970) recommended support requirements based on the rock quality designation (RQD) concept for tunnels having a diameter in the range 6–12 m and driven by a tunnel-boring machine, or when using conventional methods. Bieniawski (1984, 1992) also suggested a support network for 10-m wide horseshoe-shaped tunnels driven by conventional methods using the rock mass rating (RMR) concept. Through combining these two concepts, as in Table 4.6, a general guideline for support requirements has been evolved (see Section 1.9 and Table 1.9).

Table 4.6 Support requirements when driving a tunnel through different ground conditions (Bieniawski, 1984, 1992; Deere *et al*., 1970; Douglas and Arthur, 1983; Hoek and Wood, 1989)

Class number	Rock condition	RMR*	RQD**	Types of support
I	Excellent	81–100	90–100	Steel sets, rock bolts and shotcrete requirement: none to occasional (i.e. as and when required)
II	Good	61–80	75–90	Steel sets, rock bolts and shotcrete requirement: none to occasional (i.e. as and when required), but the requirement could be more than in class I
III	Fair	41–60	50–75	Light to medium duty sets of steel or concrete; systematic rock bolting; 50–100 mm thick shotcreting in the back or crown of the tunnel
IV	Poor	21–40	25–50	Medium-duty sets of steel or concrete; systematic rock bolting; 100–150 mm thick shotcreting in the back or crown, sides and over the rock bolts
V	Very poor	<20	<25	Medium- to heavy-duty sets of steel or concrete, including tubing, systematic rock bolting and 150 mm or thicker shotcreting to the whole section

RMR, rock mass rating; RQD, rock quality designation.

It may be noted in Table 4.6 that the wire mesh requirement with rock bolting may be from zero in good rock to 100% in very poor ground conditions. Similarly, legging behind the steel sets may be needed, from 25% in excellent rock to 100% in very poor rock.

When selecting the support network span of the workings, the standing time required and the types of ground based on the RMR should be taken into consideration. Based on this logic and an analysis of field data, the results are as shown in Figure 4.17. This figure shows that when the roof span is high and the RMR is low, immediate collapse may occur. Conversely, when the roof span is less, even when the rock mass is poor, support may not be required for a considerable time. Collapse and roof falls have occurred over time in mine openings and tunnels even when the RMR is good but the span is high.

Bieniawski (1984, 1992) also proposed that adjustment to the RMR should be done taking into account parameters such as blasting damage, change in the in situ stress and the presence of any major faults or fractures while determining RMR. However, the value of these factors when multiplied should not exceed 0.5. The over value of this factor is multiplied by the RMR determined, based on the rock strength (rating 0–15), discontinuity density (rating 1–40), discontinuity condition (rating 0–30) and groundwater condition (rating 0–15).

General applications of the rock mass classification schemes. The application of these schemes in tunnelling and drivage work not only provides a quantitative empirical guide to support requirements but also provides significant benefits, as described by Whittaker and Frith (1990):

- They allow subdivision of tunnel routing requiring different supports.
- They initiate the systematic collection and recording of the geological data.
- They provide an estimate of the unsupported span of ground and the stand-up time, and thereby phasing of support requirements can be made.

However, Bieniawski (1984) takes the following view:

- The schemes should not be used as rigid guidelines.
- Alternative schemes should also be considered.
- Application of the schemes should be judged on a case-by-case basis.
- At least two classifications must be applied.
- Rock mass quality and RMR systems have been found to be superior to others.

4.11. Past, present and future of tunnelling technology

Hartwig and Nord (1998) compared the tunnelling technology in 1973 with the technology that prevailed during 1998, and forecasted the likely scenario in 2023. The main operations they considered in their comparison are tabulated in Table 4.7. It can be seen from the table that within the 25 years spanning 1973–1998 the increase in performance barely exceeded 1% a year, while the increase forecasted for the 25-years spanning 1998–2023 was 4% a year.

Table 4.7 Comparison of the time taken and the units used for placing a round in a face of 70 m^2 cross-section in 1973, 1998 and 2023 (Hartwig and Nord, 1998)

Operation	1973	1998	2023
Drilling	3.75 hours Mechanised pneumatic drilling began. Concept of hydraulics came to the fore	2.75 hours Hydraulic drills proved faster and more efficient; use of computers for monitoring and operation began. But there were some ergonomic-based problems	1.25 hours Multi-boom, hydraulic rock drills with faster drilling up to 11 m/min of 50–65 mm diameter blast-holes. Remote control. Bit changing facilities incorporated. Equipped with charging mechanisms
Charging	0.25 hour Mostly nitroglycerine-based explosives with electric detonators in vogue	1.25 hours ANFO widely used. Emulsions popular. Non-electric detonators in use	0.25 hour Emulsions of varying strength used, suiting even the contour hole for smooth profiles. Electronic detonators used for ideal delay mechanism. Explosive with reduced toxic emissions used
Ventilation	0.50 hour	0.50 hour	0.25 hour Reverse ventilation after blasting
Scaling	0.50 hour (Manual)	1.50 hours (Manual as well as mechanised, but time-consuming)	0.50 hour Seismic and water-pressure type scaling equipment in operation
Mucking	3.50 hours	3.50 hours Electric-powered LHDs (loaders); more environmentally friendly and faster	1.75 hours Faster muckers available but not perfectly matching the drilling and other operations
Shotcrete supports	1.25 hours	1.00 hour Application of better quality shotcrete mixtures more efficient than in case I	1.00 hour Use of steel fibred reinforced shotcreting
Bolting 15 bolts	1.00 hour	1.00 hour Time-consuming, but anchored bolts replaced by untensioned grouted bars	1.00 hour Drilling rig used to carry out automatic bolting with prefixed design
Surveying	0.50 hour	0.00 hour Automatic positioning system in operation	0.00 hour

Table 4.7 Continued

Operation	1973	1998	2023
Time lost	0.75 hour	1.50 hours to account for unplanned delays	1.50 hours to account for unplanned delays
Total cycle time	12.00 hours	13.00 hours	7.50 hours
Pull	3.7 m	4.9 m	6.9 m
Advance/hour	0.31 m	0.38 m	0.92 m
Performance increase	Base case (100%)	122%	300%

The analysis shows that over the time period considered there was hardly any improvement in most of the operations, except for longer rounds with faster drilling. Scaling time, too, has increased to more than in earlier years. In the past, scaling was undertaken by the work crews standing on the muck pile. This operation is likely to be faster in the near future with the application of pressurised water jets, as described in Section 4.12.

4.11.1 Current status of tunnelling technology

To aid understanding of the status of the forecast made by Hartwig and Nord (1998), details of the important features of a current tunnelling jumbo used to undertake tunnelling and cavern operations are given below.

The jumbo considered is a computer-controlled, three-boom electro-hydraulic jumbo for fast and accurate drilling in tunnelling and cavern excavations. It is capable of covering tunnels or caverns with a coverage area of up to $18.21\ \text{m} \times 10.92\ \text{m} = 183\ \text{m}^2$. The jumbo is suitable for rounds up to 6.1 m. It is equipped with Sandvik's hydraulic rock drills that have an air consumption of 250–350 l/min, a maximum percussive pressure of 325 bar and a rotation speed of 280 rpm (max.), and provide a hole size of 45–64 mm and a cut hole size of 76–127 mm.

The rig has automatic drilling functions and boom positioning under the supervision of the rig operator. Automated drilling of a pre-planned drilling pattern combined with an extensive data collection and reporting system enables continuous control of productivity, quality and economy. In addition to face drilling, the unit can also be used for cross-cutting and bolt-hole drilling. The noise- and vibration-insulated cabin provides ergonomic and comfortable working for the operator, with proper visibility during tramming and drilling. Salminen (2016) briefly overviewed the developments in drilling technology for tunnelling operations that have taken place within the last decade:

- operator safety (safety cabins, access protectors, fire-suppression systems, etc.) and user-friendliness of machine operation (controls, control systems, operator comfort through enclosed cabins and operator chair, powerful LED lights, etc.)

- environmentally friendly low-emission diesel engines (Tier 4i and Tier 4F)
- tunnel cycle process optimisation – input/output single-cycle optimisation with the aid of ‘drilling and blasting optimisation software’ (e.g. Sandvik iSURE)
- improved tunnel-profile quality (reduced overbreak, eliminated underbreak)
- fully automated and semi-automated drilling jumbos have become the standard solution
- longer blasted round lengths due to improved drilling accuracy and stiffer and stronger drilling rods
- drilling data collection, reporting and analysis
- measurement-while-drilling (MWD) technology
- analysis-while-drilling (AWD) technology (e.g. Sandvik geoSURE)
- improved drilling speed with high-frequency rock drills, including drilling stabilising systems
- improved drilling-control systems
- multi-functionality of drilling jumbos (longhole drilling, pipe roofing, bolt hole drilling, etc.)
- mechanisation and automation of longhole drilling tasks in grouting, probing, etc., of holes
- improved serviceability and reliability of machines.

This review tallies fairly well with the forecast made by Hartwig and Nord (1998). It also verifies the development made in achieving longer rounds, which is described in the case studies in Section 4.13.

4.12. Overbreak and scaling – some innovations

Deviation from the planned profile of an opening after blasting often results in underbreak or overbreak. There are a number of parameters that could be responsible for this, including improper drilling; use of incorrect charging and explosive; the quality of the rock mass; and the presence of abnormal structures or features within the rock mass, such as fault zones, dykes, joints, etc. Sometimes an abnormal amount of water also adversely affects the profile obtained after blasting.

The result is uneven floors and sides of tunnels and openings, and therefore more scaling is required than usual. There have been innovations in scaling techniques, with conventional manual scaling using crowbars and scaling rods having been replaced by mechanised scaling. Scaling methods include

- light mechanical scaling
- hydraulic jet scaling
- roadheader scaling.

The equipment for light mechanical scaling consists of a very small hydraulic hammer attached to a crane arm and mounted on a platform. It was developed to avoid manual scaling during sublevel caving operations. It can be deployed to save time when scaling tunnels, but when the blast is not perfect comparatively more time will be required.

Hydraulic jet scaling is a similar operation to that of hydraulicking, which is an aqueous extraction method used in underground coal mining and surface mining operations. However, for scaling purposes the water pressure does not exceed 100 bar. This technique has also been reported to work satisfactorily in a properly blasted round and gives better performance than mechanical scaling. However, during poor blasting, hydraulic jet scaling also requires more scaling time.

Roadheader scaling has proved to be faster and better than the previous two techniques.

4.13. Longer rounds – a trial

As predicted by Hartwig and Nord (1998), the practice of making longer rounds through the application of multi-boom, hydraulic rock drills with faster drilling rates (up to 11 m/min) to make 50–65 mm diameter blast holes, and the use of remote-controlled bit changing facilities have come into vogue. An initiative in this regard was undertaken in 1995 at the LKAB's mines at Kiruna and Malmberget in Sweden, where trials were conducted on longer rounds up to depths of 7.5 m. Details of the project are given below.

Objectives. The objectives of the project were to optimise diameter of the large cut hole, to find the best drilling plan (pattern) and to determine the blast's damage zone in order to reduce the scaling and reinforcement required. The test area selected was the Norra Alliansen orebody at the 790 m level at the Malmberget mine. Four long drifts (tunnels) from this area were allocated for the trail.

Drilling equipment and pattern. The equipment selected to drill the large diameter pre-central hole was an AMV equipped with a Wassara ITH water-powered machine. The large diameter hole was drilled in two steps. A 165 mm diameter pilot hole was drilled and this was then reamed to 250–300 mm. The maximum hole length was to be 32 m, which was estimated based on a maximum allowable deviation of 1%. An Atlas Copco Rocket Boomer 353S (Figure 4.18) equipped with the automatic road adding system and

Figure 4.18 Atlas Copco Rocket Boomer 353S drift drilling rig for drilling 64 mm diameter holes

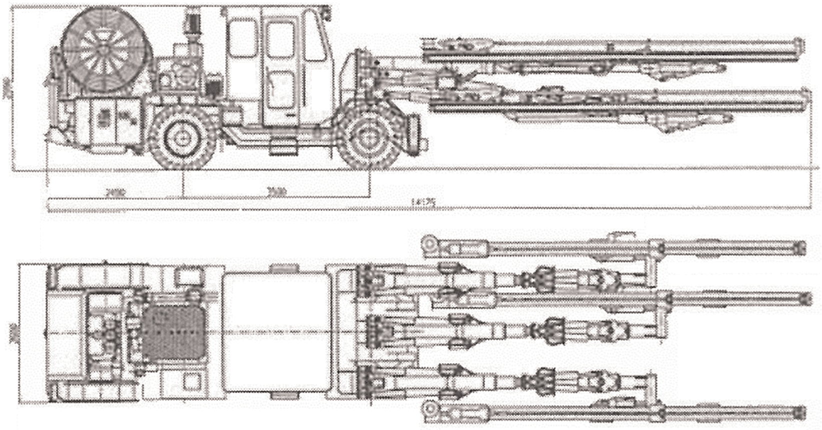
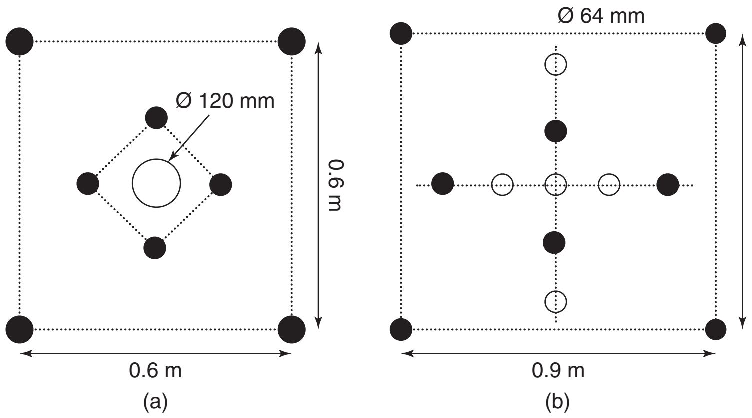


Figure 4.19 The reference (standard) round: (a) standard Kiruna parallel hole cut; (b) cut with 64 mm hole diameter (Holmberg *et al.*, 2001)



a Bever Control tunnelling position system was used to drill the drilling rounds (64 mm diameter, 7.5 m deep).

The standard drilling pattern for the 57 holes of 64 mm diameter in drift of 6.5 m × 5 m was drilled. All holes except the back holes were charged with non-cap-sensitive pumpable water-resistant emulsion explosive (velocity of detonation 7500 m/s). The back holes were charged with a 0.5 m long bottom charge of emulsion plus a 40 g/m detonation cord (KSP40). The objective was to compare this round (Figure 4.19) with the round having a central hole diameter of 250 mm or 300 mm (Figure 4.20(a)). Trials were also conducted of the corkscrew drilling pattern (Figure 4.20(c)), where position of each hole was based on its expected rock removal capability (i.e. each hole should have its optimum burden). The positions of the holes and the delays around the cut were so set that the blasting sequence was corkscrew shaped.

The tests were done using electronic detonators (40 g/m or 8 g/m detonation cord and string loaded Kimulux R in the contour holes) (Table 4.8).

Results. Advances were measured before and after scaling and compared with those achieved using standard 64 mm diameter blast holes in long drift rounds (see Figure 4.20(a)). Scaling was performed using a Mountabert BRP 30 hydraulic hammer with water at 100 bar pressure. As shown in Figure 4.21(a), rounds with larger diameter (300 mm central cut hole) holes produced better results, and even before scaling the advance was 97%. Use of electronic detonators at the contour holes gave the best results in terms of radial cracks beyond the excavation. Different explosives and initiation combinations were used as shown in Tables 4.8 and 4.9. Contour blasting using a decoupled string of emulsion initiated instantaneously with electronic detonators resulted in no blast-initiated cracks. Contour holes fully charged with emulsion resulted in radial cracks of at least 0.5 m. Thus, when electronic detonators are used, the type of explosive

Figure 4.20 (a) Standard long drift drilling pattern, 57 holes in a 6.5 m × 5 m face. (b) Drilling plan with a central hole of 250 mm or 300 mm diameter. (c) Corkscrew drilling/ignition pattern (placement of the holes is based on their rock-removal capability) (Holmberg *et al.*, 2001)

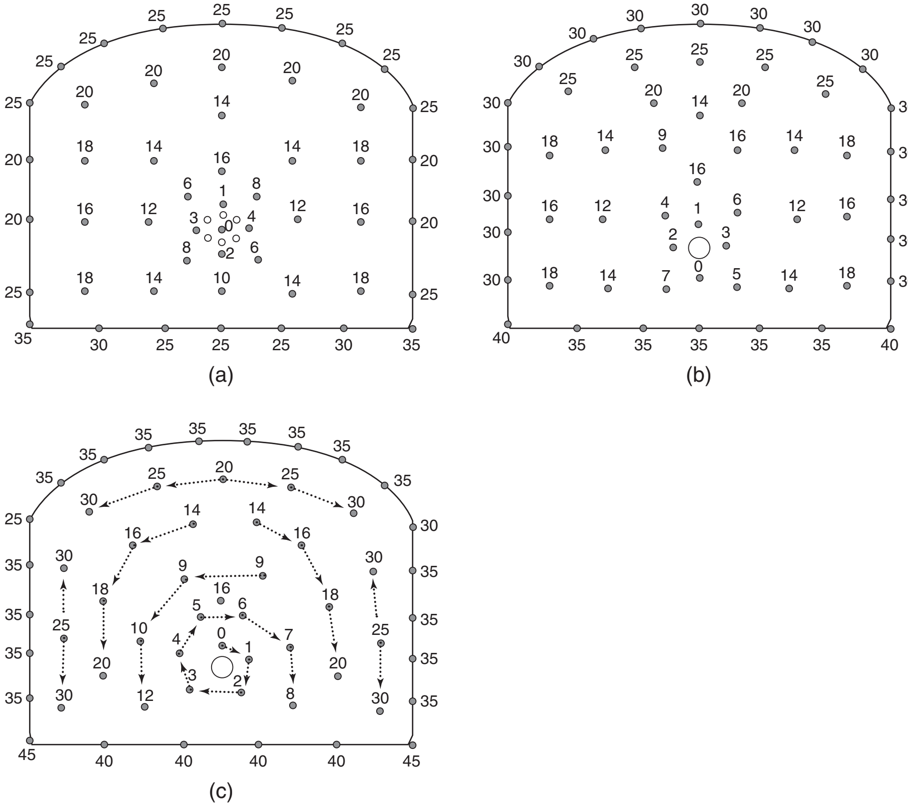


Figure 4.21 (a) Advance achieved with the large-diameter central hole. (b) Advance for long rounds, showing the progressive increase in the advance per round (Holmberg *et al.*, 2001)

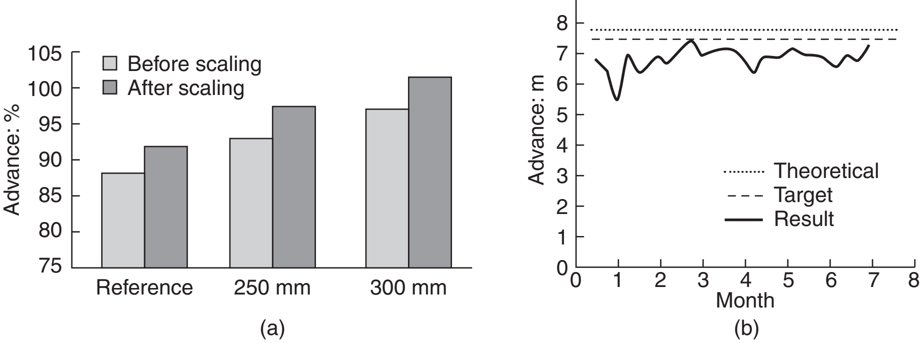


Table 4.8 Rounds tested to determine the optimal blasting plan (Holmberg *et al.*, 2001)

Contour charging method	Rounds with 250 mm diameter hole	Rounds with 300 mm diameter hole
Cord 40 g/m or 80 g/m	6	4
String-loaded emulsion	12	3
Cord 40 g/m or 80 g/m + electronic detonators	3	
String-loaded emulsion + electronic detonators		4
Total	21	11

Table 4.9 Data on contour blasting explosives (Holmberg *et al.*, 2001)

Explosive	Density: kg/l	Velocity of detonation: m/s	Gas volume STP: l/kg	Energy: MJ/kg	Linear charge concentration: kg/m
Cord 40 g/m	1.05	6500	780	5.95	0.04
Cord 80 g/m	1.05	6500	780	5.95	0.08
Kimulux R	1.21	5500	906	2.94	3.86
String-loaded Kimulux R	1.21	5500	906	2.94	0.55

at the contour holes has only a minor influence on the results achieved. At the end of the project in 1995, the advance achieved was 99.5% (Figure 4.21(b)) and the need for scaling was reduced by 50% when a large-diameter central hole was used. Based on the results of this project, LKAB has introduced the use of the predrilled large-diameter cut-hole method at the Malmberget mine.

Conclusions. The conclusions drawn from the Malmberget mine project work are as follows:

- In shorter rounds in the range of 4–4.5 m, the use of 64 mm diameter cut holes works well.
- Longer rounds (7.8 m long) were found to be economically viable.
- The quality of the contour's profile can be improved by ensuring precision in the delay interval at the contour. The contour tests also showed that no standard explosive to suit this diameter is commercially available, which is why the results achieved using 48 mm diameter contour holes were better than those achieved using 64 mm contour holes.
- Precise laser reference for alignment and accurate marking of holes are very important factors, not only to keep overbreak low but also to keep the drift-

heading in the right direction and at the right level. Use of a lifter with a lock-out angle of 3° is essential to obtain a clean floor.
- The amount of overbreak depends on factors such as the alignment of the drilling rig, the drilling accuracy, the method of scaling and the geology. The overbreak varied: it sometimes exceeded 15% but at the end it was, on average, 12%.

To minimise damage to the walls, when the perimeter holes are to be shot simultaneously the intended holes should be placed precisely as per the design. Experiments have shown that if adjacent holes are separated in time by more than 1 ms, poorer results are obtained. Such precise timing requires the use of electronic detonators. Many techniques can be used to reduce the linear charge in the contour row and the buffer row; for example:

- decoupled plastic pipe charges
- detonating cord
- string-loaded bulk emulsion
- low-density/strength bulk explosives (e.g. ANFO or emulsion with polystyrene)
- notched holes together with a very light charge.

It is not unusual for the blaster to fail to consider the effect of the charges in the rows adjacent to the often well-planned and smooth blasted contour row. Charging the adjacent rows with a heavy charge results in cracks spreading further into the remaining rock than would result from smooth blasted contour holes/rows.

Case study 4.1

Hydro project A

In a hydro project, tunnels and other openings were driven in a rocky area having a RMR in Class III. Overbreaks and collapses were common. The tunnel was horseshoe shaped (9.8 m × 7.5 m). Face drilling was done at two parallel tunnels in the same area using a three-boom hydraulic drill jumbo. The cylindrical-cut drilling pattern was adopted: four 102 mm diameter reamer holes (not to be charged) and 45 mm diameter holes in the rest of the face. The important design data and details of the explosive charging are shown in Table 4.10.

Observations.

- The use in the 22 peripheral holes of 40 mm cartridges containing in total $22 \times 3.2 = 70.4$ kg of explosive seems excessive, and is likely to create both overbreakage and damage to the surroundings.
- All the peripheral holes have been allocated *'zero' delay,* which also is not a sensible or logical practice.
- The zero delay has an explosive load of $70.4 + 04 = 74.4$ kg, which is not a sensible practice.

Consequences. The survey profiles shown in Figure 4.22(a) depict an abnormal overbreak excessive use of explosive/delay and also the total quantity of explosive used resulted in an increased peak particle velocity (PPV), which is a measure of damage to the surrounding structures (including the rock mass). The PPV reached a value of 300–600 mm/s or even more, and this is the main reason for the deterioration in the rock-mass quality and the collapses that occurred at both tunnels. The raised PPV helped in opening of the joints (widening the aperture) in the surrounding rock mass. Therefore, the continuation of this practice for more than 2 months led to a deterioration in the rock-mass class quality from RMR III to RMR IV.

Modifications. The author was recruited to this project as a consultant to advise on changes to the design. The number of holes as well as the quantity of explosive were reduced, at the peripheral holes the last delay (No. 9) was used and the quantity of explosive was reduced to from 3.2 kg/hole to 1.4 kg/hole (a reduction of about 56%) (Table 4.11). It was also suggested that smaller-diameter (25 mm or even less) explosive cartridges be used. The surveyed profile after the blast (Figure 4.22(b)) under the new blasting design correlated well with the designed profile of the tunnel.

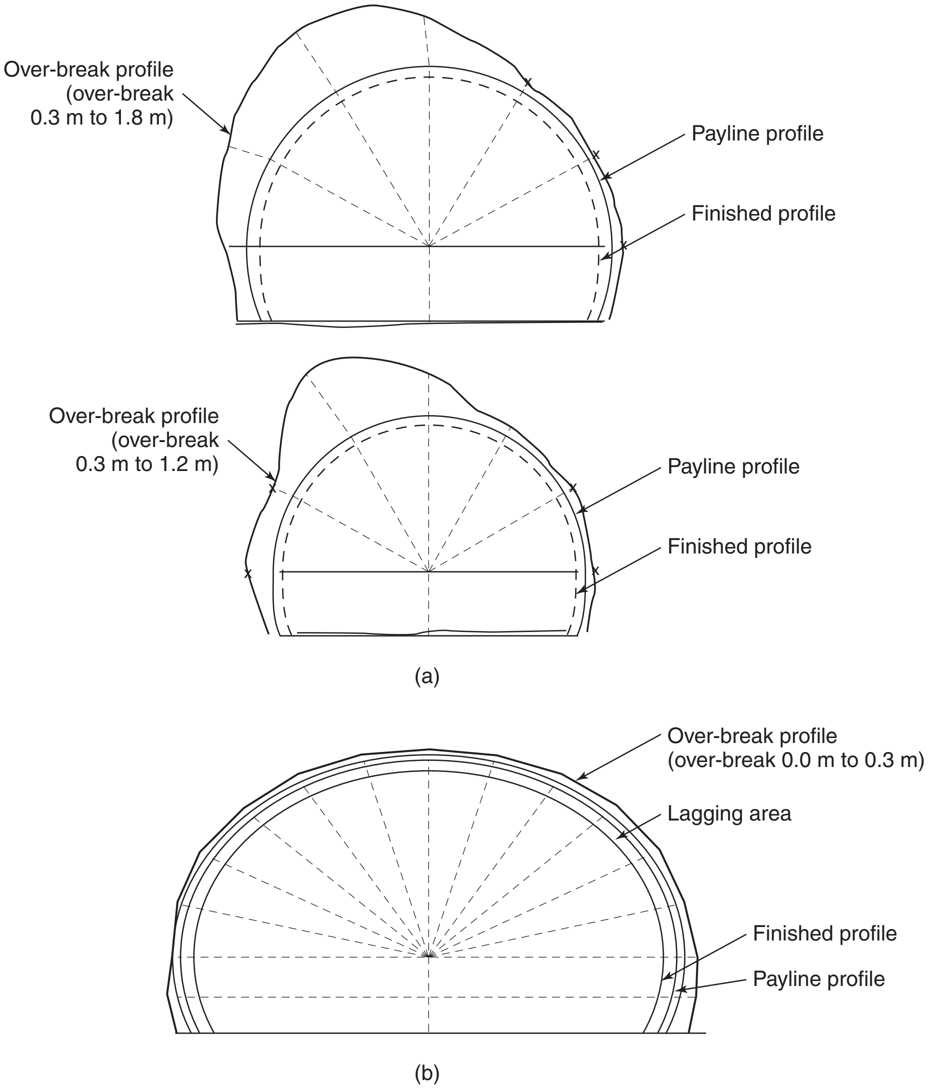
Table 4.10 Important design data and explosive charging details (cylindrical cut pattern using half second electric detonators)

	Hole diameter: mm	Delay no. (electric detonator)	No. of holes	Explosive per hole: kg	Total charge: kg	Hole depth: mm	Charge depth: mm	Stem depth: mm
Reamer holes	102	–	4	–	–	4000	–	–
Central cut hole	45	0	1	4	4	4000	3000	1000
Rest of holes	45	1–10	97	4	329.6	4000	2700	1300
Peripheral holes	45	0	22	3.2	70.4	4000	2400	1600
Total	–	–	120	–	404	–	–	–

Table 4.11 Proposed modifications to the drilling and blasting scheme

	Hole diameter: mm	Delay no. (electric detonator)	No. of holes	Explosive per hole: kg	Total charge: kg	Hole depth: mm	Charge depth: mm	Stem depth: mm
Reamer holes	102	–	4	–	–	4000	–	–
Central cut hole	45	0	1	4	4	4000	3000	1000
Rest of holes	45	1–8, 10	81	–	–	4000	3000	1000
Peripheral holes	45	9	20	1.4	28	4000	2100	1900
Total	–	–	102	–	310.6	–	–	–

Figure 4.22 Survey profiles after blasting: (a) under the existing regime, with the overbreak shown; (b) under the new regime. Payline profile – allowable over-break beyond finished profile for the purpose of payment to the contractor. Space between it and the finished profile is occupied by the lagging material.



Case study 4.2

An adit at a hydro project

Observations. At the site in question, the practice being used was as follows:

- Use of excessive drilling (number of holes in a round of 45 mm diameter), excessive explosive charge per hole and excessive total explosive per blast.
- Use of only 4–5 delays to blast the face, as against the more usual 11 delays. This resulted in the use of excessive charge (amount (kg) of explosive per delay), leading to abnormal vibrations (high peak particle velocity) during the blast and, thereby, damage to the surroundings.
- Cartridges of 32 mm and 40 mm were used, which is not a sensible practice. Ideally, at the buffer row (the row before the peripheral holes) 25 mm cartridges should be used rather than the larger cartridges.
- Peripheral holes were charged using 32 mm cartridges, whereas, ideally, line drilling only should have been used.

Consequences. The use of a limited number of delays could be considered one of the leading reasons for excessive overbreak and the formation of loose material and roof fall immediately behind and near the working faces. The profile after blasting is shown in Figure 4.23(a).

Modifications. The author was recruited to this project as a consultant to advise on changes to the design. The design was modified in terms of both the number of holes and the quantity of explosive per hole. At the periphery, line drilling with closer spacing (0.3–0.4 m) was recommended. The survey profile as obtained after these changes to the blast design is shown in Figure 4.23(b).

Inferences drawn.

- *Failure to follow the proper drilling patterns and designs and lack of the requisite know-how and knowledge*. Precision in drilling and charging operations is essential to achieve the planned advance (pull) per blast. At the sites in this case study the pull factor, which is the ratio of the drilled depth to the advance obtained after blasting, ranged from 0.5 to 0.7. This practice not only resulted in a waste of resources but also damaged the surroundings by creating ground-stability problems. As the explosive energy was not used effectively for the ground fragmentation, it was diverted to generate excessive noise and vibrations, air-blasts and deterioration of the surrounding rock mass.
- *Cartridge selection*. In the country of operation, overbreak-control explosives with small-diameter rigid plastic pipes for 11, 17 and 22 mm diameter charges (a special explosive manufactured by Nitro Nobel for use in peripheral holes) and special cartridges with diameters of 17–25 mm were not available. Therefore, the use of 25 mm cartridges (from explosive suppliers such as IEL and Orica) in the peripheral holes at some of the tunnels was recommended.
- *Working conditions*. There was a lack of provision of proper working conditions at the work faces, such as insufficient extension of service lines (water, air, electric cables and blasting cables), ventilation ducts and drainage, and poor-quality roads. Table 4.12 lists the usual lapses in working conditions that are observed, and propose measures and solutions that should be taken at any project to achieve better working conditions.

Figure 4.23 Survey profiles after blasting: (a) under the existing regime, with the overbreak shown; (b) under the new regime

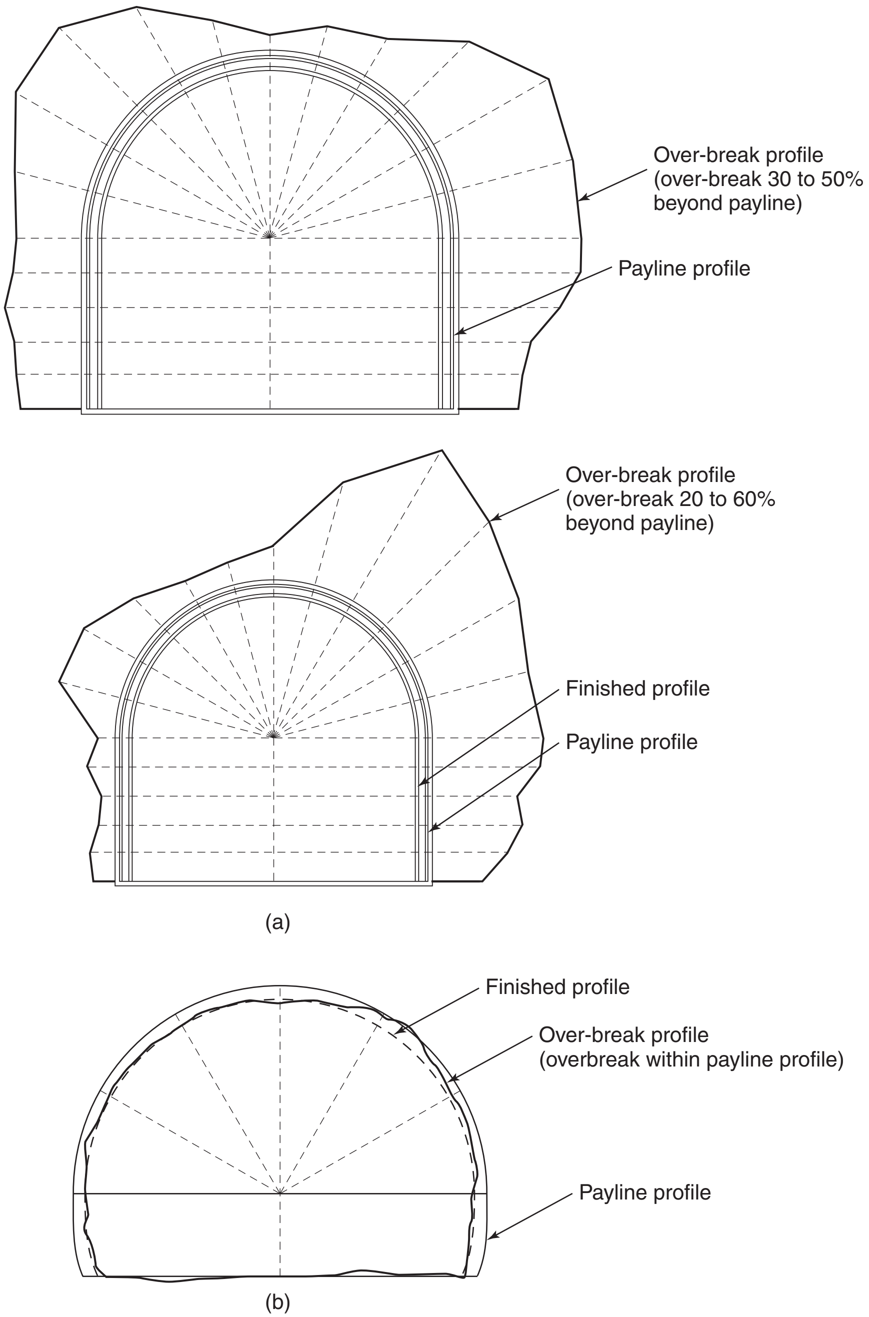


Table 4.12 Usual lapses encountered during tunnelling operations and proposed measures to resolve them

No.	Lapse	Proposed measures/solutions
1	There are undulations, overbreaks, undercuts and humps at the working faces, and drilling is carried out without making the surface of the faces even (vertical)	■ Ensure proper loose dressing and making of the face surface, including the floor (levelled as much as possible), before drilling. ■ If necessary, adjust the hole length at the hump or undercut locations when drilling the face.
2	Lack of face marking (drilling pattern, centre line and grade line)	■ A surveyor/or any other trained and competent person should mark the centre line, grade line and drilling pattern. The Precise laser reference for alignment, which is available with drill jumbos, should be used. ■ The supervisor should ensure compliance with the above before the boomer (drill operator) starts drilling the face.
3	The directions of the holes are not precisely drilled (maintained) as per their positions with respect to the face	Follow these guidelines/practices. For example: ■ The top peripheral holes should be drilled perfectly horizontally. ■ The bottom-line holes (lifters) should be drilled inclined downward with a lock-out angle of 3° to ensure a clean floor. ■ The rest of the holes should be drilled in a slightly upward direction (2–3°) so that drilling sludge will be drained off by gravity, leaving the hole clean and free from sludge. ■ The driller (boomer) should be suitably trained. ■ The supervisor at the face should ensure compliance with all the above practices.
4	Holes are not blown clean before charging	■ A compressed air blower should be used in the holes before charging them with explosive cartridges to ensure that water and drill cuttings are flushed out.
5	Lack of proper tamping of explosive cartridges when charging the shot holes	■ Soft (gentle) tamping of the explosive cartridges in the cut area and hard (tight) tamping in the rest of the area should be ensured.
6	Lack of adequate water spraying of the blasted face	■ Thorough water spraying should be ensured at the face after each blast to expose the roof (back), to suppress the dust generated by the blast and to allow harmful explosive fumes (gases) to dissolve in the water.

Table 4.12 Continued

No.	Lapse	Proposed measures/solutions
7	Lack of proper working conditions at the working faces, such as inadequate extension of service lines (water, air, electric cables, blasting cables), insufficient ventilation, and inadequate drainage and roads	■ Proper drainage and perfect condition of roads must be ensured. ■ Adequate ventilation (within 30 m of the face), sufficient illumination and extension of permanent service lines (air, water, cables, ventilation ducts) must be ensured.
8	Excessive use of explosive leading to excessive ground vibrations and damage to the surroundings	■ The vibration level pursuant to each blast should be measured using a blast-vibration measuring instrument. ■ The peak particle velocity and other parameters should be recorded for each blast. ■ It should be ensured that the parameters are within the allowable limits by making appropriate changes to the blast design. ■ The responsibility for compliance with these aspects should be assigned to competent persons.

4.14. Concluding remarks

- The shortest route with minimum required support work is the ideal solution when deciding the tunnel route and its orientation.
- Driving tunnels with the aid of explosives is a very challenging task. In soft formations or ground it is even more challenging.
- Conventional tunnelling is cyclical in nature and its progress is governed by the proper match of the individual units of an operation, such as drilling, blasting, ground reinforcement, muck disposal and services. Any mismatch could jeopardise the progress of the project.
- The adoption of proper drilling patterns, and precision in drilling and charging are essential to achieve the maximum advance (pull) per blast. A failure to do this it could result in a waste of resources and damage to the surroundings, which could lead to ground stability problems. Explosive energy, if not used judiciously, will be diverted to generate excessive noise and vibrations, air-blasts and deterioration of the surrounding rock mass.
- Any slackness (negligence) in providing proper working conditions at the face results in delays, increases costs and lowers productivity.
- Since the introduction of trackless haulage, track/rail transport currently has limited applications in civil projects.
- A battery-driven locomotive is the best choice of transportation for all types of mines and tunnels, particularly when it is used as a gathering haulage.
- Overbreak-control explosives with small-diameter rigid plastic pipes for 11, 17 and 22 mm diameter charges (manufactured by Nitro Nobel) and special cartridges in

the diameter range 17–25 mm should be used (on case-by-case basis) at the peripheral holes.

- Longer rounds (range 5–8 m) have been found to be economically viable. In such rounds a large-diameter (250–300 mm) central hole is essential.
- Precise laser reference for the alignment and accurate marking of holes is very important, not only to keep the overbreak small but also to keep the drift-heading (tunnel) in the right direction and at the right level. A lifter with a lock-out angle of 3° is essential to achieve a clean floor.
- The use of electronic detonators at contour holes gives the best results in terms of radial cracks beyond the excavation.
- The scaling time in a round is considerable. This time is likely to be reduced in the near future due to the application of pressurised water jets.
- When selecting the appropriate support network span for the workings, the required standing time and the types of ground (based on the rock mass rating) should be taken into consideration.

4.15. Questions

1. What is a tunnel? List the purposes for which a tunnel may be driven. What factors would you take into consideration when selecting the site for a tunnel, and what could be the consequences if it is improperly sited? What investigations are necessary prior to starting a tunnelling project?
2. In urban areas what type of ground is usually encountered and what care needs to be taken when driving tunnels in such areas?
3. How are the dimensions of a tunnel determined, and what are the governing parameters that need to be taken into account? List the shapes of tunnels in the order of their stability (least to most stable), and give the ratio between the whole cross-sectional area the useful cross-sectional area. In which situations are the following tunnel shapes preferred: rectangular, trapezoidal, arched and circular?
4. List the factors that govern the selection of sets of equipment for use in a tunnelling project.
5. The shortest route with minimum support work is the ideal solution in deciding the route and orientation of a tunnel. Is this statement true?
6. List the facilities that need to be established prior to starting a tunnelling project.
7. List the appliances, equipment and services that should be made available at the working site on a tunnelling project.
8. Why is the tunnel driving task very challenging? List previously used methods and techniques of driving civil tunnels, and note their limitations.
9. The conventional tunnelling procedure is cyclical in nature. List the operations involved to complete a cycle. (*Note*: You could also answer this question by drawing an illustration showing all the operations.)
10. Draw a line diagram to show the classification of the driving techniques used for the mine openings and tunnels.
11. Summarise the developments that have taken place within the last decade in the drilling technology used for tunnelling operations.

12 What is meant by the term ‘pattern of holes’, and why it is important to select a suitable pattern of holes? Draw conceptual diagrams of the drilling patterns for angled hole cuts and parallel hole cuts.

13 Describe and illustrate the technique used to provide a cut/kerf/cavity. In which situation you would recommend its application?

14 What is the technique known as ‘blasting off the solid’? Describe the technique, including the important design considerations. What are angled cut and parallel hole cut patterns? List the situations where they could be applied.

15 What is the specific geometrical relationship between the diameter of empty holes and the spacing between the empty and charged holes, for a given rock, to achieve the optimum breakage conditions?

16 Differentiate between: burn cut and cylindrical cut; fan cut and drag cut; wedge cut and V cut; pyramid cut and wedge cut. When would you select each one of them? Specify the conditions required to achieve the optimum results in each case.

17 What is stemming and why it is necessary? What is its usual length (range) during drift/tunnel blasting? How is stemming material prepared? What is water stemming and where can it be used?

18 What is the guideline that is usually followed to determine the depth of a round with respect to the cross-sectional area of the drive/tunnel?

19 Give Wilber’s equations for calculating the number of holes in ‘civil tunnels’.

20 Give the equation for calculating the fictitious diameter D used in the design of a cylindrical-cut pattern, where several empty holes are used.

21 After calculating the cut area, the rest of the area of a tunnel other than the cut holes is divided into different sections/zones. List these sections/zones.

22 What precautions should be taken when determining the charge concentration/density in the cut (area) and in the rest of the tunnel face around it? How can the charge concentration/density be assessed? What determines the charge density (i.e. the amount of explosive per metre length) in the cut-hole area, and how can it be achieved in practice?

23 Which blasting technique should be used to achieve the best correlation between the actual cross-section and the designed one? Describe the technique briefly.

24 In smooth blasting, what care should be taken when drilling the outer profile (contour holes) of a tunnel?

25 What special explosives have been developed in different countries for charging line holes (outer profile/contour holes)? Give details of the detonating cords of varying strength used for this purpose in Germany.

26 Smooth blasting is most effective in large-size drives and tunnels. Is this statement true? What are the adverse impacts of an overbreak or underbreak due to a blast?

27 Another technique that is popular for use in large-sized tunnels is pre-splitting. Describe this technique. Where would the application of this technique, with reference to civil and construction sites, be most suited?

28 How would you select an explosive for tunnelling work? Where should cartridges of 25–28 mm or 30–34 mm diameter be used? In which situations would you recommend the use of ANFO, slurry explosives and cartridges of large diameter?

29 What is a primer? The effectiveness of a primer is greatly affected by its location in a shot hole. Where should it ideally be placed to get the best results? Differentiate between direct and indirect initiation.

30 Describe the charging and blasting procedure you would follow for a 7 m × 4.5 m tunnel. Mention the necessary precautions to be observed for the blast to be effective.

31 What are reasons for a misfire? How can misfiring be avoided? How would you deal with a misfired round at the tunnel face?

32 How can the charging operation be mechanised to achieve faster charging? Describe the practices that are in current use.

33 Why is the use of ANFO in tunnels not effective for holes less than 40 mm in diameter? How is ANFO charged? What precautions must be taken when working with ANFO? Why do more than 85% of consumers in Scandinavia use non-electric detonators and ANFO in bulk quantity in mines and tunnels?

34 Suggest the type of mucking equipment for use in the following: shaft sinking, small-sized tunnels or openings, large tunnels and large-sized subsurface excavations. Propose matching transportation equipment for each of these operations except shaft sinking.

35 Make a list of underground mucking equipment. Describe briefly each piece of equipment, and give the merits and limitations of each type of unit.

36 Differentiate between the following units: overshot loaders and auto-loaders; hopper loaders and LHDs; arm loaders and scrapers; dipper shovels and hydraulic excavators (shovels).

37 How do overshot loaders work? Name a few overshot loaders that you know. What is the usual bucket capacity range of such loaders? What causes low productivity in the use of such loading units? Where are side-discharging loaders deployed? Mention their important features.

38 List the sets of equipment suitable for mucking in tunnels having a cross-section exceeding 30 m^2. Briefly describe each set.

39 What are the differences between an LHD and a front-end loader? What makes LHDs so popular that more than 75% of the world's underground metal mines use them for driving small and large-sized tunnels, chambers and wide excavations? What is their motive power? What is their bucket size (payload) range and gradient range?

40 Describe low-profile trucks and their applications in underground mines and tunnels. What gradient range is suitable for their operation? Classify low-profile trucks, giving the important features and capacity range of each type. List the companies that manufacture these trucks.

41 Since the introduction of trackless haulage, track/rail transport has found limited application in civil projects. Is this statement true? What is the usual gradient range suitable for locomotive haulage?

42 Compare locomotive haulage with rope and belt conveyor systems. What are governing factors for the success of locomotive haulage? Why is a battery-powered locomotive a better choice for all types of mines and tunnels, particularly when the locomotive is used as gathering haulage? In which situations is the use of trolley wire and diesel locomotives advantageous?

43 List the common arrangements (layouts) for transferring muck from the face to the transportation units for single-track and double-track systems.
44 Suggest a layout to achieve effective muck disposal in a trackless system when driving blind headings or tunnels.
45 Draw the ventilation schemes (according to length of tunnel) that you know for tunnelling projects, and specify the use of each system.
46 What types of fan are used for tunnel ventilation? Where should the metallic ducting from the face be terminated? Should flexible ducting be added to the metallic ducting to make the air current more effective?
47 Suggest ventilation schemes for tunnels up to 1.5 km and 2.5 km long.
48 List the methods used for driving large-sized tunnels in hard and tough rocks. Describe the important features of each method, and illustrate the methods by means of suitable sketches.
49 Suggest a set of equipment that could be deployed to carry out the various unit operations in driving the full-face of a large-sized tunnel in order to achieve fast progress per unit time.
50 There are two ways to carry out the driving operation in the pilot heading technique for tunnelling in hard rock. What are suitable conditions for the application of each of them?
51 What is the ‘heading and bench method’? What are the factors that govern the ratio between the top and the bottom excavation? What are the merits and limitations of each of the options?
52 Why is driving through soft rock or ground not an easy task? Different countries use different means and sequences of operations to excavate such ground. Illustrate these by drawing sketches showing the sequence of excavation.
53 The main problem encountered in tunnelling through soft rock or ground is the occurrence of decompression. What is decompression, and what techniques could be applied to overcome this problem? Briefly describe each technique.
54 In what circumstances is fore-polling (advance timbering) necessary? Describe this technique.
55 What is the basic difference between ‘civil tunnels’ and ‘mine openings’, particularly with regard to selecting the support system? What are desirable features that the supporting system for a ‘civil tunnel’ should have?
56 Classify the supports used for mines and tunnels.
57 Is there any relationship between roof span and stand-up time? Draw a plot of rock mass rating that represents the study by Bieniawski of roof fall in mines and tunnels.
58 Describe briefly the temporary support and its applications, and permanent support or lining by some artificial means and its applications.
59 List the different types of support that are currently in use. Give applications for each one of them.
60 Combining the concepts given by Deere *et al*. and Bieniawski, tabulate the guidelines (in general) for support requirements when driving a tunnel through different ground conditions.
61 Describe the wire mesh requirement with rock bolting for different ground and rock conditions.

62 List the general applications of the rock mass classification schemes given by various authors.

63 What conclusion can be drawn from Hartwig and Nord's comparison of tunnelling practices for the 25-year periods 1973–1998 and 1998–2023? Make a forecast for tunnelling practices in the period 2023–2048, by considering each of the unit operations involved in a tunnelling cycle.

64 List the reasons for the occurrence of overbreak and underbreak during tunnel blasting. What are the adverse impacts of overbreak and underbreak, and how can they be minimised?

65 What is scaling? How can it be accomplished? Describe the innovations that have taken place in this technique. Which scaling method is best and why?

66 In rounds longer than 5 m why is a larger diameter (300 mm) central cut hole essential? Is a special drilling rig required to drill and ream this hole?

67 Is it true that electronic detonators at contour holes give best results in terms of radial cracking beyond the excavation?

68 Draw up a table of different explosives and initiation combinations that are available for contour blasting.

69 List the techniques used to reduce the amount of linear charge required in the contour row and the buffer row.

70 Why are proper working conditions at the working faces essential?

71 What could be the result of using an excessive quantity of explosive per delay? How could it be monitored?

72 Why should the peak particle velocity be recorded for each blast? Suggest an instrument that can be used to measure this.

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Chapter 5
Mechanised tunnelling

It is the man behind the machine that matters, and thus ensuring the quality of human resources is essential. Imparting proper education and training during vacations to students, and organising vocational training, refresher courses, symposia and seminars on a regular basis for the work crews can achieve this.

5.1. Introduction

In nature, geological conditions vary from place to place and even within the same place or region. The ground may be wet or dry with high or low inflow of water (see Figures 1.4, 5.1, 5.2), and could be composed of clays, silt, sands, cobbles, boulders and/or rocks (ranging from soft sedimentary rocks to hard igneous and metamorphic rocks). The application of conventional tunnelling methods that can be applied to any rock type, but not all types of formation and not when conditions are wet, is described in Chapter 4.

Civil tunnels differ from mine tunnels in that the purpose of the latter is to exploit the minerals of interest, and once the minerals have been depleted the tunnels are abandoned. Moreover, mine tunnels are located in remote areas wherever a particular mineral of interest exists. Civil tunnels in this modern era are, in most cases, in urban areas or connect urban areas, where the use of blasting is either undesirable or prohibited. The demerits of tunnels driven with the aid of explosives include the following.

- Overbreak and underbreak can result, and therefore the resultant profiles are rough, not smooth as is desired.
- The generation of noise and vibrations in and around the vicinity of the tunnel during the construction phase. Vibrations could jeopardise the tunnel's stability, and more support work may be necessary.
- Operations or driving techniques are cyclic and not continuous.

All these factors have compelled engineers to direct their endeavours towards investigating techniques other than blasting. Such techniques may involve ground cutting, fluidising or excavating using tools, appliances, machines and equipment without jeopardising the stability of the surroundings, or allowing any ingress of water. In the past 150–200 years there have been a number of inventions that have encompassed this logic, and the technique has become known as *mechanised tunnelling*. The consistent development that has taken place in methods, techniques and equipment means that today there is hardly any locale, formation or set of conditions where mechanised tunnelling is not used.

5.2. Classification

Mechanised tunnelling can be broadly classified as (Figure 5.1):

- partial-face heading
- full-face boring.

5.2.1 Partial-face heading or tunnelling machines

As the name indicates, these machines drive or construct the tunnel by digging, excavating or cutting the in situ formation in parts, not by boring the full face at one time. To accomplish ground fragmentation based on this principle, three sets of equipment have been developed in the last 50–100 years:

- Cutting machines:
  - milling
  - ripping – disk or bar.
- Ground excavating machines:
  - excavators.
- Breakers/hammering machines.

5.2.2 Full-face boring machines

With these machines the full face is bored at one time, and the equipment is known as a tunnel-boring machine (TBM). There are various forms of TBM:

- Open face without shield:
  - open-beam machines
  - with single or double grippers.
- Open face with shield – single or double.
- Closed face with shield – slurry type.
- Closed face with an earth-pressure-balance (EPB) mechanism.

The last two TBMs and their further variants are described in Chapter 6. In this chapter the other techniques that are currently used are discussed briefly.

Figure 5.2 shows the range of geological conditions under which these machines can be used.

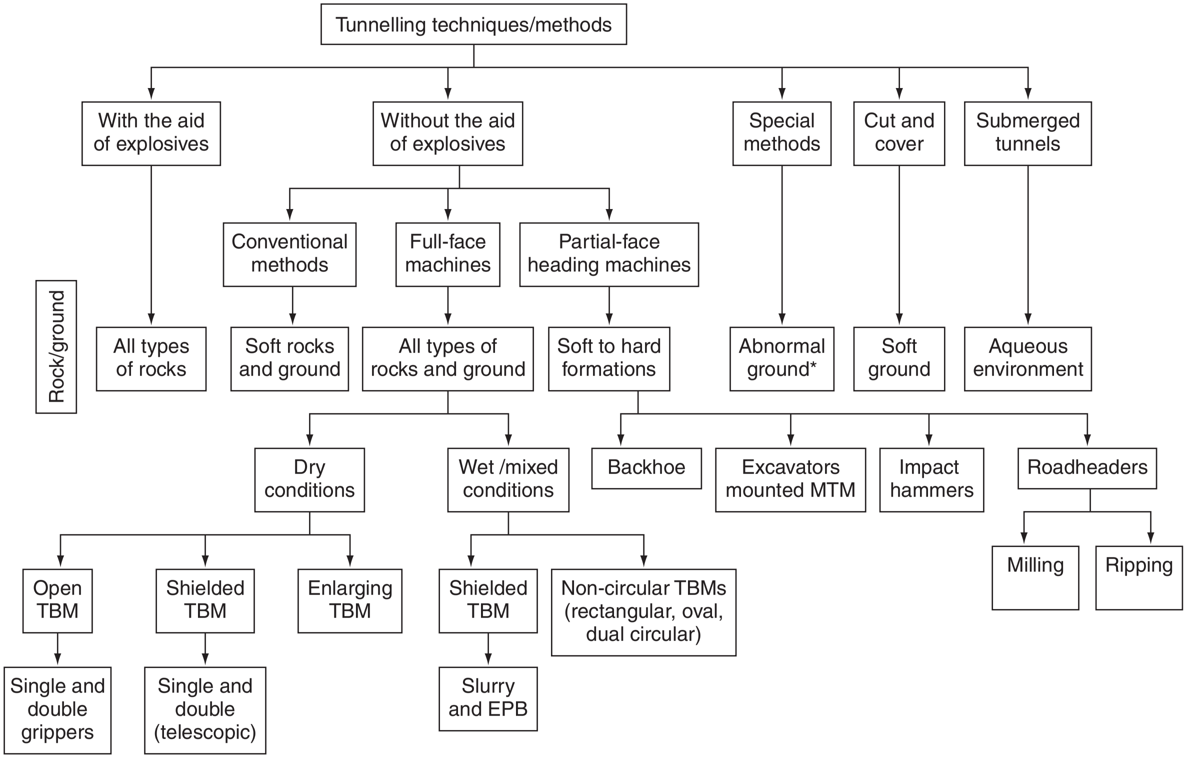
It is important to understand that it is the rock fabric (texture) upon which a TBM's performance depends. Hard and abrasive rocks are the costliest to drill due to low penetration rates and the higher cost of the cutting tools. In a situation like this, conventional drilling and blasting techniques prove advantageous.

5.3. Partial-face heading machines

The following are partial-face machines (PFM) (Fulton *et al.*, 1993; Kogelmann, 1988, 1992; Matti, 1999):

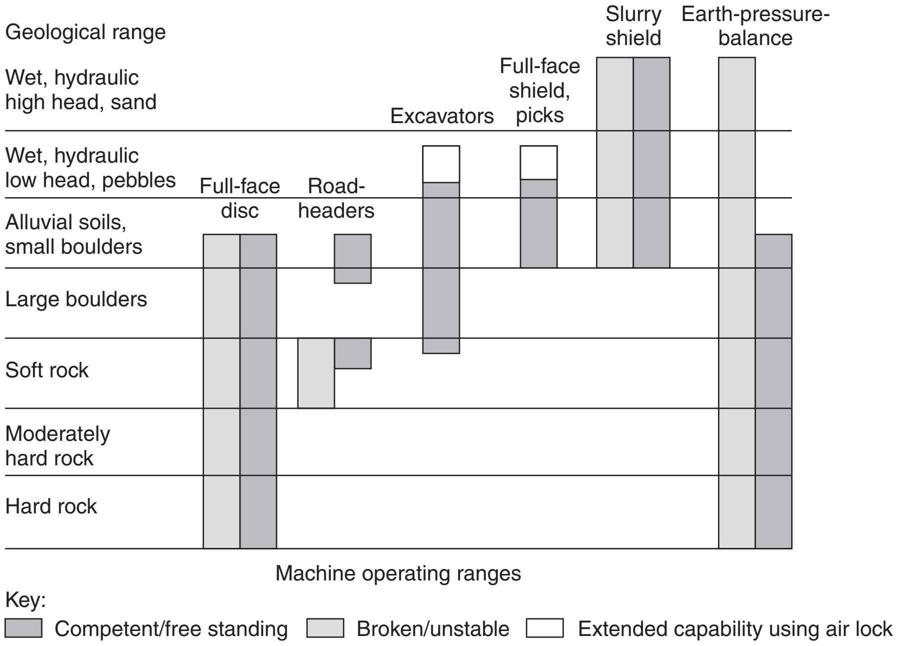
- boom miners (known to miners as roadheaders)

Figure 5.1 A general classification of tunnelling methods



*Including the pipe-jacking techniques: NATM (new Austrian tunnelling method)
EPB, earth-pressure-balance; LTM, Lee's tunnelling method; MTM, multi-tool miner; TBM, tunnel-boring machine

Figure 5.2 Operating range of machines under different geological conditions (Friant and Ozdemir, 1993)



- multi-tool miner (MTM) attachments (Lislerud, 1988)
- boom-mounted impact hammers (breakers)
- backhoe excavators (diggers).

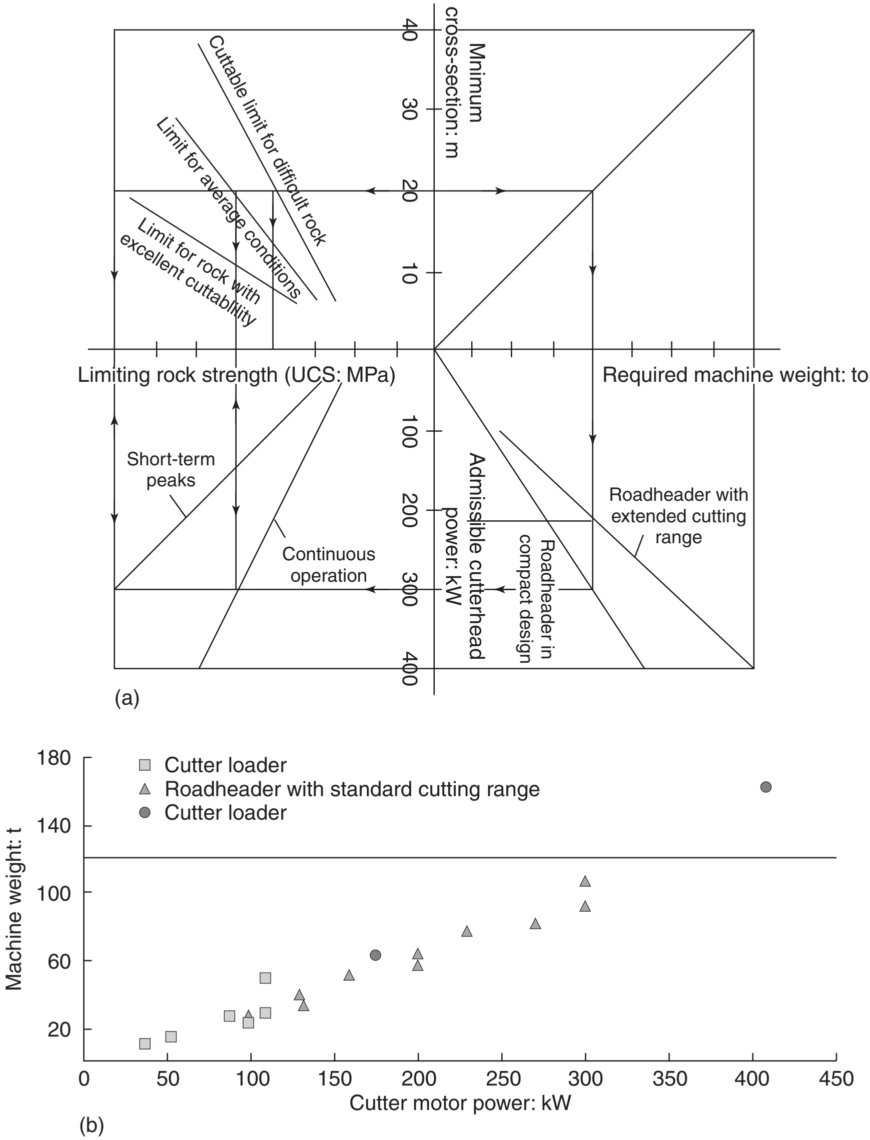
5.3.1 Boom miners – roadheaders

The roadheader, which is also known as a *continuous miner*, is a piece of equipment having a wide range of weights, power and cutting range (Figure 5.3). On the basis of these parameters roadheaders can be classified as light to heavy duty units. They are capable of covering face sizes up to 45 m^2, and can cope up with rocks with compressive strengths in the range 20–140 MPa.

The details in Table 5.1 and the indicator diagram in Figure 5.3(a) are a useful guide for selecting a roadheader based on the uniaxial compressive strength, the tunnel cross-section, and the required weight and power of the machine. Figure 5.3(b) shows the corresponding weight and power values. Tamrock-Sandvik advocates that the range of applications of roadheaders has been extended to harder formations, as shown Figure 5.3(b).

Roadheaders have a pick-laced cutter head mounted at the end of a boom that can swing up and down, left or right. The boom is most frequently tread-mounted but can also be mounted within a shield. The machine is composed of cutting, gathering and

Figure 5.3 (a) Indicative diagram used for the selection of a roadheader through the interrelationship between the weight of the machine, its power, rock strength and the operating environment. UCS, uniaxial compressive strength. (b) Relationship between the weight and power of roadheaders



delivery units. Compared with a full-face TBM a boom miner has the following features:

- *Mode of face attack and capability of dealing with different rock types*. The tools of a full-face machine such as a TBM or a shaft-boring machine (SBM) attack the full face. A PFM attacks only a part of the face at a time, and thus advances a tunnel or shaft in small increments, enabling better ground control. A TBM utilises disk and button roller cutters (indentation tools) that are capable of attacking and crushing formations with high unconfined compressive strength. Today, a TBM can work on the toughest rocks such a granite, schist, etc. Drag bits (picks) attack rock of much lower tensile strength, which averages about 10% of the compressive strength. The ploughing action of a drag bit is much more energy efficient (Crookston *et al.*, 1983), and therefore a roadheader is much lighter and has a far lower price than a TBM of equivalent power.

- A PFM is piece of self-contained equipment which is both mobile and versatile. It can be used to create tunnels the size, shape, orientation and gradient of which can be varied as desired.
- PFMs usually incorporate gathering arms and a conveyor system to move the material cut from the face to a loading point at the rear of the machine for its onward transportation using shuttle trains, conveyors, or trucks. A roadheader cutting boom is usually mounted on a crawler track but, increasingly, booms are being mounted on other machines, such as hydraulic breakers, trucks, travelling gantries and inside the shields.
- Modern roadheaders are equipped with electronic/hydraulic-controlled systems linked to microprocessor-based guidance and profile-control systems (Kogelmann, 1992; Nelsosn *et al.*, 1994). Any deviation from the desired position and orientation can be detected by the laser system and required corrections are applied automatically. This equipment can handle small boulders but not larger ones.

Based on the cutting principle, these units can be classified as

- ripper or transverse type – bar and disk
- milling or longitudinal (auger) type.

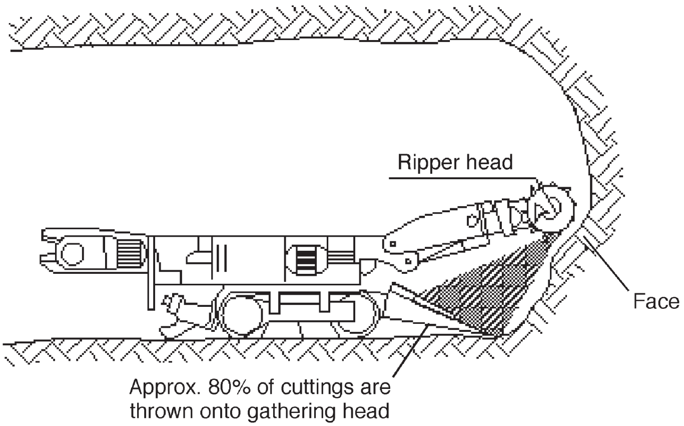
In ripper-type roadheaders (Figure 5.4), the full weight of the machine acts as the counter-reaction for the cutter head. The rock is ripped off the face and thrown onto the

Table 5.1 Classification of roadheaders based on weight and power ranges (Matti, 1999)

Roadheader	Weight range: t	Cutter head power: kW	Roadheader with standard cutting range		Roadheader with extended cutting range	
			Max. section: m^2	Max. UCS: MPa	Max. section: m^2	Max. UCS: MPa
Light	8–40	50–170	25	60–80	40	20–40
Medium	40–70	160–230	30	80–100	60	40–60
Heavy	70–110	250–300	40	100–120	70	50–70
Extra heavy	>100	350–400	45	120–140	80	80–110

UCS, uniaxial compressive strength.

Figure 5.4 Ripper or transverse type of roadheader (courtesy of Paurat)



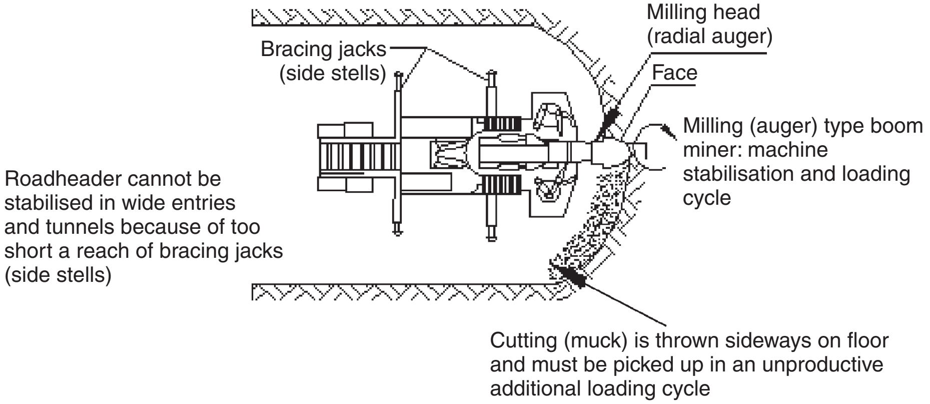
gathering head. This equipment utilises its own weight as the reaction force for cutting in a better way than the milling type of roadheaders, and no bracing jacks (stells) are required (Kogelmann and Schenck, 1982). These machines have 20–35% lower weight (which means lower price) than milling-type roadheaders of equivalent capacity. In the USA, 75% of roadheaders are of the ripper type (Kogelmann and Schenck, 1982). Ripper-type roadheaders can be further classified as bar and disk types.

In the bar-type roadheader, the cutting head consists of five to seven cutting chains with picks that run in guides all around the ripper bar. The ripper bar is hinged at the rear end, which permits the front end to be raised or lowered. In a disk-type ripper unit, there are two cutting heads, each consisting of two vertical disks laced with tipped bits. The cutting heads are carried in the front end of an extension boom.

Ripping (transverse) cutter heads cut in the direction of the face, and therefore they are more stable than milling heads of the same weight and power. These cutter heads always cause some overbreak, regardless of machine position.

Using these heading machines, it is possible to create large-sized chambers or even large-sized tunnels, which can be driven in two lifts (benches). First, the upper bench is advanced in the upper half portion of the face, and then the lower bench is driven. In milling-type roadheaders, a cylindrical or cone-shaped cutter head rotates in line with the axis of the cutter boom (Figure 5.5) (Kogelmann and Schenck, 1982). The cutting force is exerted mainly sideways, which prevents utilisation of the full weight as a counter-force. When cutting harder rock, the machine is braced against the side walls with hydraulic jacks (stelling). This consumes time, and requires the use of bracing jacks, which protrude sideways and make the machine inflexible in narrow headings. For wider and higher tunnel faces, particularly in hard rock, these types of header are unsuitable because their bracing jacks (stells) cannot reach both the side walls (ribs) and the roof to stabilise the roadheader (see Figure 5.5) (Kogelmann and Schenck, 1982).

Figure 5.5 Milling or longitudinal roadheader (courtesy of Paurat)



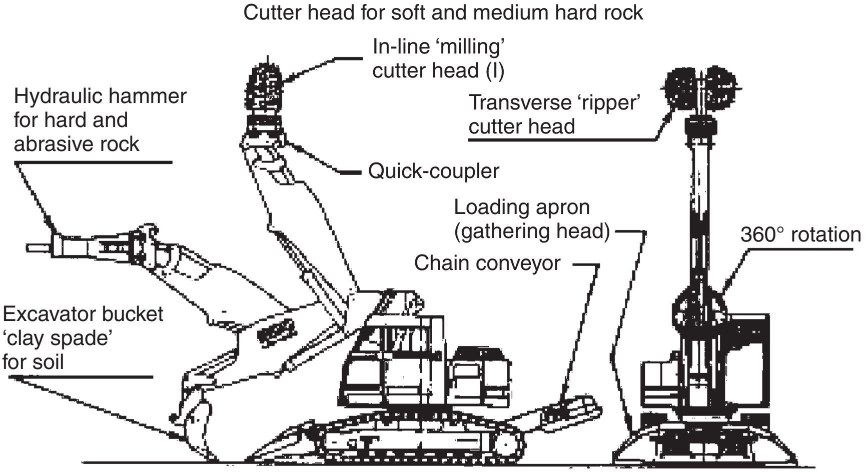
At present, roadheaders with interchangeable cutter heads, either ripper or milling (auger), are available. In the UK, 65% of roadheaders are of the milling type. A two-boom milling-type roadheader is also available, and in some designs the heads are exchangeable with ripper-type heads. Milling (longitudinal) heads have lower cutting speeds. This results in lower pick consumption. The pick array on these heads is easier to arrange because both cutting and slewing motions go in the same direction.

5.3.2 Multi-tool miner (MTM) attachments

The past decade has seen a quiet but dramatic revolution in the tunnelling industry (Kogelmann *et al.*, 2003). The key to this has been a revolution in hydraulics, which has resulted in reliable cutter heads, hammers and excavators with attachment capabilities. Alpine Equipment Corporation, the leading North American manufacturer of roadheaders, has developed a line of flexible and cost-effective (low cost per cubic metre of excavation) partial-face machines. These machines can be equipped with cutter heads, hammers and excavator buckets (Figure 5.6). These three excavation systems are available with quick-couplers for rapid exchange at the face whenever changing ground conditions require it. The MTM is the Swiss army knife of construction equipment. It provides three machines for the price of one. The Alpine Multi-Tool Miner system includes the following attachments:

- cutter head – for excavating soft and medium hard rock
- hydraulic hammer – for breaking large and hard boulders, and for the excavation of extremely hard seams and intrusions
- bucket and clay-spade – for excavation and mucking out of soft soil
- drill mast and roof bolter – for drilling exploratory holes ahead of the tunnelling machine and for installation of rock bolts for exceptional conditions
- shotcrete manipulator – the boom can be equipped with a shotcreting nozzle
- grout and cement injector – in exceptional cases, grout and cement can be injected into the ground

Figure 5.6 Excavator with attachments for multiple tasks



- breasting plate – in an emergency the robotic boom can be used to press a breasting plate against the face, thus closing the open tunnelling machine
- man basket – the robotic boom can be equipped with a basket
- crane – the robotic boom can be converted into a crane and tool carrier.

The introduction of quick-change couplers means that it takes less than a minute (as claimed by the manufacturers) to change from a bucket to a hammer or a cutter head, and the excavator's operator does not have to leave the cab. European tunnelling projects where this equipment has been used include cross-passages at the Weser tunnel in Germany, the Oberburg tunnel and the N20 Zurich bypass in Switzerland.

5.3.2.1 Other utilities of excavator-mounted cutter heads

- Cutter heads can be used both for tunnel drivages and for scaling and profiling in drill-and-blast operations. This results in savings through safety.
- Remote-controlled excavators are being used for hazardous work such as mine clearing and digging for unexploded ordnance (*Heavy Equipment News*, 2003). In Germany, many nuclear power plants are being decommissioned. Remote-controlled mini excavators equipped with cutter heads are employed for selective removal of radioactive concrete. Selective removal is imperative because the handling and storage of radioactive materials are extremely expensive.
- Roadheader-type machines have been used for many years for shaft sinking (Kogelmann, 1992). Remote-controlled mini excavators with cutter-head attachments are ideally suited for the excavation of small-diameter shafts because they remove the need for a person to be in a shaft bottom containing dangerous equipment.
- In a tunnelling project (Kogelmann, 1992; Martin *et al.*, 2003), it was found that costs were reduced by about 25% when using an Alpine cutter loader (ACL)

compared with a new Austrian tunnelling method (NATM) roadheader. The ACL (Figure 5.7) consists of a CAT EL300 excavator, a transverse cutter head, a loading apron and a chain conveyor. In competent rock the average advance rate was 5 m/day. In difficult ground where a lot of spiling was required, the advance rate fell to 1.20 m/day. Squeezing ground at one of the portals exerted such high forces that the heavy steel channel spiling was bent and deformed. No shield or TBM could have tunnelled through this difficult ground.

5.3.3 Impact hammers/hydraulic breakers for tunnelling

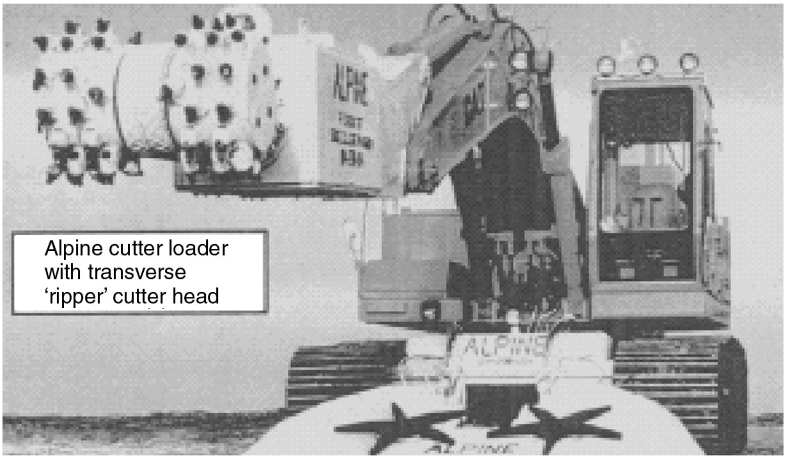
Impact hammers are recommended for use in competent and sound rock, especially if very abrasive, of up to about 200 MPa uniaxial compressive strength. If strata are fissured or laminated, rocks of much higher strength can be excavated economically with hammers (Hertzen, 1987). Heavy and powerful hammers (breakers) (2000–12 000 J; 378–1211 kg m) have demonstrated high production rates. A modern Rammer G120 hammer, mounted on a CAT 245 excavator has produced 300 m^3 of hard limestone in 1 h (Kurihara *et al.*, 1995).

5.3.3.1 Mounting alternatives for hammers

Excavator-mounted hammers are very effective for the rapid excavation of benches in tunnels and caverns where the previously driven top heading permits working from a free face.

However, high-energy hammers require heavy excavators that are so large they fit only into tunnels with large cross-sections (>70 m^2), and the tunnels have to be of sufficient width in order to permit access to the face for loaders for muck collection and haulage (Hertzen, 1987). The Alpine Equipment Corporation has developed loading apron and chain conveyor attachments that fit onto standard excavators and allow excavator-mounted hammers to work in narrow tunnels (Kurihara *et al.*, 1995).

Figure 5.7 An Alpine Equipment Corporation cutter loader (ACL)



5.3.3.2 Other versions of hammers

- Portal (gantry)-mounted hammers – for excavation and scaling of large cross-section tunnels and caverns.
- Hammer shaft sinkers – a hammer can be mounted on a platform (stage), rails (Alimak style) and on crawlers.

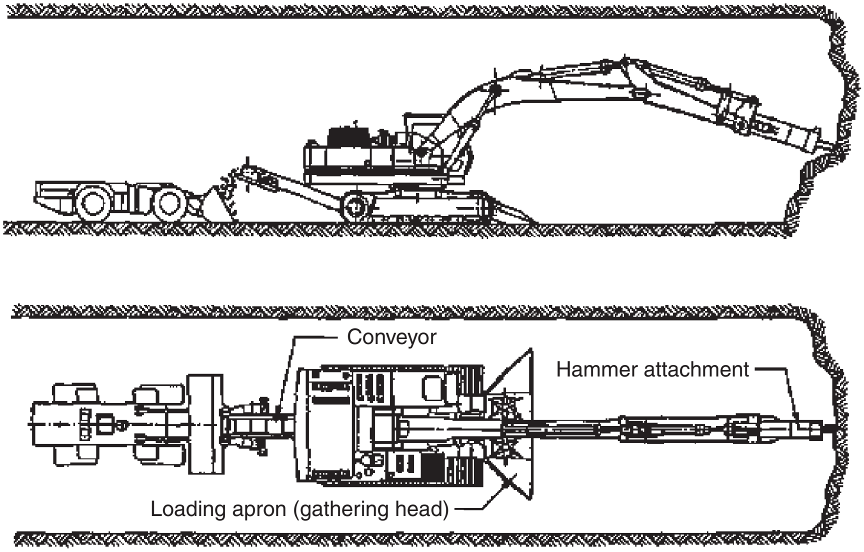
5.3.4 Hammer mounted on roadheader chassis

Small and light excavators do not have sufficient weight and strength to accept a high-energy hammer needed for efficient rock tunnelling. In order to combine the versatility and compactness of roadheaders with the hard-rock excavation capability of high-energy impact hammers, Alpine Equipment Corporation, in cooperation with Rammer Oy, has developed hammer attachments that can be retrofitted to roadheaders of any make and model (Kogelmann, 1992). In Figure 5.8, a hammer tunneller with a loading and conveying system for excavation of narrow tunnels is shown.

Hammer tunnellers and hammer shaft sinkers thus have the potential to increase considerably the capacity of hard rock excavation. This opens important new applications for hammer hard rock miners which were previously the domain of drill-and-blast operations and expensive TBMs and mobile miners tooled with disk cutters. Applications of such units include

- hard rock excavation where blasting is forbidden, restricted or limited to daylight hours
- square or oval shafts which cannot be drilled
- non-circular tunnels in hard rock

Figure 5.8 Hammer tunneller with loading and conveying system for excavation of narrow tunnels (Framer and Glossop, 1980; Kurihara *et al.*, 1995)



- drivage of tunnels and cross-passages that are too short for economical use of a TBM
- enlargement of shafts around a pilot hole
- squaring off a circular tunnel, bored by a TBM, to a horseshoe shape with a flat floor
- enlargement of railroad and highway tunnels
- excavation of slopes and inclines in hard rock
- scaling and dinting in mines and tunnels
- production of ores and minerals in mines.

5.3.4.1 Excavation procedure and cycle of operations

This technique is suitable for the tunnels with a cross-section exceeding 30 m^2. In tunnels smaller than this the restricted space will pose operational problems. In narrow tunnels (widths <8 m); only one 'hammer and excavator' set can work at the face. The work is usually divided into following unit operations:

- excavation by the hammer
- muck handling by the excavator
- scaling and handling the scaled muck
- supporting the tunnel using a suitable type of support.

If the tunnel cross-section is >70 m^2, due to large-sized face hammering and muck handing operations can be carried out simultaneously. In this situation the work progresses in the following manner:

- excavation by the hammer and scaling
- muck handling by the excavator
- supporting the tunnel using a suitable type of support.

For these longer tunnels, if the tunnel can be driven in two opposite directions from its middle there is the added advantage of being able to make the best use of the resources (men, machines and services). For tunnels exceeding 7 m in height, the work can be divided into two benches.

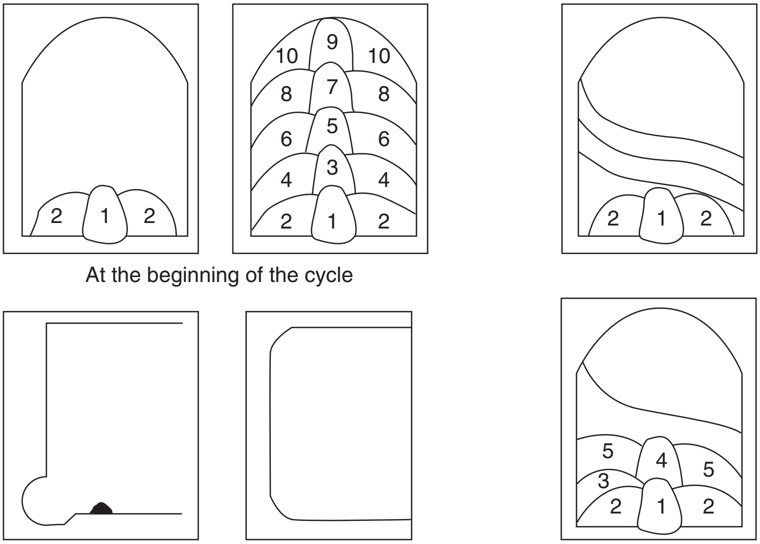
5.3.4.2 Hammer working cycle

Excavation at the tunnel face is first made at 1–1.5 m above the floor at the centre of the tunnel. This first cut is made to a depth of 1–2 m. This small ditch or slot is then extended towards the sides and floor of the tunnel. Once this large slot has been created, the hammer is used to break the ground, working in sections until the final shape and size of the tunnel have been achieved. The cycle is then repeated to advance further. The procedure is illustrated in Figure 5.9(a). If the rock mass is jointed, the natural planes of weakness are used to achieve maximum gain, or yield, of the hammer's impact (Figure 5.9(b)).

5.3.5 Excavator buckets

Buckets (Figure 5.10) of excavators are used for the excavation of soft soil such as clay, silt and sand, and for mucking out of blasted rock (Fulton *et al.*, 1993;

Figure 5.9 Working sequence for a hydraulic hammer: (a) normal ground conditions; (b) when formations are inclined



At the beginning of the cycle

At the completion of the cycle

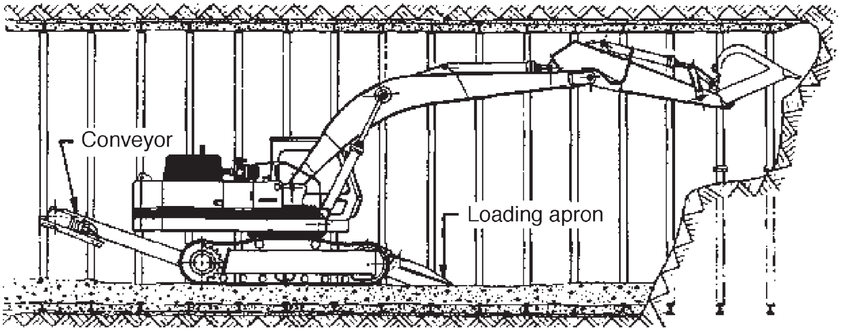
(a)

(b)

Kogelmann, 1993). Buckets can be mounted on roadheader chassis, portals (gantries) and shields.

In conclusion, it should be noted that the advice of an experienced engineer who has dealt with this equipment before could prove a useful guide during the bidding, planning and execution stages.

Figure 5.10 Soft ground excavation with a standard bucket



5.3.6 Heading machines – rock-mass excavation procedure and sequence

The working cycle of 'heading machines', which have been described in the preceding sections (Sections 5.3 to 5.3.5), consists of two operations:

- rock cutting and muck disposal
- supporting the exposed roof that has been created (in a situation where the roof is competent and does not require any support the operation becomes continuous).

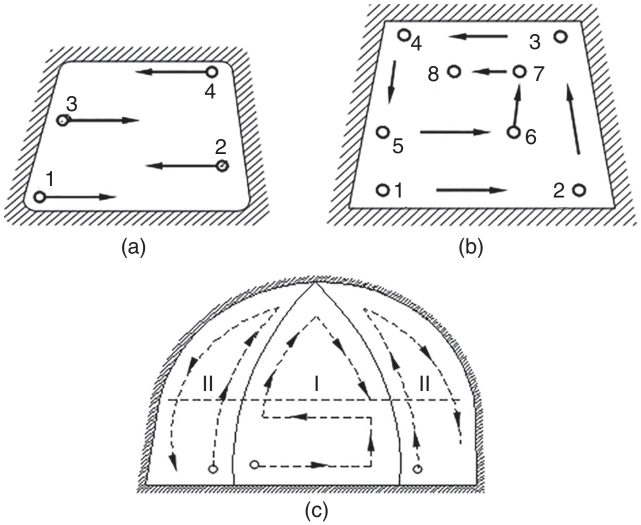
There are different ways of excavating the rock mass (Figure 5.11):

- excavating the perimeter first and then the central part, if the strata are friable
- ripping the bottom first and then the upper part, to take advantage of undercutting (this gives better advance/output rates)
- if different bands or layers of the strata are encountered, the softer band can be attacked first and the other afterward
- if the roof rock is weak it is better to attack the central portion first and then to rip the sides of the face/working.

5.4. Full-face boring machines

A machine that attacks the whole face at one time is known as a 'full-face machine'. Such machines include tunnel-boring machines (TBMs), shaft-boring machines (SBMs) and raise-boring machine (RBMs). Full-face machines differ from partial-face machines (described above) in several ways. Mechanical rock excavation is the use of equipment to create tunnels in rocks with varying degrees of hardness, from extremely hard (gneiss

Figure 5.11 Working sequence of heading machines, including roadheaders: (a) attacking from bottom to top; (b) attacking the perimeter; (c) attacking the middle of the face first, then sides



and granite), to medium hard (mica schist, breccia, claystone, limestone, etc.), to soft (e.g. coal). A TBM consists of a rotating head fitted with rock-cutting tools. This head is forced into the tunnel face, but prior to this a gripping mechanism is extended hydraulically against the tunnel's walls to transmit thrust. A single pass is sufficient to create a round or elliptical (oval) hole (i.e. full face). The cuttings are removed by the cutter-head buckets or a scoop that transfers them to a conveyor belt. After completing a boring stroke, the tunnelling machine is advanced by hydraulically pulling the gripping mechanism in from the tunnel walls, and then stroking forward and resetting the gripper to a new forward position on the walls. In this way the unit is set up for the new position.

Historically, Herman Haupt made the earliest attempt in 1856 in the United States to develop hard rock TBMs; but for about a century after that, nothing further happened. It was James Robbins who established the first real milestone in 1952 when his company built the world's first successful full-face tunnel boring machine, 8 m in diameter, for the Oahe Dam diversion. At present, companies such as Robbins, Wirth, Lovat and Herrenknecht are in the arena, and all are aiming to provide full-face tunnel boring technology that can achieve faster advance rates with automation within practical limits, continuous production (with as few interruptions as possible) and safer working conditions. Details of hard rock TBMs made by some of these companies are described below, which will help in understanding the basic principles and types of equipment that are available for these tasks.

5.4.1 Robbins TBMs

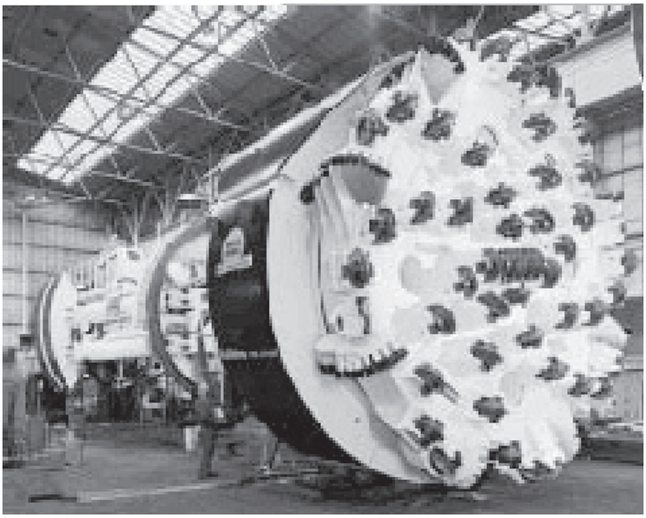
The Robbins Company (Solon, OH, USA) produces equipment that can be used to make openings of varying configuration and in varying environments. The units are suitable for mine development, steep inclines, deep tunnels and sub-sea tunnels. Its models are known as

- main-beam TBMs (Figure 5.12)
- single-shield TBMs (see Figure 5.13)
- double-shield TBMs (see Figure 5.13)
- earth-pressure-balance machines (EPBMs)
- crossover TBMs.

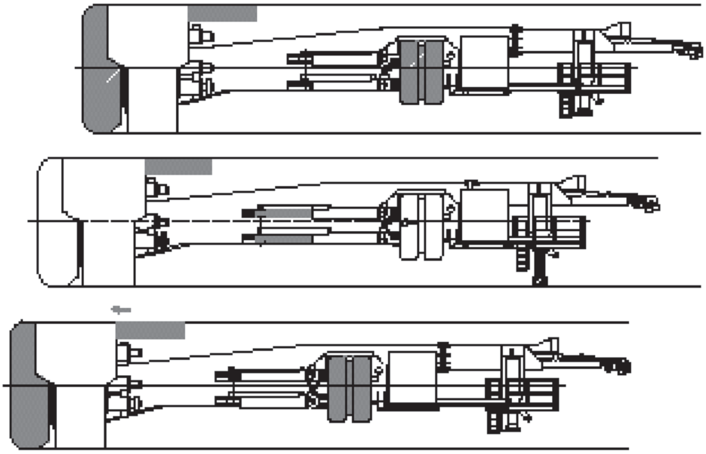
A Robbins main-beam TBM is suitable for tunnelling in hard rock. It is an open TBM without any shield. The basic design consists of a cutter head mounted on a robust support and main beam (Figure 5.12(a)). As the machine advances, a floating gripper assembly on the main beam transmits thrust to the sidewalls without putting bending loads on the gripper cylinders. A conveyor installed inside the main beam transfers muck from the face to the rear of the machine. This design allows crews to make quick work of routine maintenance. It also facilitates the installation of ground support – shotcrete, rock bolts, ring beams or steel mesh – near the face.

Main-beam TBMs have even been used successfully in fractured rock or squeezing ground. Most of these machines involve a high capital outlay, and the conditions where they should be deployed vary from one place to another; as such, most of these units,

Figure 5.12 (a) 8 m diameter TBM designed for hard granite; (b) Open beam TBM working cycle: (top) initial position; (middle) re-grip; (bottom) bore again. Note the relative position of TBMs advance/movement (courtesy of Robbins)



(a)

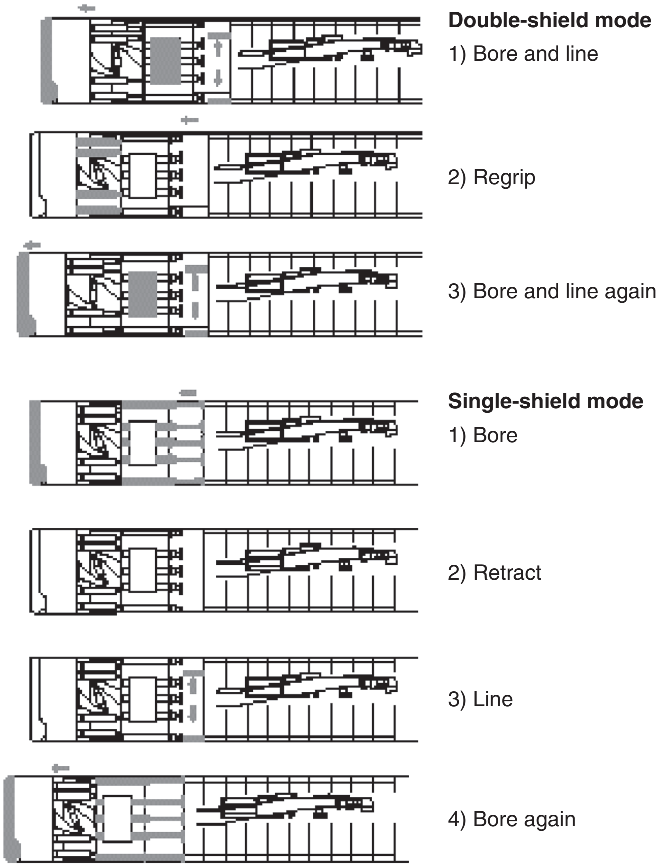


(b)

particularly the cutter heads, are custom made. Main-beam TBMs can be equipped with a flat, low-profile cutter head with rear-changing cutters to suit blocky ground, or open cutter heads with front-changing cutters to suit hard rocks. Custom-designed cutter heads provide optimum conditions for cutter spacing and muck removal, which can mean reduced cutter costs and cutter-head wear.

A sliding support shoe and a hydraulically actuated roof and side supports stabilise the cutter head during boring and keep it centred. This feature helps in minimising

Figure 5.13 Boring cycles of Robbins shielded TBMs (courtesy of Robbins)



vibrations, and thereby a reduction in the cutter wear and structural fatigue of the machine. Floating grippers allow operators to steer both horizontally and vertically while boring. The manufacturer can supply this unit with numerous options, such as rock-bolting equipment or a ring-beam erector, auxiliary thrust systems, electrical and hydraulic systems for safety in gassy conditions, sound-proofed and air-conditioned cabins for operator comfort, and programmable logic controllers, shock-resistant TV cameras and monitors for automated operations.

Table 5.2 gives the specifications for the largest, middle and smallest models of main-beam and shielded TBMs produced by Robbins. It can be seen that the diameter range for the hard rock TBMs is 12–2 m and for the shielded TBMs 12–1.6 m. The degree of thrust and power required indicate just how powerful these machines are. The disk cutters manufactured by Robbins range in size from 150 mm (6 in.) to 500 mm (20 in.) in diameter (Table 5.3). Table 5.4 gives the details of some typical tunnels and Table 5.5 describes a few tunnels driven within the last decade.

Table 5.2 Specifications of the largest, middle and smallest range models of Robbins main-beam and shielded TBMs (courtesy of Robbins)

Series	Diameter	Power	Max. torque*	Cutter thrust	Shield thrust	Auxiliary thrust
Main-beam TBM, specifications						
340	9–12 m (29–40 ft)	3465 kW (4645 hp)	7330 kN m (5 406 600 ft lb)	20 215 kN (2270 tons)		
200	5–7 m (16–23 ft)	2205 kW (2955 hp)	2820 kN m (1 080 000 ft lb)	12 000 kN (1350 tons)		
100	2.5–3 m (8–10 ft)	1000 kW (1340 hp)	560 kN m (413 000 ft lb)	6120 kN (690 tons)		
Double shields, specifications**						
340	9–12 m (29–40 ft)	3500 kW (4690 hp)	13 400 kN m (9 913 300 ft lb)	20 215 kN (2270 ton)	51 000 kN (5740 ton)	102 000 kN (11 580 ton)
140	3.5–5 m (11–17 ft)	1500 kW (2010 hp)	2400 kN m (1 770 200 ft lb)	9300 kN (1050 ton)	18 600 kN (2100 ton)	37 200 kN (4200 ton)
80	1.6–2.5 m (5–8 ft)	520 kW (700 hp)	750 kN m (553 600 ft lb)	2600 kN (290 ton)	5200 kN (580 ton)	10 400 kN (1160 ton)

* For single-speed machines, higher torque can be supplied with a two-speed or variable-speed drive.
** Auxiliary thrust: double shield only.

Table 5.3 Disk cutter specifications for some of Robbins models (courtesy of Robbins)

Disk cutter diameter	Capacity	Mounting method
165 mm (6.5 in.)	53 kN (12 000 lb)	Front and back loading: V-block
305 mm (12 in.)	120 kN (27 000 lb)	Front loading: V-block and O-mount
457 mm (18 in.)	222 kN (50 000 lb)	Front and back loading: wedge-lock
483 mm (19 in.)	311 kN (70 000 lb)	Front and back loading: wedge-lock

As described above, Robbins main-beam TBMs, which are suitable for competent to slightly fractured rocks, are available for tunnel diameters in the range 3–15 m (10–50 ft). An example of where a unit of this type was deployed at a hard rock project in Queenston, Ontario, Canada, in 2013:

Machine type:	main beam
Diameter:	14.4 m (47.5 ft)
Tunnel type:	hydroelectric
Tunnel length:	10.4 km (6.5 miles)
Owner:	Ontario Power Generation (OPG)

Table 5.4 Some typical tunnels (courtesy of Robbins)

Location	Highlights
1825–1843, River Thames, London, UK	In 1806, Sir Marc Isambard Brunel invented a rectangular shield and used it to drive a tunnel below the River Thames
1881, Gotthard, Switzerland	Earliest known railway tunnel (16 km)
1956, Humber River, Canada	First use of 280 mm rolling disk cutter for crystalline limestone
1972, Orichella, Italy	First use of double-shield TBM in broken ground formations
1978–1998, TARP, Chicago, IL, USA	World's first 10 m diameter TBM – it is said that Chicago more bored tunnels than any other city
1987–1991, Channel Tunnel, England/France	Developed a new machine to manage the 10 bar water pressure anticipated in the worst sections of the tunnel – a dream of 100 years came true
1989, St Lawrence, Canada	The tunnel design included a steep decline and an incline, precluding the use of muck cars. First use of the Boretec conveyor system
1998, Cleveland, OH, USA	First use of a double-shield TBM for small-diameter 2.2 m sections
Gotthard and Loetschberg tunnels, Switzerland	Longest railway tunnels: Gotthard (57 km); Loetschberg (34 km)

Table 5.5 Some typical tunnels of the last decade

Name	Country	Purpose	Length: km	Year completed
Lotschberg	Switzerland	Railway	34.5	2007
Zhongnanshan	China	Road	18	2007
Guadarrama	Spain	Railway	24.6	2007
Eiksund	Norway	Subsea road	7.7	2008
Firenzuola	Italy	Railway	15.2	2009
Hakkoda	Japan	Railway	28.4	2010
Pajares	Spain	Railway	24.6	2010
Gotthard base tunnel	Switzerland	Railway	57	2016

Another example, in which three units were deployed in Malaysia in 2013, is described in Section 5.4.1.3.

5.4.1.1 Robbins single-shield TBMs

As discussed in Chapter 6, a shield is a safety guard or cover for to protecting the operator, machine and equipment against any abnormal occurrences. Single-shield TBMs have been designed for tunnel geology ranging from soils to rocks. Single-shield

TBMs use the lining to counteract the forward thrust, but these machines are designed with the same hard-rock specifications as main-beam and double-shield machines. Robbins single-shield TBMs are available in diameters of 1.6–15 m (5–50 ft). An example of where a custom-made single-shield TBM has been used is in boring the Madrid–Valladolid rail line in Spain in 2009:

Diameter:	10 m (32.8 ft)
Tunnel type:	rail
Tunnel length:	10.5 km (6.5 miles)

5.4.1.2 Robbins double-shield TBMs

Double-shield TBMs are versatile. They can be used on rocks that are likely to be heterogeneous (not uniform throughout) and also to install tunnel linings as and when required. When boring in competent rocks, a double-shield TBM grips the side walls like a main-beam TBM, which enables it to achieve similar rates of advance. When a lining is required, the dual thrust systems allow a double-shield TBM to bore and install the lining simultaneously. In the worst ground conditions, when the rock is so broken that no lateral force can be applied to the tunnel walls, the machine operates as a single-shield type, using the lining to react to the forward thrust. Shielded TBMs feature the following:

- Low-profile cutter heads – in blocky ground a flat, low-profile cutter head with rear-changing cutters provides face support, prevents cutter-head stalling, and protects workers during cutter changes. The cutter heads are custom designed.
- Lining systems – a segment erector in the tail shield installs prefabricated lining, which could be concrete segments, cast iron or ring beams and lagging.
- Probing/grouting – rock drills for probing the ground ahead and equipment for grouting in front of the machine in wet conditions can be integrated in any shield design.
- Sealing systems – if water is an issue, wire-brush seals can be installed in the tail shield where the segments are erected, protecting the work area from inflows. For extreme water pressure, the machine can be designed with a sealed cutter-head support that acts as a pressure bulkhead against water inflows.
- Digital guidance system – continuous information is provided to the operator regarding the machine's location relative to true alignment and corrective steering adjustments.
- Drive – can be two-speed electric, variable frequency or hydraulic.

An example where a double-shield TBM has been deployed is at the Giant Water Tunnel in the Alimineti Madhava Reddy (AMR) project in India in 2012:

Machine type:	double-shield TBMs assembled onsite
Diameter:	2 × 10.0 m (32.8 ft)
Tunnel type:	water transfer
Tunnel length:	43.5 km (27.0 miles)

5.4.1.3 Robbins earth-pressure-balance machines

Robbins manufactures earth-pressure-balance machines (EPBMs) for use where the geology comprises soft soils to weathered rock. EPBMs are used in the construction of rail tunnels, metropolitan subway systems, highway tunnels and other projects where the tunnel will be constructed either partly or completely in soft soil beneath the water-table. The following types of cutter head are available for EPBMs:

- back-loading disk cutters and drag picks, for use where soil with boulders or massive rock is expected
- drag picks only, where no rock is expected
- full coverage with drag picks and partial coverage with disk cutters, where occasional boulders are expected
- copy cutters, to overcut the tunnel for steering.

It has a cutter head with the largest opening capacity in the industry, driven by a proven variable-frequency drive system. EPBMs have a digital guidance system, which gives a continuous display of the actual tunnel alignment versus the design alignment, and information for accurately building segment rings. One project where such a unit has been used is in the Pahang and Selangor states, Malaysia, in 2013:

Machine type:	four 6.5 m (21.4 ft) diameter EPBMs
Tunnel type:	rail
Tunnel length:	2030 m (6660 ft) and 2500 m (8202 ft)

5.4.1.4 Robbins crossover TBMs

As described in Section 6.18, Herrenknecht AG (Schwanau, Germany) has developed multi-mode TBMs for special cases. Similarly, Robbins has introduced Crossover TBMs for time-saving, efficient tunnelling and to meet the challenges posed by ground having a mixed geology, which comprises a little bit of everything, such as hard rock, soft rock, boulders, soil and weathered rock. These TBMs are designed to cross between ground conditions that would typically require multiple machines. They are also known as ‘hybrid’ or ‘dual mode’ machines in the tunnelling industry. Robbins produces two crossover TBMs:

- The XRE TBM – Crossover (X) between Rock (R) and EPB (E) – is ideal for mixed soils with rock.
- The XSE TBM – Crossover (X) between Slurry (S) and EPB (E) –is ideal for mixed to soft ground under water pressure.

An XRE TBM was used on the Grosvenor Decline Tunnel in Queensland, Australia. The machine was used to excavate two mine access drives at rates 14 times faster than a traditional roadheader. The last drive was completed in 2015.

Machine type:	crossover (XRE) TBM
TBM diameter:	8.0 m

Tunnels: two decline tunnels at 1 : 6 and 1 : 8
Geology: hard rock and mixed ground, ranging from soft clay and soil to sandstone and basalt
Project owner: Anglo American

Another XRE unit was launched in September 2015 for a project in Mexico City, Mexico:

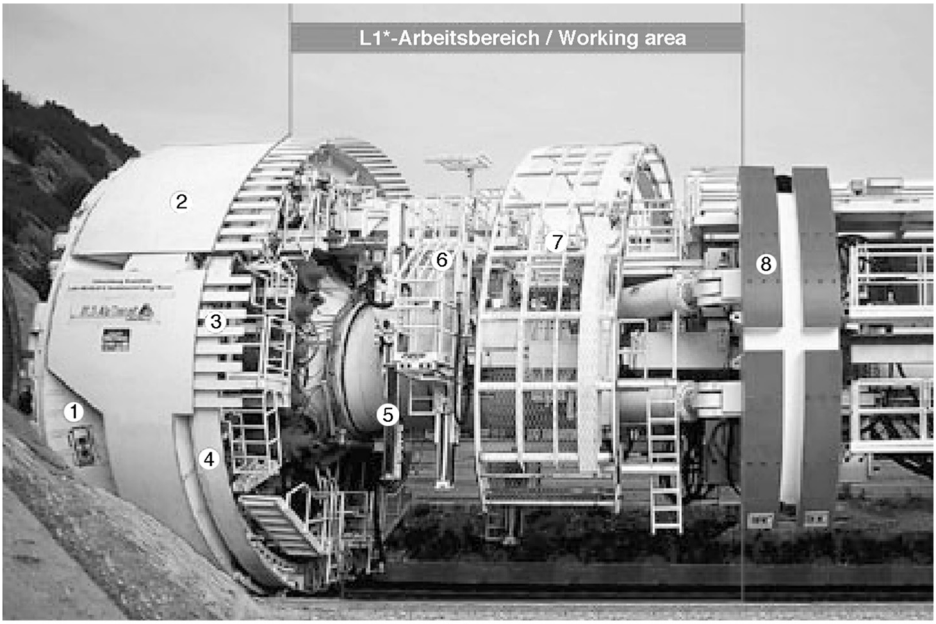
Machine type: crossover XRE (Rock/EPB)
TBM diameter: 8.7 m (28.5 ft)
Tunnel length: 5.9 km (3.7 miles)
Geology: fairly competent to weathered volcanic rock, soft sands and clays

5.4.2 Herrenknecht's hard-rock TBMs

5.4.2.1 Gripper TBMs

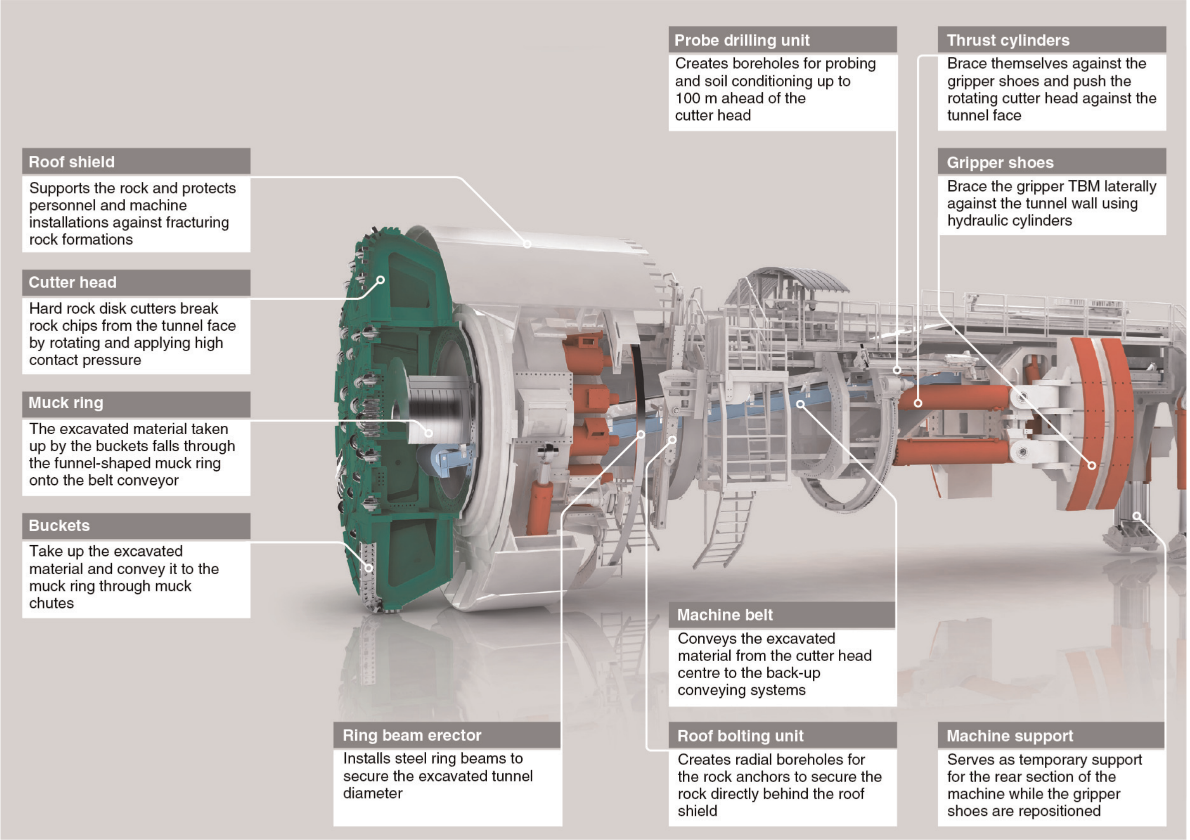
Single- and double-gripper machines (Figures 5.14–5.16) – the gripper principle is simple and is suitable for boring in solid rock formations. The rocks can be stabilised at the

Figure 5.14 Gripper TBM. (a) 1, cutter head; 2, gripper (roof) shield; 3, finger shield; 4, ring beam erector; 5, anchor drill; 6, work cage with safety roof; 7, wire-mesh erector; 8, gripper plates (shoes). L1 area for rock support. (b) Gripper TBM with its various components and their functions (courtesy of Herrenknecht AG)



(a)

Figure 5.14 Continued



Roof shield
Supports the rock and protects personnel and machine installations against fracturing rock formations

Cutter head
Hard rock disk cutters break rock chips from the tunnel face by rotating and applying high contact pressure

Muck ring
The excavated material taken up by the buckets falls through the funnel-shaped muck ring onto the belt conveyor

Buckets
Take up the excavated material and convey it to the muck ring through muck chutes

Ring beam erector
Installs steel ring beams to secure the excavated tunnel diameter

Probe drilling unit
Creates boreholes for probing and soil conditioning up to 100 m ahead of the cutter head

Machine belt
Conveys the excavated material from the cutter head centre to the back-up conveying systems

Roof bolting unit
Creates radial boreholes for the rock anchors to secure the rock directly behind the roof shield

Thrust cylinders
Brace themselves against the gripper shoes and push the rotating cutter head against the tunnel face

Gripper shoes
Brace the gripper TBM laterally against the tunnel wall using hydraulic cylinders

Machine support
Serves as temporary support for the rear section of the machine while the gripper shoes are repositioned

(b)

Figure 5.15 A single-gripper TBM for larger-diameter tunnels (courtesy of Herrenknecht AG)

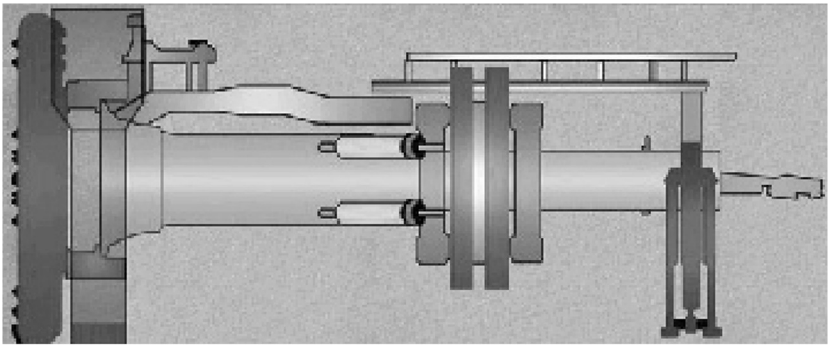
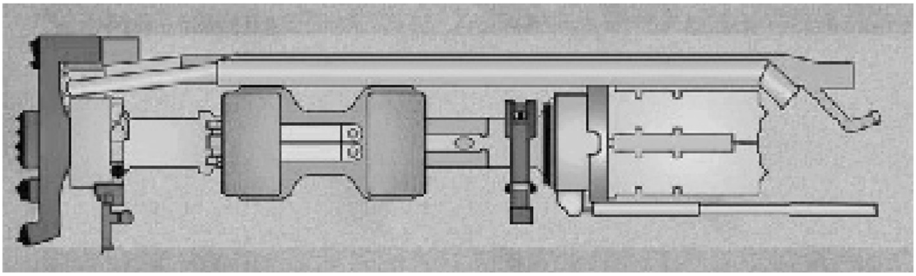


Figure 5.16 A double-gripper TBM for smaller-diameter tunnels (courtesy of Herrenknecht AG)



nearest and earliest possible point from the front face. Substantial automation has been incorporated in these units. The cutter head is equipped with cutters (disks). The rotating cutter head presses the disks against the tunnel face, applying high pressure. The disks perform rolling movements on the tunnel face, causing loosening of the rock. The excavated rock, usually described as ‘chips’, is picked up by buckets (openings in the cutter head) and transported via hoppers onto the conveying system. The TBM conveyor transports the material for the complete length of the TBM to the transfer band between the TBM and the back-up system. From there, the excavated material is transported via conveyors either to the outside or to the train of muck cars.

The TBM has a gripper system that extends radially against the tunnel walls. Hydraulic cylinders push the cutter head against the tunnel face so that another section of tunnel can be excavated. The maximum stroke depends on the piston length of the thrust cylinders. After completion of a stroke, excavation is interrupted and the machine is repositioned.

An additional support system stabilises the gripper TBM during the repositioning cycle. Tunnelling performance of a gripper TBM depends highly on the time required for undertaking rock stabilisation measures. To secure the rock, conventional methods, such

Table 5.6 Technical details of gripper TBMs deployed in the longest railway tunnels in the world: Loetschberg and Gotthard, Switzerland (courtesy of Herrenknecht AG)

	Steg/Raron (Loetschberg)	Bodio (Gotthard)	Faido (Gotthard)	Amsteg (Gotthard)
Diameter of cutter head: m	9.43	8.83	9.33/9.63	9.58
Number of disk cutters	60	58	62	62
Diameter of disk cutter: m (in.)	0.431 (17)	0.431 (17)	0.431 (17)	0.431 (17)
Cutter head power: kW	3 500	3 500	3 500	3 500
Maximum thrust force: kN	22 800	27 488	27 488	27 488
Maximum gripper force: kN	63 334	72 142	72 142	72 142
Cutter head torque: kN m	14 216	13 627	13 627	13 627

Metric equivalent: 1 in. = 0.0254 m.

as anchors, nets and shotcrete, as well as segment lining, are used. The rock stabilisation arrangements are as close as 4.2 m behind the cutter head. The single-gripper machine provides the opportunity for early rock stabilisation immediately behind the cutter head, as shown by the L1 area in Figure 5.14(a). Six single-gripper TBMs equipped with a rock support mechanism were used in the construction of the longest railway tunnels in the world, the Gotthard (57 km) and the Loetschberg base tunnel (34 km) in Switzerland. A ring erector, two anchor drills and a wire-mesh erector were used with this machine for the installation of rock support in the Loetschberg tunnelling project. Installation of segments and shotcrete are performed in the back-up area.

Table 5.6 gives the technical details of gripper TBMs deployed in the longest railway tunnels in the world (Merzagora *et al.*, 2013) and Table 5.7 highlights the operational details of the gripper TBM and its significant features.

The single-gripper machine shown in Figure 5.15 was used at Tscharner, Switzerland, when a TBM without a shield was used to drive a tunnel of 9.53 m diameter. The machine braces itself at the back by means of two gripper plates against the rock. It has the merit of making a spacious working area available for the installation of the rock supports in L1 (see Figure 5.14).

The double-gripper machine shown in Figure 5.16 has a total of four hydraulically-operated gripper plates. A machine of this type was used at Zurich with a diameter of 3 m. In comparison with the single-gripper type, however, the use of double-gripper machines leaves free space for the placement of rock support.

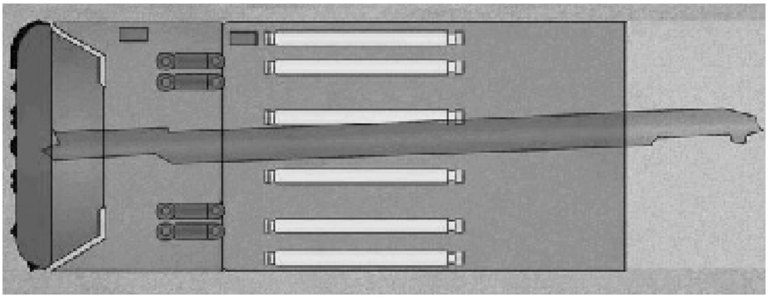
5.4.2.2 Single-shield and double-shield machines

Single-shield units (Figure 5.17) are suitable for soft rocks. A tunnel lined with concrete segments is driven. During tunnelling, the single-shield TBM is supported by hydraulic thrust cylinders pressing against the most recently installed segment ring.

Table 5.7 Operational details of gripper, single-shield and double-shield TBMs (courtesy of Herrenknecht AG)

Geology, diameter, range and technical details	Significant features
Gripper TBM *Geology*: hard and stable rocks *Diameter range*: 2–12.5 m *Excavation*: disk cutters break chips from the tunnel face by applying high contact pressure *Removal*: buckets, muck chutes and a muck ring remove the excavated material onto a central belt conveyor *Thrust*: hydraulic thrust cylinders brace against the gripper shoes and push the cutter head forward *Tunnel support*: rock anchors, steel mesh, steel arches or shotcrete, depending on the geology	■ High advance rates with precision in stable rock formations ■ With measures taken to secure rocks it also ensures safety in fault zones ■ Successful deployment of four units at the Gotthard base tunnel
Single-shield TBM *Geology*: soft, brittle rock to hard rocks *Diameter range*: 1.5–14 m *Excavation*: disk cutters break chips from the tunnel face by applying high contact pressure *Removal*: buckets, muck chutes and a muck ring remove the excavated material onto a central belt conveyor *Thrust*: hydraulic thrust cylinders in the shield or a jacking frame in the launch shaft push the machine forward *Tunnel support*: segmental lining or pipe jacking	■ High advance rates possible in all kinds of rock ■ Also suitable for use in brittle and non-stable rock formations ■ With prior soil conditioning can be used in groundwater-bearing formations ■ Smallest-diameter TBM but produces a powerful torque (160 kN m)
Double-shield TBM *Geology*: all kinds of stable and unstable rock *Diameter range*: 2.8–12.5 m *Excavation*: disk cutters break chips from the tunnel face by applying high contact pressure *Removal*: buckets, muck chutes and a muck ring remove the excavated material onto a central belt conveyor *Thrust*: hydraulic main thrust cylinders or the auxiliary thrust cylinders push the machine forward *Tunnel support*: segmental lining	■ High advance rates possible in stable rock due to the continuous tunnelling operation ■ Suitable for use in all kinds of rock and in formations with faults ■ 290 tunnel rings (9690 mm diameter TBM) built in 1 week is a world record

Figure 5.17 Single-shield TBM: (a) conceptual diagram; (b) various components and their functions (courtesy of Herrenknecht AG)



(a)

Double-shield TBMs (also referred to as ‘telescopic shields’) (Figure 5.18) combine both tunnelling principles (gripper and shield) in one machine. This enables high thrust performance in alternating changing geological conditions through changing between the two modes. The lining segments are installed parallel to drilling.

The operational details of single- and double-shield TBMs and their significant features are given in Table 5.7.

5.4.3 Performance indicators

The governing factor for TBMs is the net progress per day, which ultimately leads to the cost per metre of advance. The most important considerations that contribute to these performance indicators are

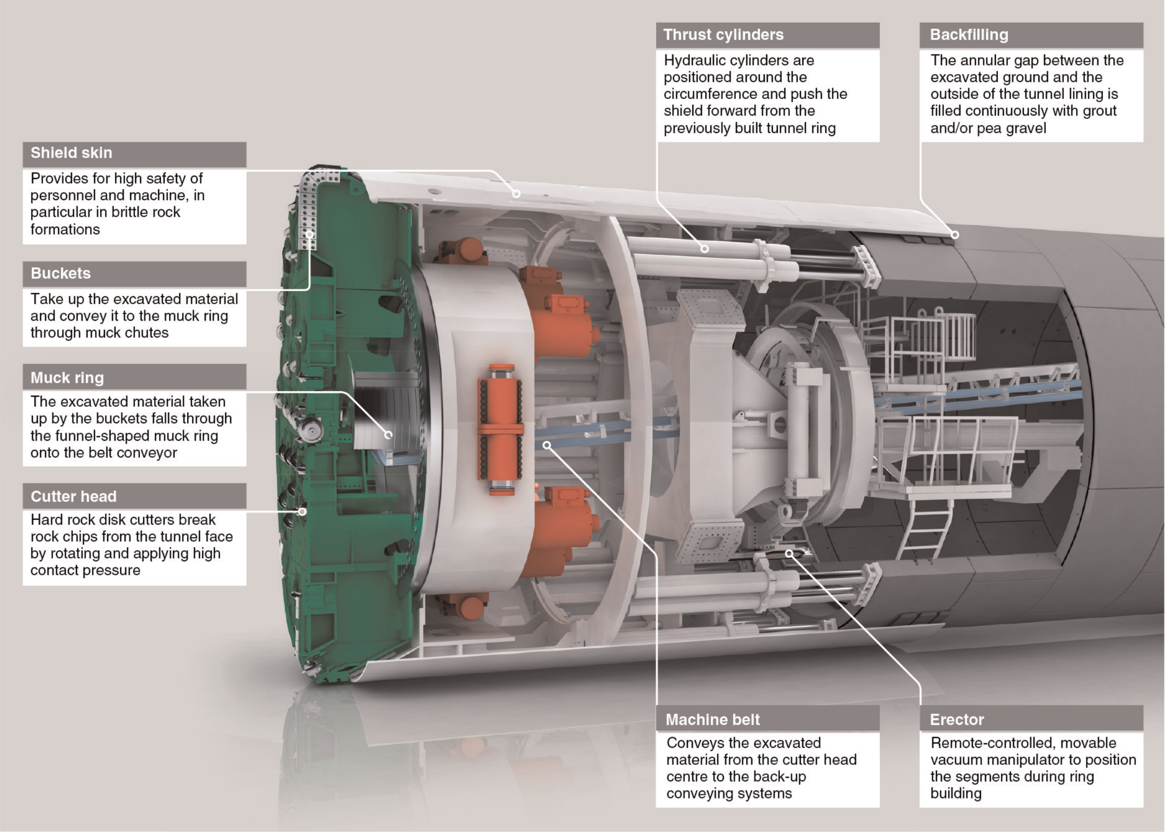
- TBM availability
- TBM utilisation
- cutter consumption
- muck haulage rates
- machine resale value.

5.4.4 Some highlights of full-face boring machines

One of the limitations of partial face machines (PFMs) is they it uses drag bits (picks), which are only capable of cutting soft and medium-hard rocks up to an unconfined (uniaxial) compressive strength (UCS) of 130 MPa (Matti, 1999; Parkes, 1988), with one exception: special picks tipped with carbide and PDB (polycrystalline diamond blanks) can cut rocks of up to 207 MPa UCS. Full-face TBMs are capable of working with all types of rock, from the softest to the toughest, as shown in Table 5.8.

The preparatory work required for the utilisation of a full-face TBM is considerable, in order to house the machine and its back-ups. This work could be the preparation of launching tunnels, shafts (in some cases) and excavations. In addition, the time for delivery, transport to site and assembly of the TBM is significant.

Figure 5.17 Continued



Shield skin
Provides for high safety of personnel and machine, in particular in brittle rock formations

Buckets
Take up the excavated material and convey it to the muck ring through muck chutes

Muck ring
The excavated material taken up by the buckets falls through the funnel-shaped muck ring onto the belt conveyor

Cutter head
Hard rock disk cutters break rock chips from the tunnel face by rotating and applying high contact pressure

Thrust cylinders
Hydraulic cylinders are positioned around the circumference and push the shield forward from the previously built tunnel ring

Backfilling
The annular gap between the excavated ground and the outside of the tunnel lining is filled continuously with grout and/or pea gravel

Machine belt
Conveys the excavated material from the cutter head centre to the back-up conveying systems

Erector
Remote-controlled, movable vacuum manipulator to position the segments during ring building

(b)

Table 5.8 Parameters influencing the advance rates of TBMs

Machine parameter	Geological and geomechanical parameter
Cutter head rpm	Rock strength
Cutter head thrust	Hardness
Cutter head torque	Abrasiveness
Disk geometry	Jointing
Disk wear	Bedding/foliation
Disk diameter	Schistosity
Cutter arrangement	Orientation relative to the tunnel axis

Due to their high capital cost, long mobilisation time and the need to construct starter and tail tunnels, a tunnel length of about 3 km is required to make the use of a full-face TBM economically feasible (Handwith and Dahmen, 1982).

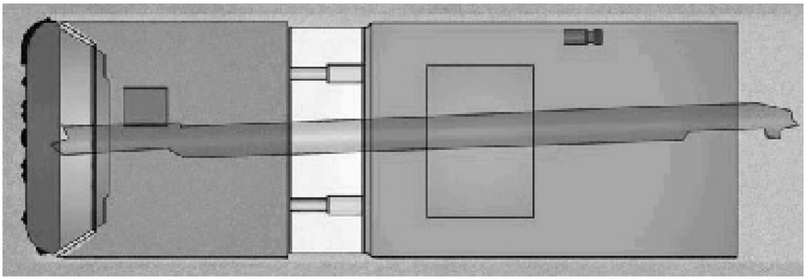
A shaft-boring machine (SBM), even when the pilot hole is already prepared, requires a shaft depth of at least 250 m in order for its use to be competitive with a conventional drill-and-blast excavation.

5.5. Back-up system

The removal of muck from the tunnel is critical. The use of continuous conveyors (such as the one supplied by Boretec) can boost excavation rates significantly. The manufacturers claim that this system can maximise overall advance rates and minimise system downtime. In addition to higher TBM utilisation, advantages of continuous conveyor systems include

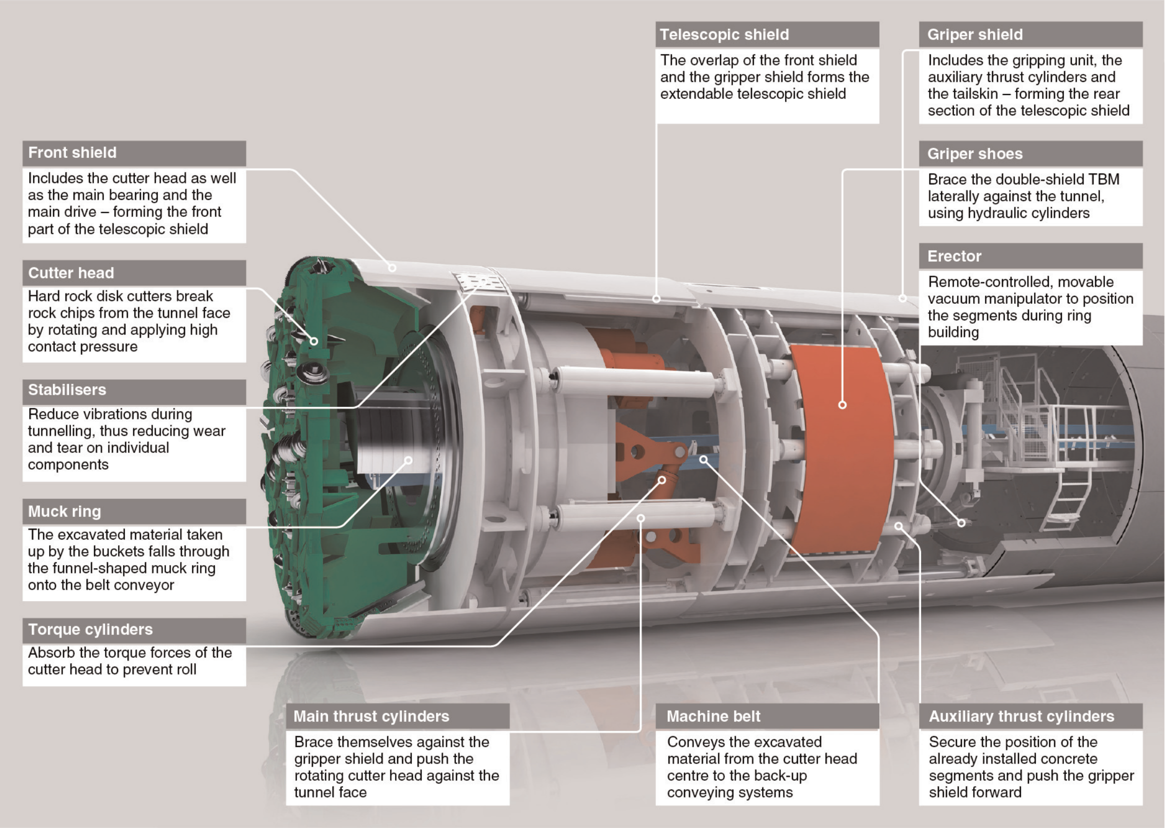
- fewer tunnel personnel required
- lighter rolling stock can be used
- reduced ventilation requirements
- less tunnel congestion
- improved tunnel safety
- adaptability to tunnel inclines and declines.

Figure 5.18 Double-shield TBM: (a) conceptual diagram; (b) various components and their functions (courtesy of Herrenknecht AG)



(a)

Figure 5.18 Continued



(b)

5.5.1 Single-track back-up systems

Back-up systems should be short and simple to operate and maintain. When the tunnel is small or short, or the equipment assembly area is confined, a single-track back-up is usually preferred. In longer tunnels, when the tunnel diameter allows for the passing of muck cars, a mobile California switch positioned 50–150 m behind the back-up system could provide better productivity.

5.5.2 Double-track back-up systems

If the tunnel is large and long enough, and if the rolling stock already exists to be utilised, a double-track back-up system can be selected. A California switch is often a part of the layout. Use of a remote car-moving mechanism will always allow locomotives to lead. However, double-track systems are more complex and require skilled operators and excellent logistical planning. Their advantage is increased production rates. Other arrangements/provisions that need to be established for a double-track system are

- fewer tunnel personnel required
- lighter rolling stock can be used
- reduced ventilation requirements
- less tunnel congestion
- improved tunnel safety
- adaptability to tunnel inclines and declines.

5.6. Boring system

In hard rock, the rock-cutting mechanism of a TBM has a direct impact on the performance and efficiency of the machine. This means that the cutting tools should be arranged and used in a manner that produces the largest-size cuttings. In a TBM, this is accomplished by increasing individual cutter loads to attain deeper penetration into the rock. Deeper penetration, in turn, allows wider cutter spacing. The combination of deep penetration and wide concentric cuts, or kerfs, produces the largest average chip size. With proper design, a hard-rock TBM can achieve an excavation efficiency of 3–6 hp h/ton. The information on rock types and geological and geomechanical parameters listed in Tables 5.8 and 5.9 can be used to develop a prediction model to be in the TBM design. In addition, useful guidance can be obtained from consulting with TBM manufacturers and experienced engineers.

The boring or excavation mechanism is the most important part of a TBM and is responsible for its effectiveness. It consists of

- cutter head and cutting tools
- cutter-head drive
- thrust system.

The rock is removed from the face by means of disk cutters, which roll with an applied load in concentric kerfs over the face of the tunnel. The advance rate of a TBM is influenced by machine-related, geological and geomechanical parameters, as listed in Table 5.8 (Friant and Ozdemir, 1993; Nilsen and Ozdemir, 1990).

The uniaxial compressive strength, tensile strength and point load index of the rock correlate well with the penetration rate. These properties are the basis for various prediction models and should be available from the geological investigations. In addition to the above-mentioned properties, the prediction model should take into account the considerable influence of the schistosity and jointing of the rock. The most relevant factors noted in the petrographic study (thin sections) should be given due importance. When evaluating TBM performance, emphasis should not be placed only on the traditional mineralogical and petrographic study (Nilsen and Ozdemir, 1990), or on a discussion of the rock type or origin (as commonly seen in most geotechnical reports). Factors that are of key importance in the evaluation of TBM performance and cutter wear are

- grain suturing/interlocking
- micro-fractures
- orientation, directional properties
- grain size/shape/elongation
- content of particular hard minerals (e.g. quartz, garnet and epidote)
- any other unusual microscopic features.

Rock anisotropy, such as foliation (see Table 5.8) and/or bedding, can have a significant effect on TBM performance (Nelsosn *et al.*, 1994). The Brazilian tensile strength test can provide a reliable indication of the degree and extent of rock anisotropy. This information, together with punch penetration and/or fracture toughness tests, can be used to develop an assessment of the influence of the rock anisotropy on the TBM performance.

The net advance rate is a linear function of cutter head rpm and the penetration of a disk per cutter-head revolution. In principle, the relationship between the penetration and the cutter thrust can be obtained from the following equation (Lislerud, 1988):

$$P = \left(\frac{F}{F_1}\right)^b \tag{5.1}$$

where P is the net penetration (mm/rev), F_1 is the critical thrust to attain 1 mm of penetration (kN), F is the thrust (kN) and b is an exponent.

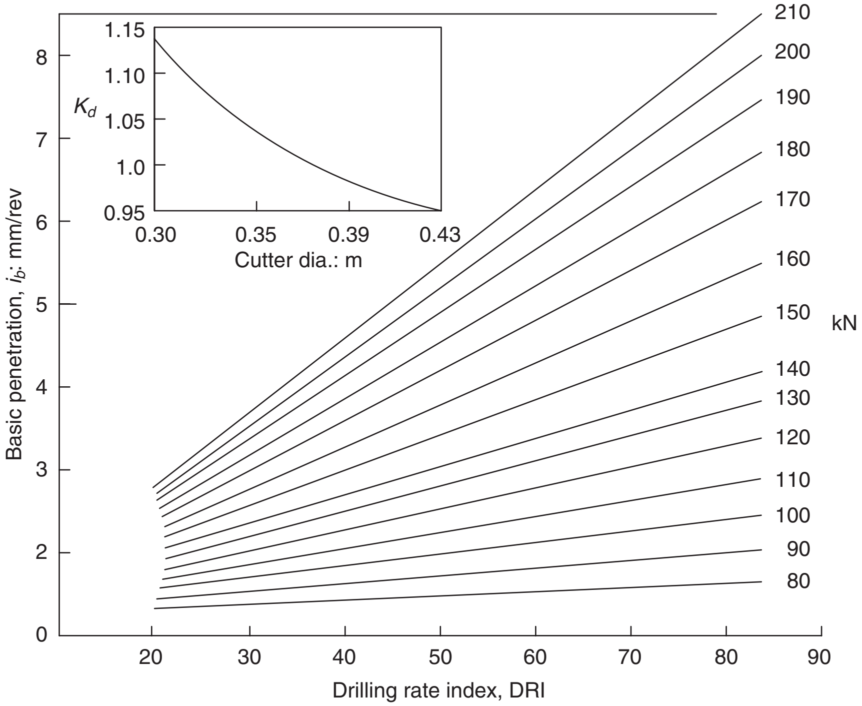
F_1 is to a great extent determined by the geology, the diameter of the disk and the kerf spacing. The exponent b is determined by F_1 and the geology, and is in the range 1.7–2.5 for many rocks. The influence of the cutter thrust on the rate of advance is also governed by the type of formation (ground and rocks).

Lislerud developed a TBM performance prediction based on rock-mass factors (rock-mass jointing, intact rock strength, brittleness and abrasivity) and machine factors (thrust per cutter, cutter-edge bluntness, cutter spacing, cutter diameter, torque capacity and rpm, and cutter-head curvature and diameter) (Lislerud, 1988; Lislerud *et al.*, 1983):

$$P = i_b K_s K_d \tag{5.2}$$

where K_s is the correction factor for the joint rating and frequency, K_d is the correction factor for the cutter diameter and i_b is the basic penetration rate (mm/rev). The basic

Figure 5.19 Relationship between the drilling rate index (DRI) and the penetration rate. K_d, correction factor for cutter diameter



penetration rate is a function of the thrust per disk and the drilling rate index (DRI), as shown in Figure 5.19. The DRI is based on testing described by the Norwegian Institute of Technology.

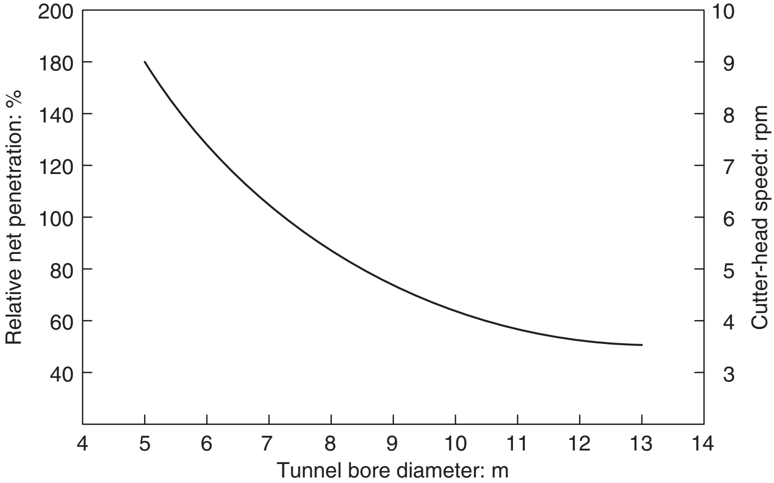
Looking at the above equations, it can be seen that these methods require a considerable amount of geotechnical investigation.

Penetration rates versus tunnel diameter for different rock types were studied by Nelsosn *et al.* (1994) and Stevenson (1999), as shown in Figure 5.20. The analysis shows that higher penetration rates can be achieved for diameters in the range 3–5 m in hard rocks and 3–6 m for soft rocks. For the same diameter range, the penetration is about 1.4–1.5 times faster in soft rocks.

In terms of rock strength, Framer and Glossop (1980) have derived a relationship between cutter thrust F_L, penetration rate P and rock tensile strength σ_{tf} by equating the energy input per unit length of cut to the energy required to satisfy fracture surfaces in the rock:

$$P = \frac{KF_L}{\sigma_{tf}} \tag{5.3}$$

Figure 5.20 Bore diameter as a function of penetration rate and cutter-head speed



The value of K was obtained by least-squares regression of eight cases studied. The equation can be written as

$$P = \frac{624F_L}{\sigma_{tf}} \quad \text{in SI units} \tag{5.4a}$$

with P in millimetres per revolution (mm/rev), F_L in kilonewtons (kN) and σ_{tf} in kilopascals (kPa); or

$$P = \frac{0.0158F_L}{\sigma_{tf}} \quad \text{in Imperial units} \tag{5.4b}$$

with P in inches per revolution (in./rev), F_L in pound-force (lbf) and σ_{tf} in pounds per square inch (psi).

Based on the performance of the Robbins TBMs in hard rocks, Graham (1976) suggested a similar equation. He used unconfined compressive strength σ_{cf} in the range 140–200 MPa (20 000–29 000 psi) to study this parameter.

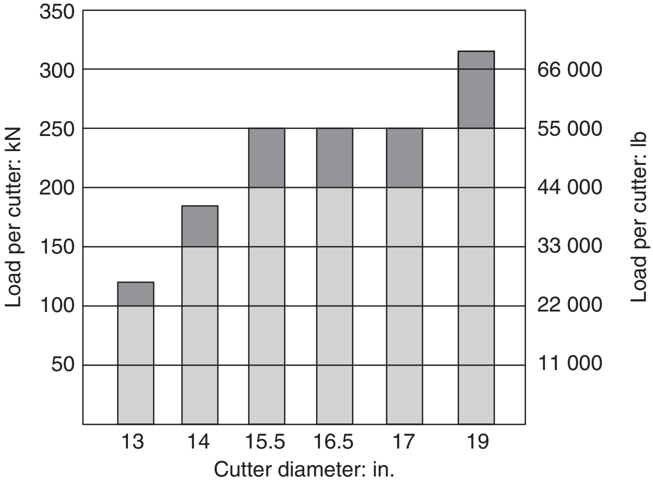
$$P = \frac{3940F_L}{\sigma_{cf}} \quad \text{in SI units} \tag{5.5a}$$

$$P = \frac{0.1F_L}{\sigma_{cf}} \quad \text{in Imperial units} \tag{5.5b}$$

5.6.1 Disk diameter

In order to increase the penetration of the disk cutters, and thus the net rate of advance, there has been steady development of cutters over the past 20 years. This has led to the

Figure 5.21 Disk diameter versus load per cutter



achievement of higher bearing capacities, enabling increased cutter thrusts (Figure 5.21), which in turn has led to larger bearings and, consequently, larger disk diameters. In order to maintain economical wear, cutters should not be used to their theoretical capacity (crosshatched area in Figure 5.21) (Weber, 1990). For most current-day projects, cutters with disk diameters of 416 mm (16.3 in.) and 432 mm (17 in.) are common; at the end of the 1980s, 483 mm (19 in.) disk cutters were favoured for so-called 'high-powered TBMs'. Robbins manufactures disk cutters up to 500 mm (20 in.) in diameter.

5.6.2 Cutter-head speed

The bearings and seals of the disk cutters permit a speed (rpm) equivalent to a rolling speed of 150 m/min of the gauge cutters. The cutter-head speed is inversely proportional to the cutter-head diameter:

$$n = \frac{X}{D} \tag{5.6}$$

where n is the cutter-head speed (rpm), D is the bore diameter (m) and X is the speed factor (rpm; currently 45–50 rpm).

In their analyses of machine speed during the period 1980–1998, Nelsosn *et al.* (1994) and Stevenson (1999) showed that for tunnel diameters in the range 3–6 m the usual speed was 5–15 rpm, and for tunnel diameters exceeding 6 m it was 4–8 rpm. Stevenson's analysis of the cutter thrust for different rock types showed that in the period 1980–1990 it was 150–250 kN, while in 1990–1998 it was 175–250 kN. Since then the cutter thrust has increased to a maximum of 300 kN: 140–200 kN for sedimentary rocks and 150–300 kN for hard rocks.

Table 5.9 Cutting tools used in conjunction with various tunnelling machines

Rock type	Compressive strength: kPa (psi)	Cutting tool and combination of forces	Type of attack
Very soft to soft	0–124 000 (0–18 000)	Drag, chisel, picks Applying very high torque and low thrust	Point, i.e. applying force parallel to rock surface
Soft to hard	4895–313 700 (710–45 500)	Disk cutter Applying high thrust and medium torque.	Small surface area of contact, cutting force normal to rock surface (indenture tools)
Very hard	241 300 and higher (35 000 and higher)	Roller studded with buttons Applying very high thrust and high torque	Large surface area of contact, cutting force normal to rock surface (indenture tools)

5.7. Rock-cutting tools and their types

Cutting tools are essential in the process of cutting rocks. The type of cutter used with a heading machine and TBM depends on the type of rock for which the equipment is to be used (Table 5.9). Very soft rock requires very high torque and low thrust (Figure 5.22(a)), soft to medium-hard rock requires very high thrust and medium torque (Figure 5.22(b)) and hard rocks require high thrust and high torque (Figure 5.22(c)). Figures 5.23(a) and 5.23(b) show the effect of the compressive strength of the rock on boring rates and costs, respectively. A comparison of costs of conventional drill-and-blast and tunnel boring is shown in Figure 5.24.

Figure 5.22 Types of cutting tool: (a) drag pick – for very soft to soft rocks (very high torque, low thrust); (b) disk cutter – for medium hard to hard rocks (medium torque, high thrust); (c) roller stud with buttons – for hard rocks (high torque, very high thrust)

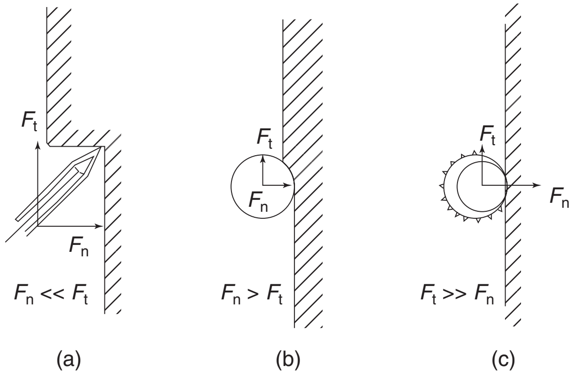
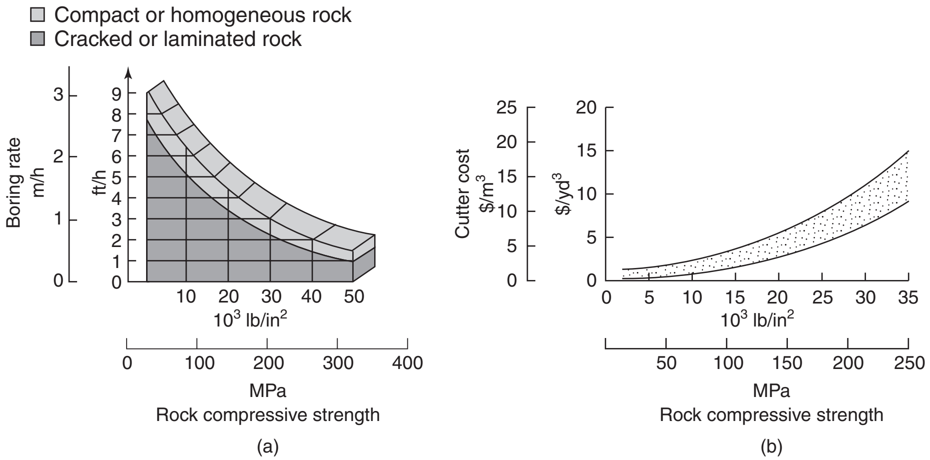


Figure 5.23 Effect of compressive strength on (a) boring rate and (b) cost of cutter



5.8. Cutting-head configuration

In soft ground conditions, drag cutters are usually used throughout the cutting-head face, but for other rocks various combinations of cutter types and their layouts are relevant. The configuration of a TBM cutting head has three distinct zones: the centre, the face and the outer gauge cutters (Whittaker and Frith, 1990). In some designs, the centres of the cutters are arranged in the form of a tricone in order to facilitate rock breakage. Depending on the hardness of the rock, the main face area is usually excavated using disk or roller cutters (or drag cutters for soft rocks). The gauge cutters are located at the outside edge of the cutting head to excavate the opening of the desired size.

Figure 5.24 Comparison of cost of conventional drill-and-blast and tunnel boring

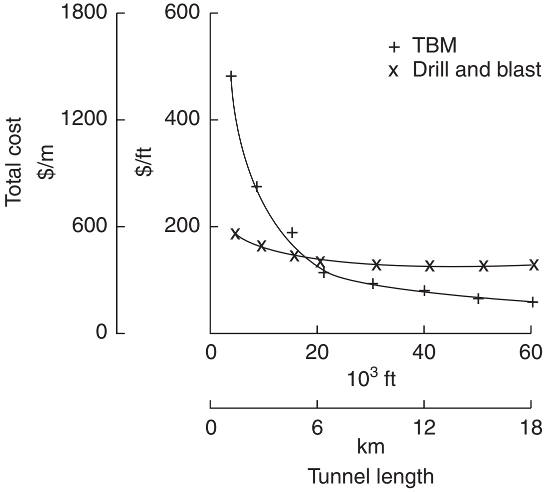
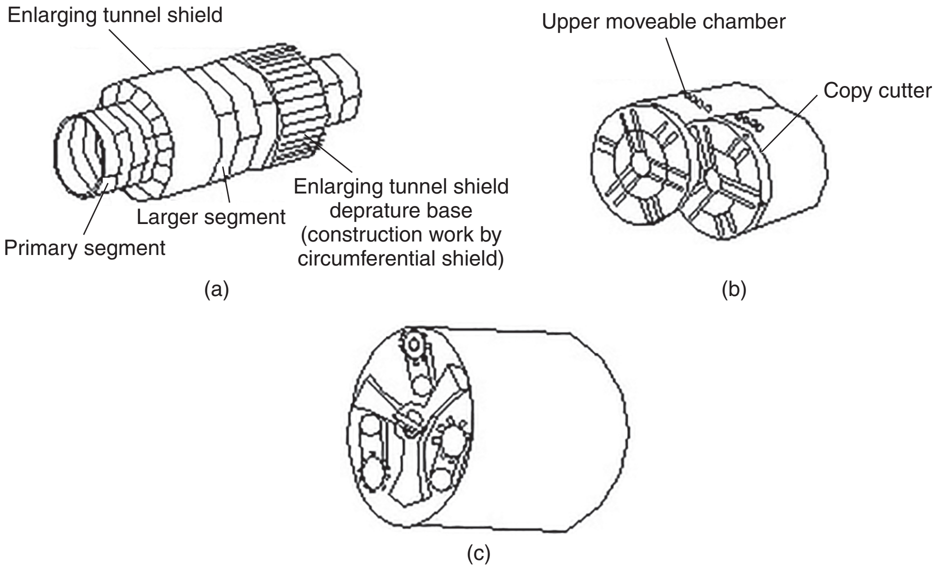


Figure 5.25 (a) Rectangular shaped shield; (b) oval shaped shield; (c) dual circular shaped shield



5.9. Some developments

5.9.1 TBMs other than circular shaped

The use of a full-face TBM results in a circular shape that has about 29% less effective area of utilisation compared to a rectangular-shaped opening. Where the circular profile is not mandatory on account of ground stability, other shapes should be preferred. New developments include shields that are rectangular, oval and dual circular shaped (Figure 5.25), and enlarging tunnel shields (used to enlarge the existing tunnels) (Hamburger and Weber, 1993; Imai *et al.*, 2002). The rectangular shield machine has the following features:

- The cutter excavation mechanism can excavate a rectangular section as uniformly as a conventional circular shield machine.
- A mixing mechanism inside a cutter pressure chamber can knead the excavated material within the chamber. A rotating bulkhead that rotates in the opposite direction to the cutter increases the kneading effect and enables stable kneading of even the gravel layer.
- Cutter bits having tip ends with dull corners to deal with gravel layer are used.
- The cutter torque is high enough to excavate the gravel layer.
- An over-cutter capable of excavating a rectangular section is used. This enables over-cutting to be performed for the construction of curved lines.
- The application of a portal-frame type erector in the assembly of segments enables the handling of heavy weight concrete segments. A segment spread system is also adopted.
- The machine is most suitable for soil such as gravel layers that require sufficient kneading.

5.9.2 Extruded concrete lining – construction method

The newly developed extruded concrete lining (ECL) construction method does not use segments for lining and lies somewhere between the shield method and the new Austrian tunnelling method (NATM) (see Section 7.1). As it possesses the advantages of both the shield and the NATM methods it is receiving much attention as a construction method (Kurihara *et al.*, 1995), although the ECL method still has problems with high water pressure and sharply curved sections. The ECL method is more economical than the shield tunnelling method, which uses segments for lining, and its technology is highly regarded because of the possibility of containing potential adverse effects on the environment, including ground subsidence.

The Lee tunnelling method (LTM) (see Section 7.3) involves making small-diameter tunnel to provide the initial opening, and then widening this to a large-sized tunnel using conventional drilling and blasting techniques (see Figure 7.5).

The parent–child shield tunnelling machine is an earth-pressure-balance shield machine (see Section 6.9) that can be used to construct a tunnel that has variable sectional diameter because the parent shield contains the smaller child shield, which is separated and removed during excavation. Parent–child shield machines commonly use the components installed in the shield. The parent–child shield machine progresses as an integrated unit to excavate a tunnel of large cross-section. When it arrives at the specified location, the integrated unit is converted to the child shield machine, and the parent machine allows the child machine to take off to excavate a tunnel with a smaller cross-section. Therefore, a tunnel having two different cross-sections can be continuously excavated without providing vertical shafts, and thus the construction cost is reduced. This unit is useful in sewerage and railway tunnels. A larger cross-section is required at the station portions of railway tunnels, to accommodate a platform, than in the rail portions.

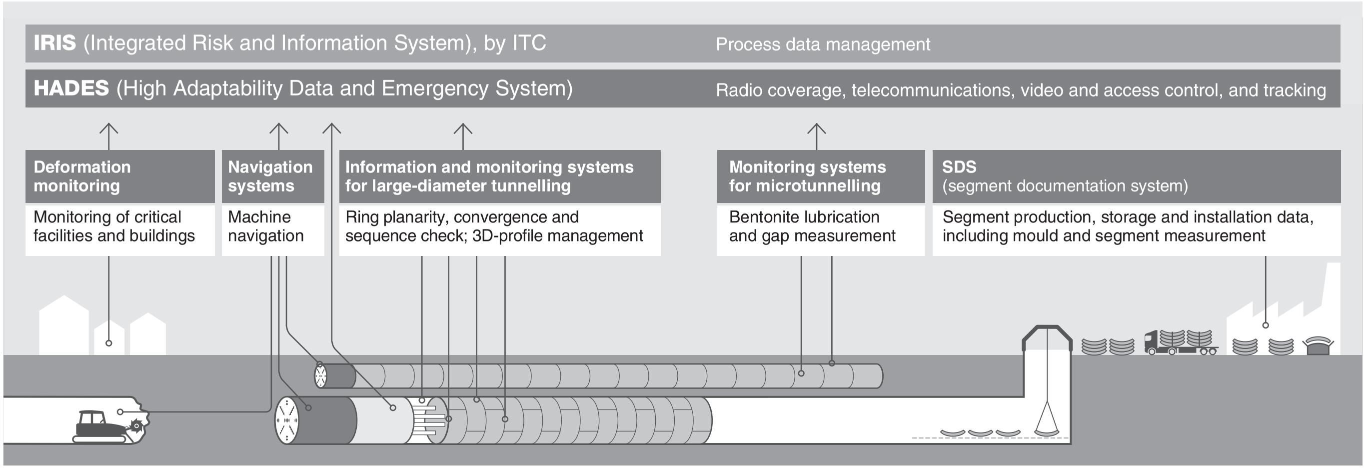
5.9.3 Sonic soft-ground probing

Sonic soft-ground probing (SSP), a seismic probing procedure, was developed by Herrenknecht to improve safety. It probes ahead virtually and warns the TBM operator ahead of time when significant geological changes are to be expected. Specially adapted loudspeakers and microphones are installed in the cutter head. The loudspeakers send sound waves into the ground every second, and the microphones pick up the reflected signals, which are recorded simultaneously. A data-recording giant located on the back-up system evaluates the measured and statistical data, and produces a visual display showing significant geological changes up to 40 m ahead of the cutter head. SSP has already delivered precise predictions.

5.9.4 Integrated risk and information system

The integrated risk and information system (IRIS) produced by ITC Engineering (Figure 5.26) is an integrated system for data management and is specifically designed for tunnelling using TBMs. It links data concerning the machine technology, navigation and progress made in real time to achieve better overall control.

Figure 5.26 Integrated risk and information system (IRIS) by ITC Engineering (courtesy of Herrenknecht AG)



5.10. Comparison of tunnelling techniques

Table 5.10 gives a comparison of the conventional drilling-and-blasting tunnelling technique (see Chapter 4) and the method of tunnelling using TBMs and roadheaders. The following are the major aspects of the comparison:

- The conventional method can be used for any shape and size of tunnel, turning radius, rock strength and rock quality designation (RQD). However, it is a cyclical operation and is not very suitable for use in running, squeezing, boulder, glacial till and faulty zones/areas.
- TBMs are the better choice for tunnels exceeding 3 km in length and to achieve faster progress, but the equipment has high capital costs and long lead-times (procurement period). Operations done with TBMs are continuous, but the use of these machines is practically restricted to circular sections.
- Partial face roadheaders (PFMs) can be a good choice for tunnels not exceeding 3 km in length, and can be used to obtain any shape and size of tunnel. The initial cost of these machines is 15–30% of the cost of a TBM but higher than for conventional methods. PFMs work very well for compressive strengths up to 150 MPa. They are associated with better progress and percentage utilisation than conventional methods but less than for TBMs.

5.11. Concluding remarks

- Contrary to tunnels driven for the mining, which are usually located in remote areas, in most cases civil tunnels need to be driven in urban areas, where blasting is virtually prohibited. This scenario has given rise to other techniques, which may involve ground cutting, fluidising or excavating using tools, appliances, machines and equipment without jeopardising the stability of the surroundings or allowing any ingress of water.
- ‘Mechanised tunnelling’ is the result of number of innovations made over the last 150–200 years. Today there is hardly any location, formation or set of conditions where mechanised tunnelling is not used.
- Partial face-heading machines (PFMs) and full-face tunnel-boring machines (TBMs) are the two categories of machine used in mechanised tunnelling. PFMs construct a tunnel by digging, excavating or cutting the in situ formations in parts, whereas TBMs bore the whole face at one time.
- Boom miners (cutting machines (milling or ripping) known as ‘roadheaders’), multi-tool miner (MTM) attachments, boom-mounted impact hammers (breakers) and backhoe excavators (diggers) are the various types of PFM.
- A PFM is piece of self-contained equipment that is both mobile and versatile. It can be used to create tunnels of which size, shape, orientation and gradient can be varied as desired. A PFM is composed of cutting, gathering and delivery units.
- The cutting boom of a roadheader is usually mounted on a crawler track, but increasingly booms are mounted on other machines such as hydraulic breakers, trucks and travelling gantries and inside machine shields.
- Modern roadheaders are linked to microprocessor-based guidance and profile-control systems. Roadheaders are now available that have interchangeable cutter heads, either ripper or milling (auger).

Table 5.10 Comparison of tunnelling techniques (courtesy of Tamrock)

Parameter	Drilling and blasting	TBMs	Roadheaders
Configuration			
Size	Any	Civil: 1.5–19 m diameter Mining: 1.75–8 m diameter	Boom height governs the size, but it can be any
Shape	Any	Any	Arch and rectangular
Length	Shorter lengths up to 3 km	Lengths >3 km	Up to 3 km; longer can be tried
Gradient	Not exceeding 18°	Not exceeding 6°	Not exceeding 6°
Turning radius	Any	30–60°	30–60°
Rock strength			
Uniaxial compressive strength (UCS)	Any	Up to 220 MPa	Up to 70 MPa with light-duty machines and 150 MPa with heavy-duty machines; beyond this value performance is not guaranteed
Rock quality designation (RQD)	All ranges	Not good if RQD is 25–45%	Good for all RQD
Geological conditions			
Running ground	Not suitable unless pre-grouted	Specially designed machines	Not suitable
Squeezing ground	Some difficulty	Some difficulty	Some difficulty
Boulder and glacial till	Drilling difficult	Difficult for boulders but okay for till	Boulders not that difficult; till okay
Faults	Precautions required, ground must be supported but excavation not difficult	Faults difficult to handle; faults wider than 10 m cannot be handled	Medium difficulty
Operational details			
Air blasts and slaps	Yes; but can be reduced by delay blasting	None	None
Dust generation	Very dusty after blasting	Very dusty	Some dust
Noise level	High, due to drilling and blasting	Not that much	Medium level
Multi-drift excavation	Possible	Not possible	Not usually used

Table 5.10 Continued

Parameter	Drilling and blasting	TBMs	Roadheaders
Partial face excavation	Possible	Not possible	Possible
Working schedule	Cyclical	Continuous	Continuous
Muck removal	Flexible, using track or trackless equipment	Conveyor belt discharge onto rails or trucks	Collecting arms and conveyor belt discharge onto rails or trucks
Versatility and mobility	Maximum	Machine practically fixed to circular section	Face is accessible; support work can be done without significant shutdown
Performance and costs			
Progress rate	5–40 m/week	Faster (50–200 m/week)	About 15–90 m/week
Equipment utilisation	35%; higher in multiple faces	40%	60%
Initial cost	Not high	Very high	Medium (0.15–0.3 times cost of TBM)
Lead time	Very short	3–18 months to obtain a TBM	Not more than 3–6 months
Renting option	Usually not rented	Usually not rented	Usually rented, if small project

- In the UK, 65% of roadheaders are of the milling type. A two-boom milling-type roadheader is also available. In some designs, the heads are exchangeable with ripper-type heads.
- The use of hydraulics has produced reliable cutter heads, hammers and excavators with attachment capabilities. The Alpine Equipment Corporation has developed a line of MTMs (multi-tool machines) which are flexible and cost-effective. These machines can be equipped with cutter heads, hammers and excavator buckets. These three excavation systems are available with quick-couplers for rapid exchange at the face whenever changing ground conditions require it.
- MTM includes the following attachments: cutter head, hydraulic hammer, bucket and clay-spade, drill mast and roof bolter, shotcrete manipulator, grout and cement injector, breasting plate, man basket and crane. That is why this system is known as the ‘Swiss army knife’ of the construction industry.
- Impact hammers are suitable for sound and fractured rocks up to about 200 MPa UCS. Heavy and powerful hammers (breakers) in the 2000–12000 J (378–1211 kg m) range have demonstrated high production rates. Excavator-mounted hammers are very effective for rapid excavation of benches in tunnels and caverns. The Alpine Equipment Corporation has developed hammer attachments that can be retrofitted to roadheaders of any make and model. Hammer tunnellers and shaft sinkers are very useful where blasting is forbidden.

- Excavators with buckets are being used to excavate soft soil such as clay, silt and sand, and for mucking out of blasted rock. Buckets can be mounted on roadheader chassis, portals (gantries) and shields.
- TBMs without shields are of two types: Robbin's open-beam machines and Herrenknecht's single- or double-gripper machines, which are suitable for hard rocks. The Robbin open-face machines with a single or double shield can be used for geologies ranging from soils to rocks. A double-shield TBM is versatile: it can be used for heterogeneous rocks and can install tunnel linings when required.
- The rock fabric (texture) governs the performance of the TBM. Hard and abrasive rocks are the costliest to drill due to the higher costs of the cutting tools required, and in such situations use of the conventional drilling and blasting technique may be preferred.
- TBMs involve high capital outlays, and the conditions in which they may be deployed vary from one place to another. Therefore, most of these units, particularly the cutter heads, are custom made to achieve optimum cutter spacing and muck removal for the particular project.
- The rock-cutting mechanism of a TBM has a direct impact on its performance and efficiency. A prediction model can be developed based on rock types, geological and geomechanical parameters, and advice from the TBM manufacturer and experienced engineers. The model should take into account the schistosity and jointing of the rock. This information, together with punch penetration and/or fracture toughness tests, can be used to develop an assessment of anisotropy.
- Very soft rocks require very high torque and low thrust. A soft to medium hard rock needs very high thrust and medium torque. For hard rocks, high thrust and torque are required.
- Back-up systems should be short, simple to operate and simple to maintain. Removing muck from the tunnel is critical. Continuous conveyors can boost excavation rates significantly.
- Where a circular profile is not mandatory on account of ground stability, other shapes should be preferred.
- 'That can't be done!' This sentence is only true until the contrary is proved. For engineering achievements in particular, boundaries are a motivation, never a limit.
- The partnerships between clients, planners, construction companies and manufactures have resulted in developments in tunnelling technology to produce safe, reliable and very long-lasting tunnel structures, even in new and highly complex terrains. For example, mechanised tunnelling has been successfully undertaken for
  - large road tunnels deep beneath a strait
  - railway tunnels through enormously complex mountain ranges
  - water tunnels under tremendous ambient pressures.

5.12. Questions

1. 'It is the man behind the machine that matters.' Is this statement true? How can the quality of human resources be ensured?
2. List the types of ground encountered in nature.

3 Where do civil tunnels usually need to be driven in this modern era? Why is the use of blasting almost prohibited or considered unsuitable in these areas?

4 List the demerits of tunnels driven with the aid of explosives.

5 The limitations of tunnels driven with the aid of explosives have compelled engineers to investigate other techniques. List these techniques.

6 Draw line diagram to classify tunnelling methods. Where do the following find their application: special methods, cut and cover method, submerged method?

7 Illustrate how the geology governs the selection of a particular type of tunnelling method.

8 What is mechanised tunnelling? Give a brief history of this concept. Describe how development has occurred in and the current status of this technology.

9 List the types of partial-heading machine, and describe how each one of them functions.

10 List the types of full-face boring machines, and describe how they function. List the various forms of TBM and a give brief description of each one.

11 How does the rock fabric (texture) influence the performance of a TBM?

12 Give a classification of roadheaders based on their weight and power range. Give the range of the uniaxial compressive strength for each class.

13 What do you understand by the term ‘mechanised tunnelling’? How does it differ from conventional tunnelling where the tunnel is driven with the aid of explosives? List the limitations and demerits of tunnels driven with the aid of explosives.

14 Give a general classification of tunnelling techniques/methods based on the ground and rock conditions.

15 Draw a line diagram to illustrate how the operating range of a machine differs under different geological conditions.

16 Describe partial-face heading machines, giving a brief history of their development. List three sets of equipment that fall in this category, and describe each one.

17 Where do conventional drilling and blasting techniques prove to be advantageous over the use of TBMs?

18 Compared to a full-face TBM, a roadheader differs in several respects, list them.

19 Is there any difference between a partial-face machine roadheader and a continuous miner? Describe a continuous miner, and classify the types of this machine based on weight and power range. Mention the features that a modern roadheader is equipped with.

20 Based on the cutting principle, classify roadheaders and describe the features of each type. Is it possible to use these machines to create large-sized chambers or even large-sized tunnels? If so, how is it accomplished? Are roadheaders with interchangeable cutter heads available?

21 List the attachments available for the Alpine Multi-Tool Miner, and state what each one is used for. How are quick-change couplers useful for changing from one attachment to another?

22 The multi-tool miner is the Swiss army knife of construction equipment and it provides three machines for the price of one. Do you agree with this statement?

23 Describe how excavator-mounted cutter heads find application in scaling, use as a remote-controlled excavator, and shaft sinking.

24 Describe impact hammers, and note the type of rocks they can be used on.

25 Explain why excavator-mounted hammers are very effective for rapid excavation of benches in tunnels and caverns.

26 Describe the following, giving their uses: portal (gantry)-mounted hammers; hammer shaft sinkers.

27 Hammer tunnellers and hammer shaft sinkers have the potential to increase considerably the capacity of excavation of hard rock. List the applications of such units.

28 List the types of full-face boring machines. How do they differ from partial-face machines?

29 Describe a TBM, giving details of how it works. What shapes of tunnel can be bored using a TBM?

30 Give a brief historical review of hard-rock TBMs. List the companies that produce such machines and describe what they are aiming to achieve with regard to full-face tunnel boring technology.

31 Describe the main beam TBM produced by Robbins, and illustrate its working cycle. Why, in most cases, are the cutter heads custom-made? The manufacturer can supply this unit with numerous options: could you list them?

32 Looking at Table 5.2, what inference do you draw in terms of the range of diameters and the degree of thrust and power that these units require? What is the diameter range of the disk cutters? When and where was the Robbin double-shield TBM for small-diameter (2.2 m) drives in hard rock first made?

33 What particular features have been designed for the Robbin single-shield tunnelling machine? Do these machines have the same hard-rock specifications as the main-beam and double-shield machines?

34 Why is the Robbin double-shield TBM considered versatile? When a lining is to be installed, can the machine bore simultaneously? In which situation does this TBM operate as a single shield machine, using the lining to react to forward thrust?

35 Elaborate on the following features of the Robbin shielded TBMs: low-profile cutter, lining systems, probing/grouting, sealing systems, and digital guidance system.

36 Describe Herrenknecht's single- and double-gripper machines. How does the gripper system work? What parameters influence the tunnelling performance of a gripper TBM?

37 When undertaking a tunnelling project using a Herrenknecht machine, what sets of equipment are necessary to undertake rock-support installations? Differentiate between the single- and double-gripper machines.

38 List the performance indicators that influence the net progress per day of a TBM.

39 List the limitations of a partial-face machine (PFM) in terms of its ability to work in only some types of rock formation, unlike full-face TBMs which can work in all types of rock.

40 List the preparatory work required before the implementation of a full-face TBM. List the factors that make the use of such a machine economically

unfeasible for lengths less than 3 km. In addition, mention the limitations of a shaft-boring machine (see Chapter 9).

41 List the operational (machine-related), geological and geotechnical parameters that influence the advance rate of a TBM.

42 Removing muck from the tunnel is critical. How can continuous conveyors (such as the one supplied by Boretec) boost excavation rates significantly? List the advantages of this type of system.

43 Describe a single-track back-up system, including its utility in a tunnelling project. What is a mobile California switch and how can it help achieve better productivity?

44 Describe a double-track back-up system and the situations for which a machine of this type would be selected. What are limitations of this system?

45 In a tunnelling project, how would you make effective arrangements/provisions for the following: ventilation, electricity supply, water and compressed air supply, ground support, illumination, communication, and other equipment (not covered by the above)?

46 In hard rocks, why does the rock-cutting mechanism of a TBM have a direct impact on its performance and efficiency? How should the cutting tools be arranged and used to produce the largest sized cuttings?

47 Why is it necessary to develop a prediction model based on the rock types and geological and geomechanical parameters?

48 List the three components of a boring or excavation mechanism.

49 Why should the most relevant factors noted in a petrographic (thin sections) analysis be given due importance? List the factors of key importance when evaluating TBM performance and cutter wear.

50 Does rock anisotropy have a significant effect on TBM performance? Which test can provide a reliable indication of the degree and extent of rock anisotropy?

51 Give Lislerud's equation for the relationship between penetration rate and cutter thrust.

52 Give the equation used to determine cutter-head speed.

53 Draw up a table of the different types of cutting tools/bits or picks that are commonly used for various types of rock: very soft to soft, soft to hard, and very hard.

54 List the three distinct zones of a TBM cutting-head configuration. How much less effective area of utilisation does a circular opening have compared with a rectangular-shaped opening?

55 List the new developments in shield TBMs and briefly describe each one.

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Chapter 6
Shield tunnelling in soft ground

Production together with productivity, and safety together with good health, are two sides of the same coin.

6.1. Introduction

A shield, in the context of tunnelling, is a safety guard or cover for protecting workers, machines, equipment and utilities against ground collapse, water flooding, surrounding pressure or a mishap of any kind that could arise from any direction in the intended tunnel. The first application of such protection was in 1806, when Sir Marc Isambard Brunel invented a rectangular shield for use when driving a tunnel below the River Thames in London which was constructed over the period 1826–1842. Brunel's shield consisted of a number of cells in each of which one worker could work independently and be secure. The cells were firmly installed within the shield skin and, after excavation of a section (one length or round), the whole shield skin was pushed forward using hydraulic jacks.

Apart from Brunel's shield, which was rectangular, during the period 1826–1914 all the shields used tunnels driven at different locations (prominent among these being subway tunnels in London and New York, a road tunnel in Berlin, and railway tunnels in Orleans and Paris) were circular in shape (Maidl and Gipperich, 1996; Maidl *et al.*, 1996). The first use of compressed air was during the 1886–1890 driving of the City–South subway in London. Initially, tunnels were lined using bricks, while later cast-iron and concrete were used.

Today, the shield tunnelling method is very popular. For example, it was used during the construction of the Channel Tunnel. Each section was divided into four segments: English land-side, English sea-side, French land-side and French sea-side. The service tunnel was kept ahead of the main tunnels and forward probing was done to establish a better geological database and to treat/improve the ground in advance (Maidl *et al.*, 1996).

6.2. The function of the shield

All modern closed-shields operate on the same principle as the shield used by Marc Isambard Brunel. A modern shield is a metallic cylinder assembly that is pushed forward along the intended direction of the tunnel at the same time as the soil/ground is excavated (Kurihara *et al.*, 1995; Maidl and Gipperich, 1996). Thus it is a mobile safety device that is responsible for

- Digging the ground from the face safely while maintaining ground and water pressures within allowable limits (i.e. under control), and securing the void created until the final lining is installed.
- Minimising, or preferably avoiding, surface settlement. This means there must be minimum disturbance to the original ground conditions and water regimes.

6.3. Shield tunnelling – classification

Supports are also required for

- the tunnel face (forward end)
- the shield area (circumference and length of shield)
- behind the shield.

The supporting of the tunnel face (forward end) is the most important aspect when deciding on the type of shield to use in a tunnelling project. Figure 6.1 outlines the techniques that are currently used to control the groundwater and support the forward end of the tunnel.

The following paragraphs define and describe some of the terms used in Figure 6.1. The two main types of shield are open and closed; if the forward end is open and without any cover it is an open shield, but when it is covered or closed it is known as a closed shield. Open shields are employed in competent rocks or ground, and closed shields are used in unstable rocks or ground.

6.4. Open shield

This system is used in situations where there is no requirement to counteract earth and groundwater pressure at the face. Rather it is used at locales where the groundwater has already been lowered. Face support is achieved mechanically, meaning that either the

Figure 6.1 Shield tunnelling classification based on techniques used to control the groundwater and support the forward end of the tunnel

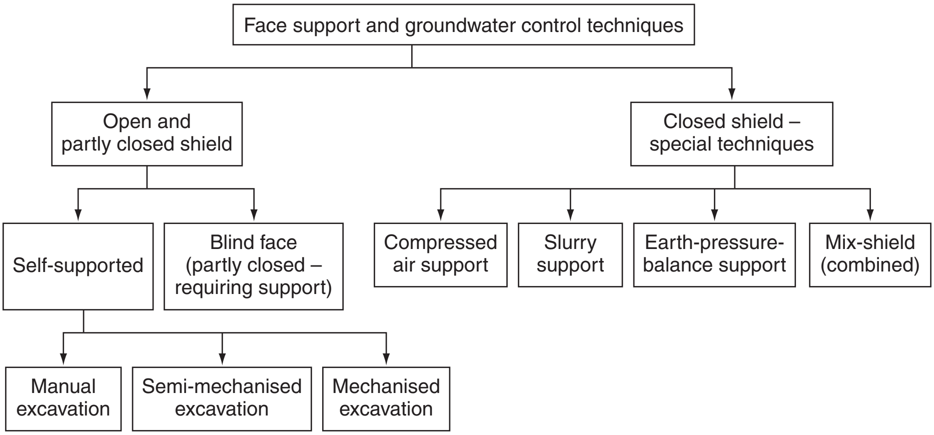
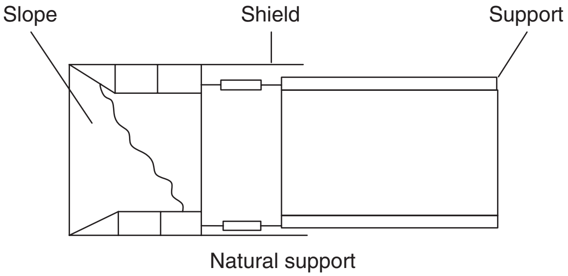


Figure 6.2 Conceptual diagram showing natural support at the face



groundwater must be lowered by the application of available techniques, or advance grouting at the face is essential. Different types of open shield are distinguished based on the ground excavation mechanism, which could be manual, partial-face excavation or full-face excavation. The shields may have cross-sections other than circular in shape – they can be rectangular or semi-circular also. Older versions of these shields are used in manual excavation, and such applications can still be found in countries where labour is cheap. In countries where labour is costly, manual excavation with open shields is not used. Manual excavation suffers too from the disadvantage of slow progress.

6.4.1 Self-supported – manual excavation

This is possible when the ground at the face is dry and stable (Maidl and Gipperich, 1996). When the ground is dug at the face it is piled up at its natural angle of repose. When using large-diameter shields, the face can be shelved into several compartments, enabling a larger volume of ground to be handled safely at any one time (Figure 6.2).

6.4.2 Blind face (partly closed, requiring support)

In this method the forward end of the tunnel (face) is divided into a number of segments. The face is supported using wooden members, and is dug manually from the top towards the bottom. The erection of the support is done simultaneously with the face digging. However, the method is slow and tedious. Sometimes the breast plates can be pushed hydraulically to the face.

6.4.3 Semi-mechanised and mechanised support

When full-face rotating disk cutters are used, the operation becomes fully mechanised (see Chapter 5). A mechanised shield (Figure 6.3) is equipped with an integrated unit that can excavate and load the ground beyond the shield and erect the lining. It also has a protective casing and jacks for the movement of the shield. In full-face cutting, the cutting wheel used for ground excavation also serves the purpose of face support, and prevents any collapse. If excavation is by the use of some cutting tools such as backhoes, roadheaders, etc., it is known as semi-mechanised or partial-face extraction (Figures 6.4 and 6.5).

Figure 6.3 Mechanical shield

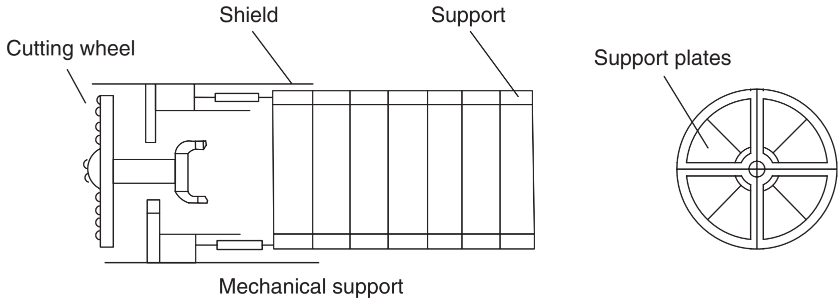
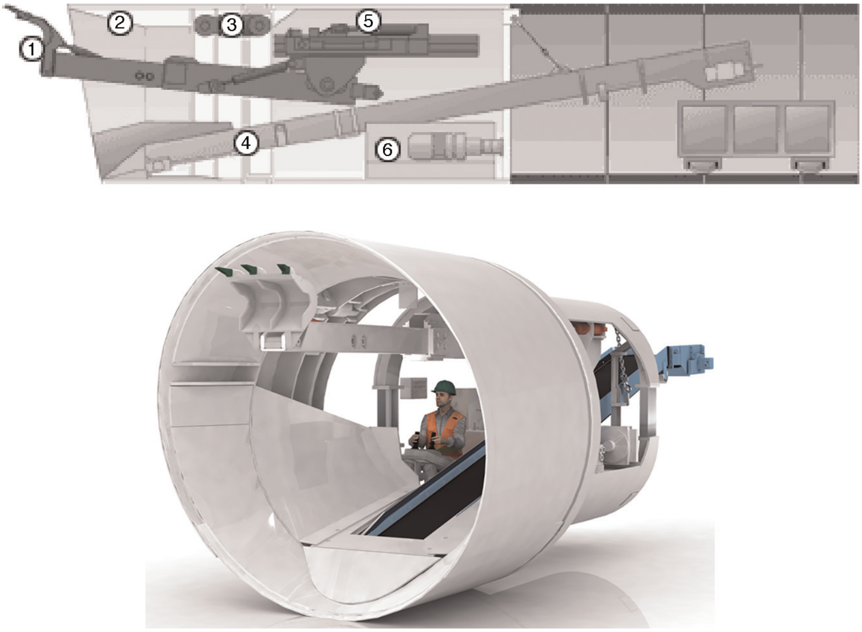


Figure 6.4 Shield with a partial-face excavator: 1, excavator; 2, shield; 3, steering cylinder; 4, conveyor belt; 5, machine pipe; 6, hydraulic power pack (courtesy of Herrenknecht AG)

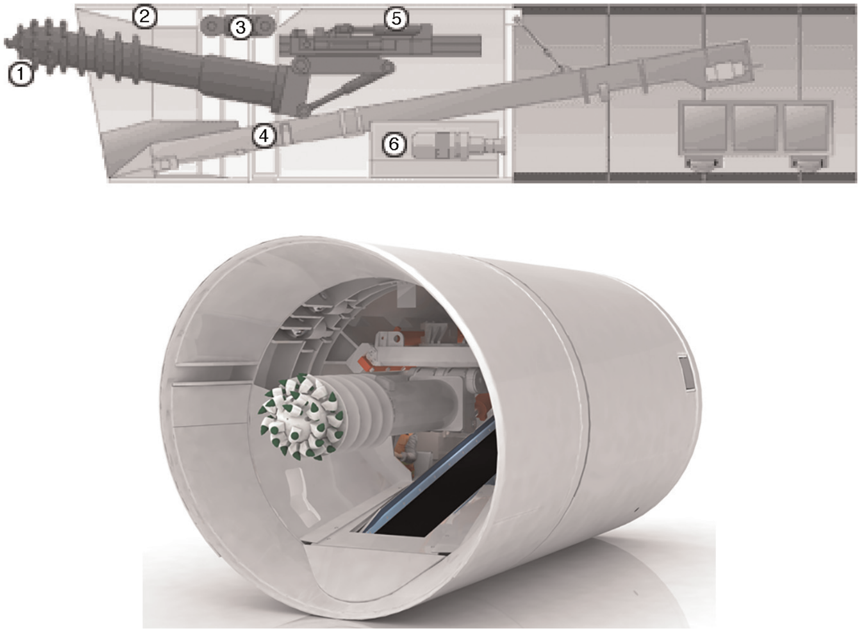


6.5. Partial-face extraction units

In these units, ground excavators, which can be shovels, bucket teeth or hydraulic hammers, are installed within the shield. These attachments are chosen based on the geological conditions. Advantages that these units provide include

- simplicity in operation and handling
- flexibility of choice in a variety of conditions
- simple installation
- lower capital and running costs than full-face tunnel-boring machines (TBMs) and units.

Figure 6.5 Partial-face shield with a roadheader: 1, roadheader; 2, shield; 3, steering cylinder; 4, conveyor belt; 5, machine pipe; 6, hydraulic power pack (courtesy of Herrenknecht AG)



Some machines offer the ability to rapidly change the extraction technique. An excavator, as well as a roadheader boom, can be installed on the same basic device. The exchange requires little effort and can be implemented at very short notice. Supports can be erected during tunnelling.

6.5.1 Partial-face shield with excavator

In loose soil, the use of an excavator (see Figure 6.4) is an established choice. Depending on the characteristics of the ground, the universal digger can be equipped with an excavation shovel, bucket tooth or hydraulic hammer. A rapid exchange of tools can be easily accomplished. The extracted material is removed by means of conveyor belts or scraper conveyors.

6.5.2 Partial-face shield with roadheader

With this technique, tunnels can be economically driven in rocks having an unconfined compressive strength up to 80 MPa. The extraction takes place via a longitudinal cutting head fitted with a round-shaft chisel. The extracted material is removed via the circulating conveyor spiral (see Figure 6.5).

6.5.3 Modular system

Herrenknecht AG, Germany, has developed a modular system that allows an interchange between these two options – roadheaders and backhoe excavators. Application of these units is usually confined to small diameters, but sometimes it is used for large

Table 6.1 Operational data for partial-face excavation machines (courtesy of Herrenknecht AG)

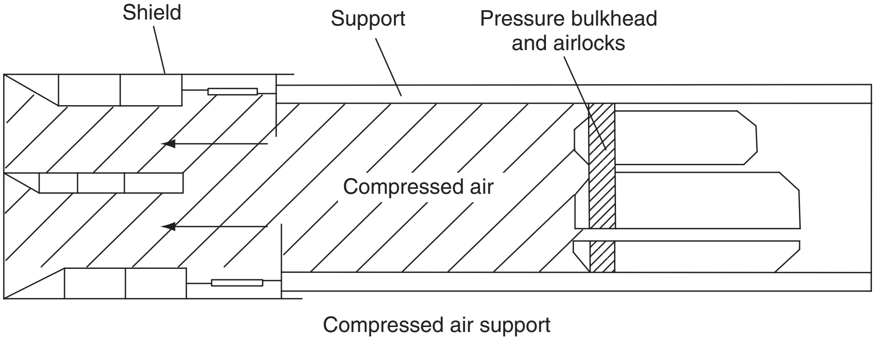
Geology, diameter range and technical details	Significant features
Geology: soft ground, heterogeneous ground, rocks (up to 80 MPa) *Diameter range*: 1.5–12 m *Excavation*: either a road header or an excavator is used to remove the soil *Tunnel face support*: mechanical support (e.g. extended forward shield at tunnel crown or transverse platforms) *Removal*: belt conveyor or chain conveyor removes the excavated material *Thrust*: hydraulic thrust cylinders in the shield or a jacking frame in the launching shaft push the machine forward *Tunnel support*: segmental lining or pipe jacking	■ Usable in all non-groundwater geologies ■ Various tools for various geologies are available ■ Easily and quickly convertible ■ Precise control of the excavation as the operator is just few metres away from the open tunnel face ■ Low operating costs ■ More than 500 units have been supplied worldwide

diameters up to 12 m. The operational data of partial-face excavation machines and their significant individual features are given in Table 6.1.

6.6. Compressed air shields

Holding water pressure under control pneumatically is a concept that was first used in 1886–1890 during the driving of the City–South subway in London. The method should not be used to counteract ground pressure, especially in porous ground (Makata, 1981). It works on the principle that water pressure at the working face increases linearly with its distance from the groundwater level above (in the presence of confined water such as that of artesian groundwater) (Figure 6.6).

Figure 6.6 Compressed air shield – conceptual diagram



In order to avoid water ingress, the compressed air pressure should be higher than or equal to the highest water pressure at the tunnel face. The water pressure is at its highest at the lowest point of the tunnel face (i.e. at the invert).

Thus, if the air pressure inside the tunnel is adjusted to be exactly the same as the water pressure at the invert, no water will enter into the void. However, in practice, the air pressure inside the tunnel remains the same at any point. This means that the air pressure at the crown area of the tunnel is higher than the water pressure, and this would cause air to be released in this area. Where there is little cover (overburden) there is a danger that, due to the phenomenon of flow, the soil particles lose their balance, and this could lead to a blow-out (Makata, 1981). However, this technique finds applications where (Maidl and Anheuser, 1996; Maidl and Gipperich, 1996; Makata, 1981)

- the soil types do not support lowering of the groundwater level due to technical, economical or ecological reasons
- lowering of the water level could cause severe subsidence of the overlying ground
- tunnelling is required to be positioned below a water body.

The technique suffers from the following limitations:

- Adverse working conditions limit the working hours for the crews. If the water pressure is above 4 bar the method may not be technically suitable as the relevant regulations in most countries do not allow compressed air pressure at the working face to exceed this limit.
- The minimum cover over the tunnel, equal to or double the tunnel diameter, is based on the ground type and the position and nature of water regimes (underneath a surface with a free groundwater level, underneath bodies of water with a secured bed, or underneath bodies of water without a secured bed) (Maidl *et al.*, 1996).
- High permeability of the ground could make this method impossible (e.g. in medium coarse or coarse gravel ground). Such ground would need to be treated by grouting, freezing or sealing, which would increase costs. Beyond a water coefficient of permeability $k = 10^{-4}$ m/s the air would displace the water in the pores and escape.
- The technique requires a launching shaft, through which a regular supply of compressed air must be ensured, failing which water would enter into the shield and tunnel. To make the working area airtight, a bulkhead with the provision of airlocks is constructed. Separate airlocks could be provided for workers and materials, or they could be combined. Modern designs allow the use of a movable bulkhead to reduce the volume of space under compressed air pressure, but in such cases the lining behind the bulkhead must be watertight. The airlocks can even be built within the shield, so that only the tunnel driving is undertaken in compressed air, while ring building is carried out under normal atmospheric pressure.
- The current regulations require the provision of a medical pressure chamber outside the working area for treatment of persons in the event of compressed air

disease, and also for testing workers under compression and decompression by a physician.

- Air consumption Q depends on the type of ground, which could be normal water-bearing ground or ground having a high permeability that requires more compressed air. The air consumption is given by Hewett's relationship: Q (m^3/min) $= 3.66d^2$ to $7.32d^2$, where d is the tunnel diameter (m) (Maidl *et al.*, 1996).

A combination of this technique with other relevant techniques has been considered, and has been used in some specific situations, as described in Section 6.10. Mitsubishi, Japan, has developed an excavation shield where only the excavation chamber is under pressure.

6.7. Slurry shield

This technique came to the fore after the 1960s when bentonite was introduced to act as what is known as 'active support'. The Japanese are known for their slurry shields. In this technique (Figures 6.7–6.9) (Maidl and Anheuser, 1996; Maidl and Gipperich, 1996; Maidl *et al.*, 1996), a suspension in water and either bentonite or clay of some other type is used to support the tunnel face. This suspension (having high pressure) is pumped into the closed excavation chamber in front of the tunnel face. When the pressurised slurry enters into the earth mass (ground) in front of the face, a cake is formed very quickly (within 1–2 s). This is known as a 'filter cake'. The water is retained behind this cake. The use of polymers in place of bentonite has also become commonplace. The cake is then excavated by tools in the excavation chamber and mixed with supporting fluid. This is how slurry, consisting of excavated ground and the supporting

Figure 6.7 Conceptual diagram of a slurry shield

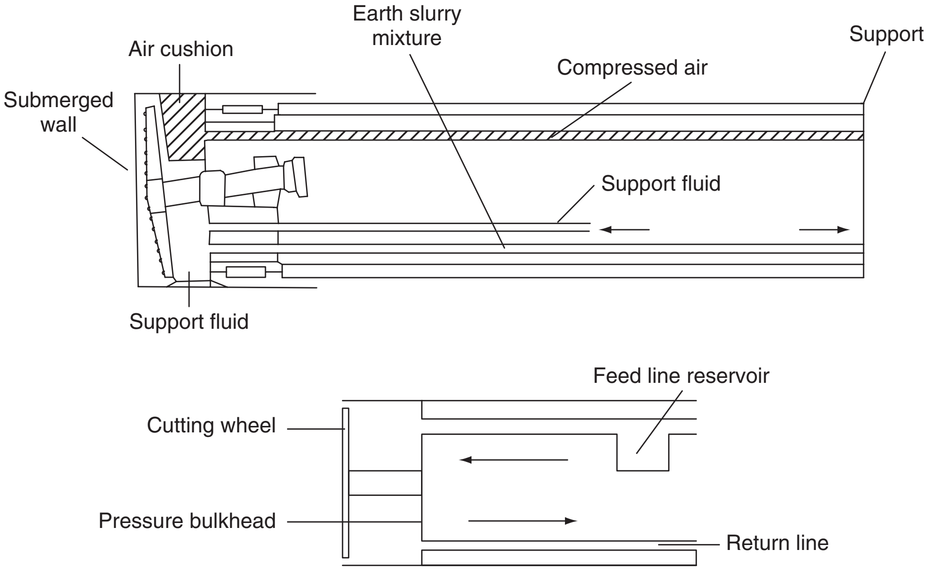
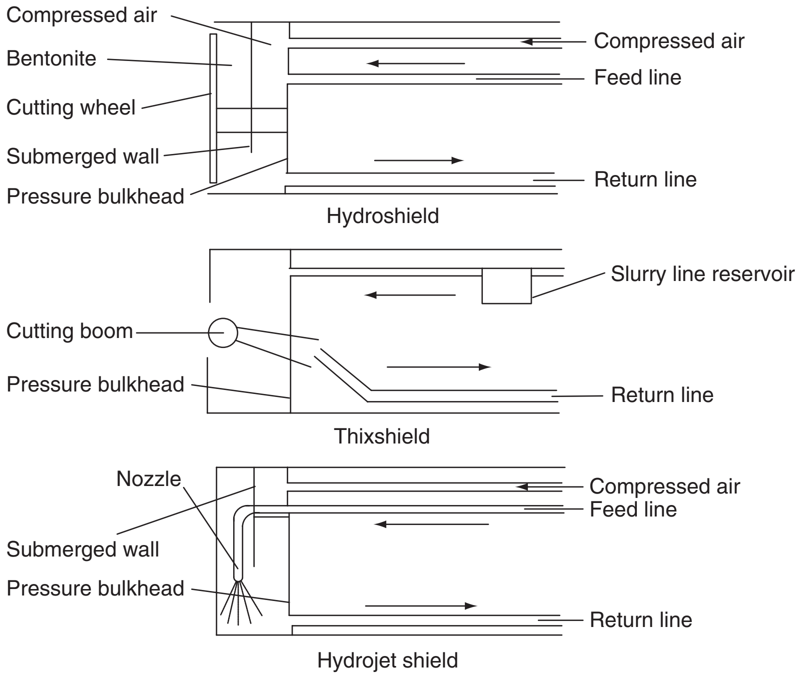


Figure 6.8 Slurry shields of different types



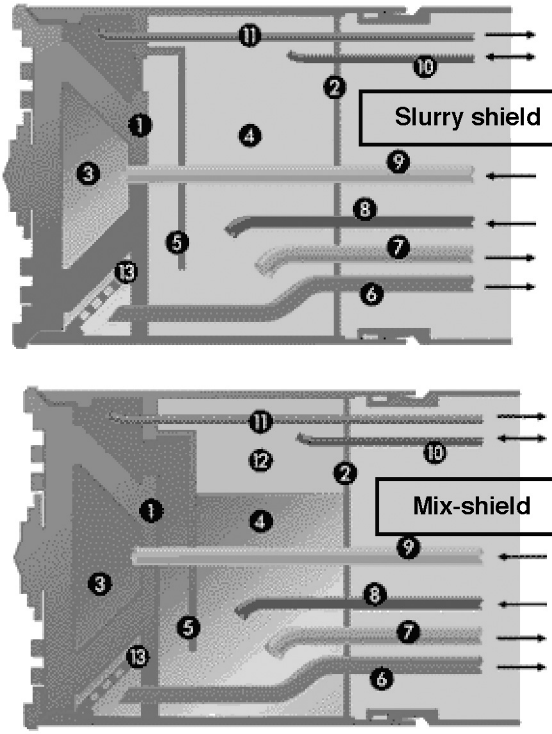
fluid, is formed. This slurry is transported to the surface through pipes and discharged into separation tanks. The fluid from these tanks is separated out for recirculation.

Disadvantages of the slurry shield include the difficulties and costs that are experienced at the separation plant. Permeability of the ground also plays an important role in this technique. Slurry shields are designed for sand or silt, and so the technique is more popular in coastal areas. It has, for example, found application in the coastal cities of Japan.

The cutting wheel of this shield is flat and closed. A few openings are provided for entry into the face to deal with obstacles but these openings are closed when the excavation cycle begins. The tools are usually teeth and knives that are arranged radially in rows. The head can rotate in either direction. Ground enters into the shield through slits that are arranged in a particular pattern. The aperture of the slits restricts the maximum solid size; the solids expected from the ground excavation should be compatible with the hydraulic transport. The supporting fluid enters into the upper part of the excavation chamber, and the spoil (suspension fluid and ground) is extracted in the lower part, where the mixing mechanism is situated.

In this system, the support pressure at the face is governed by the circulation of the slurry. Its quantity is regulated and monitored using sensors. The system is monitored

Figure 6.9 (a) Slurry shield and mix-shield – conceptual diagrams: 1, submerged wall; 2, pressure wall; 3, extraction chamber; 4, pressure chamber; 5, communicating pipes; 6, slurry conduction line; 7, pressure chamber conveyor pipe; 8, pressure chamber supply pipe; 9, extraction chamber supply pipe; 10, compressed air supply and outlet; 11, extraction chamber ventilation; 12, compressed air buffer; 13, suction screen. (b) Mix-shield TBM with its various components and their functions (courtesy of Herrenknecht AG)



(a)

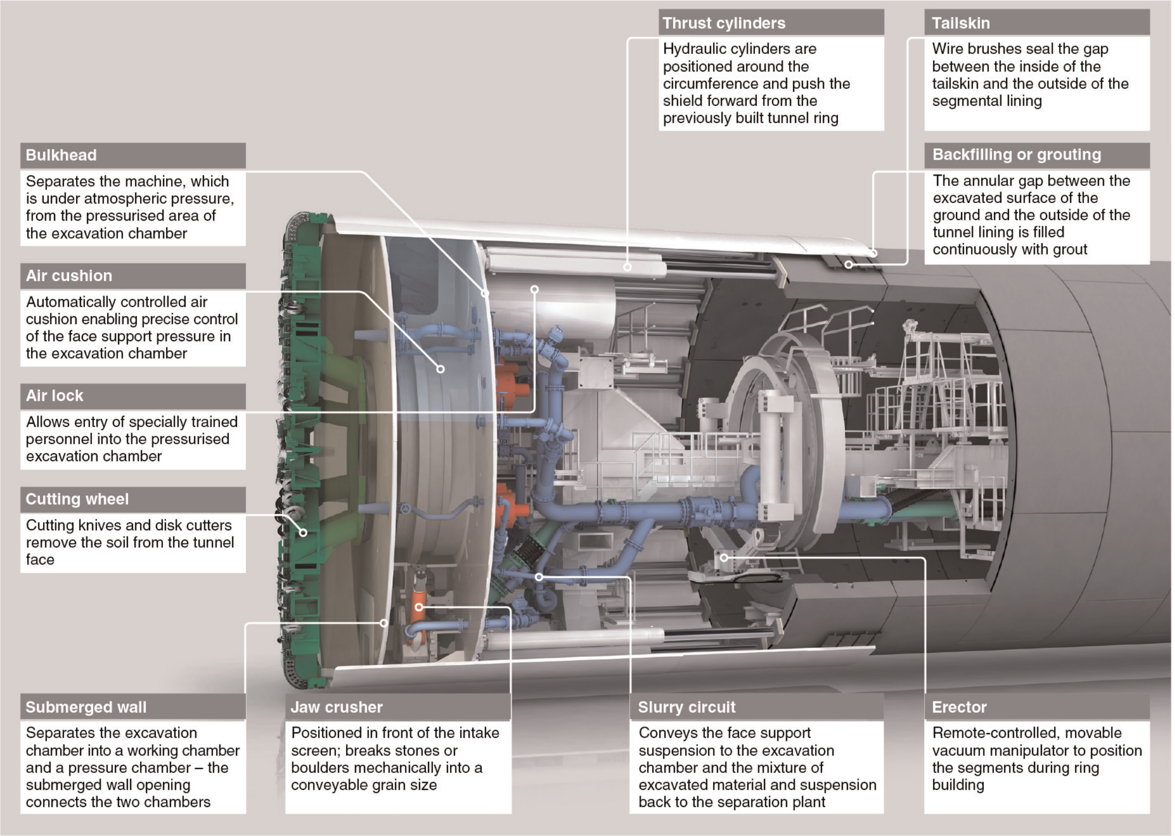
in the control room, which is located at the surface. Most of the operations are automated but operator intervention is needed in abnormal situations. Slurry shields can be classified according to the supporting fluid used (Table 6.2).

6.8. Slurry and mix shield

A slurry shield can be used if the geology of the ground is suitable (see the grading curves in Figure 6.15 later in this chapter). A modified design of a slurry shield, known as a mix shield, is available for use where there is some uncertainty about the type of ground that will be encountered (Kurihara *et al.*, 1995; Maidl and Anheuser, 1996). Table 6.3 gives the operational data and significant features of a slurry shield.

A solid section of the soil at the working face is loosened by the cutting wheel, which rotates in the bentonite suspension, and soil and other solid particles are mixed into the suspension. The shield area in which the cutting wheel is rotating is designated as the

Figure 6.9 Continued



(b)

Table 6.2 Classification of slurry shields according to the supporting fluid used (Maidl and Anheuser, 1996) (see Figure 6.8)

Slurry shield type	Support fluid	Remarks
Slurry shield	Clay suspension	Developed by Japanese companies and suited to Japanese conditions
Hydroshield – same as mix-shield	Water–bentonite suspension. Sometimes this is also called a bentonite shield	Used in all kinds of loose sands. Suited to European conditions. Developed by Wayss & Freytag, Germany
Thixshield – combination of slurry support and partial-face excavator. The excavator excavates the tunnel face. The cutter head can be positioned automatically or manually	Same as a hydroshield. The function of the cutter head is to retain solid particle sizes that cannot be transported in the slurry system	Geological range of applications are the same as for the hydroshield, but tunnelling through soft rocks/formations is possible. The cutter head retains solids that cannot be transported by the slurry system
Hydrojet shield – instead of mechanical excavation by means of a cutting wheel, the ground in the excavation chamber is excavated through a jet of fluid	Fluid jet, usually a water jet	German design. It is possible to enter the excavation chamber to remove material such as roots, foundations, stones, etc., that are detached from the ground

Table 6.3 Operational data for a mix shield TBM (courtesy of Herrenknecht AG)

Geology, diameter range and technical details	Significant features
Geology: heterogeneous ground (sand, gravel, high water permeability and high water pressure) *Diameter range*: 4.2–19 m *Excavation*: cutting knives and disk cutters remove the soil *Removal*: hydraulic conveyance of the excavated material through a closed slurry circuit *Thrust*: hydraulic thrust cylinders in the shield push the machine forward *Tunnel support*: segmental lining	■ Maximum tunnelling safety due to precise support of the tunnel face with automatically controlled air cushion ■ Can be used where there is high water pressure (>15 bar) ■ Large diameters (up to 19 m) possible

extraction chamber (3 in Figure 6.9) and is separated from the shield section, which is under atmospheric pressure, by the pressure wall (2). The bentonite suspension fed in by the supply pipe (9) is admitted to the extraction chamber via an air bubble (communicating pipe, 5) at a pressure equal to that of the earth and water that lies ahead, which thereby prevents uncontrolled penetration of the soil and loss of stability at the working face.

Control of the supporting pressure in the extraction chamber does not take place directly via the suspension pressure or the pressure in the supply pipe, but rather via an air cushion. It is for this reason that the extraction chamber behind the cutting wheel is separated from the pressure wall by a so-called ‘submerged wall’ (1). The area where the submerged and pressure walls are located is designated the ‘pressure chamber’ (4).

Whereas the front, earth-side area of the machine is completely filled with suspension, behind the submerged wall the suspension only reaches to just below the machine axle, and it is held at the exact desired pressure by the compressed air cushion, which is precisely controlled by a compressed air regulator (10). This enables better adjustment in response to fluctuations in the bentonite circuit.

The soil that has been loosened and mixed with the suspension is pumped via the conveyor pipe (7) to the separator outside the tunnel. In order to prevent blockages of the conveyor pipe and ensure that the discharge pumps can work without disruption, a screen (13) located in front of the suction nozzles prevents stones and lumps of earth from entering the suction pipe (6).

Outside the tunnel, the liquid and solid parts of the bentonite–soil mix have to be separated in order to efficiently transport the extracted material away from the construction site for disposal, and to process as much of the bentonite suspension as possible for return to the slurry circuit. The separator consists of vibration sieves for filtering out the gravelly grain classes and hydrocyclones which, depending on the cost and capacity requirements, have separating capacities that can extend down to silt grain classes. The liquid phase of the overflow from the stage 1 hydrocyclone is fed from the interim container to the stage 2 hydrocyclone and finally lands in the collecting tank where it is enriched with fresh suspension from the suspension mixer. Before it can be transported to the depot, water has to be removed from material that has passed through both of the hydrocyclones.

The tunnel is usually lined with steel-reinforced concrete lining segments, which are positioned and fastened by the erector in the shield area behind the pressure wall under atmospheric pressure conditions. The remaining fissure between the outside of the lining segment and the diameter of the excavation cavity is continuously injected with mortar via the injection openings in the tailskin.

Mix shields can be used for geological conditions where an unstable working face or mixed geology is expected. In this mode of operation (see Figure 5.9) the extraction chamber (3) is completely filled with suspension while the pressure chamber behind the submerged wall supports the suspension with a compressed air buffer (12). In order to prevent blow-outs or ground seepage at the working face, an adjustable compressed air regulator automatically monitors the air pressure. The communicating pipes (5) ensure pressure compensation between the extraction chamber and the suspension in the pressure chamber (4) behind the submerged wall (1). The suspension is fed via the supply pipe (9) directly into the extraction chamber (3), and is removed via the slurry conduit (6) directly out of the extraction chamber behind the suction screen (13). The build-up of sediment below the communicating pipes is prevented by periodic flushing over the feed pipe pressure chamber and the conveyor pipe pressure chamber.

If geological conditions are such that a stable working face is expected (e.g. in hard rock or cohesive soil) the machine can be effectively used as a slurry shield without compressed air support, similar to the Herrenknecht micro-tunnelling system (AVN) machines (see Chapter 8). The conversion from mix shield to slurry shield (see Figure 6.9) is carried out by closing the compressed air supply (10) and outlet lines, the extraction chamber ventilation (11), the pressure chamber conveyor pipe (7), the pressure chamber supply pipe (8) and the communicating pipes (5). All these changes can be carried out in the tunnel itself. Due to the closing of the communicating pipes (5), after the modification only the pressure chamber (4) is subject to atmospheric pressure. The suspension circuit alone (i.e. the intake and output of the pumps) then regulates the working face support.

6.9. Earth-pressure-balance (EPB) shield

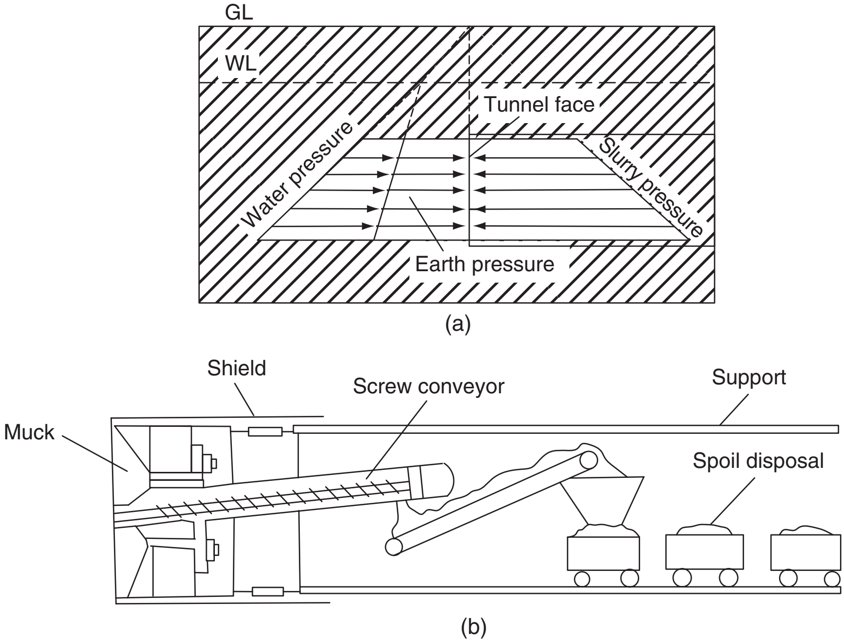
This technique is applicable in soils that are not stable (Kurihara *et al.*, 1995; Maidl, 1996; Maidl and Anheuser, 1996). Creating a supporting pressure prevents loss of stability at the working face. With the earth-pressure shield (Figures 6.10 and 6.11), in contrast to the other shields which rely on a secondary support medium, the soil loosened by the cutting wheel serves to support the working face. The shield area in which the cutting wheel rotates is designated as the extraction chamber and is separated from the shield section, which is under atmospheric pressure, by the pressure wall.

The soil is loosened by the tools of the cutting wheel, drops through the openings in the cutting wheel into the extraction chamber, and mixes with the plastic pulpy soil that is already there. Transferring the power of the tunnelling jacks from the pressure wall to the pulpy soil prevents uncontrolled penetration of the soil from the working face into the extraction chamber. At the point when the pulpy soil mixture is in the extraction chamber, the pressure of the earth and water, which lies ahead, causes a state of equilibrium to be reached, and the jacks no longer compress the chamber.

The material (spoil or muck) that has been extracted is removed from the extraction chamber by a screw conveyor. The amount of material conveyed is regulated by the revolutions of the screw and the diameter of the opening of the upper screw valve.

The screw conveyor transfers the extracted material to the first conveyor belt of the conveyor-belt cascade. Extracted material reaches the so-called ‘reversing belt’ via these belts. The transport cars for the extracted material in the back-up system in the reversing operation are loaded via this belt.

Figure 6.10 Conceptual diagrams for EPB shields: (a) method to counter water and earth pressures; (b) mechanical components and arrangements in the EPB concept. GL, surface ground line; WL, groundwater level



If the TBM is operated open (open mode), the screw for transporting the extracted material is bypassed and the extracted material is transported to the machine belts by the cutting wheel. To enable the extracted material to be offloaded to the machine belt, the muck ring, located in the pressure wall, has to be retracted.

The tunnel is usually lined with steel-reinforced concrete lining segments, which are positioned and fastened by the erector in the shield area behind the pressure wall under atmospheric pressure conditions. The remaining fissure between the outside of the lining segment and the diameter of the excavation cavity is continuously injected with mortar via the injection openings in the tailskin.

The slurry system suffers from problems of separating excavated material from the suspension fluid, in terms of the space required for its discharge and the costs involved (Maidl, 1996; Maidl and Anheuser, 1996). Also, the process is not very environment friendly. Thus the concept of EPB is an improvement over slurry shielding. This system has the following features:

- It can be used in ground with a high percentage of silt/clay.
- No separation plant is needed.
- With little cover, there is no danger of blow-outs through pulpy support slurry.

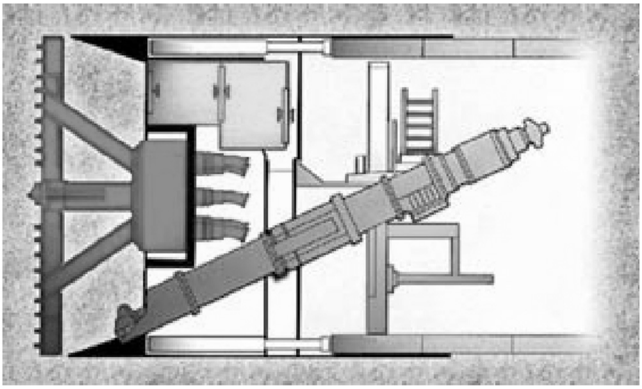
- Mechanical excavation ensures better performance and accessing the tunnel face (under pneumatic air pressure) is possible (this sometimes needs to be done to remove obstacles).
- It does not require secondary support in the form of compressed air, suspension media or breast plates. Rather, the material is cut mechanically by the cutting wheel, and serves as a support medium.
- The material that is yielded by the rotating cutting head is not allowed to fall into the excavation chamber but is diverted to mix with the plastic earth slurry.

This technique can give satisfactory results if the material to be excavated possesses some of the following features (Maidl, 1996): good plastic deformation; pulpy to soft consistency; low inner friction; and low permeability. Usually, in practice, not all these requirements are met by the ground to be excavated, and this, in turn, means ground conditioning. For conditioning purposes, the addition of water, suspension material (bentonite, clay or polymer) and mud becomes essential so that the ground becomes 'earthy slurry', which stabilises the tunnel face. The earth slurry has to be pressurised to counteract the incoming forces at the tunnel face. Material is removed from the excavation chamber by a screw conveyor. The material taken out from this chamber is removed in a controlled manner to avoid reduction of earth pressure in the excavation chamber, and thus settlement. Transport through the tunnel can be undertaken by deploying units such as belt conveyors, track-bound haulage or trackless trucks. Table 6.4 gives operational data and the significant features of an EPB TBM.

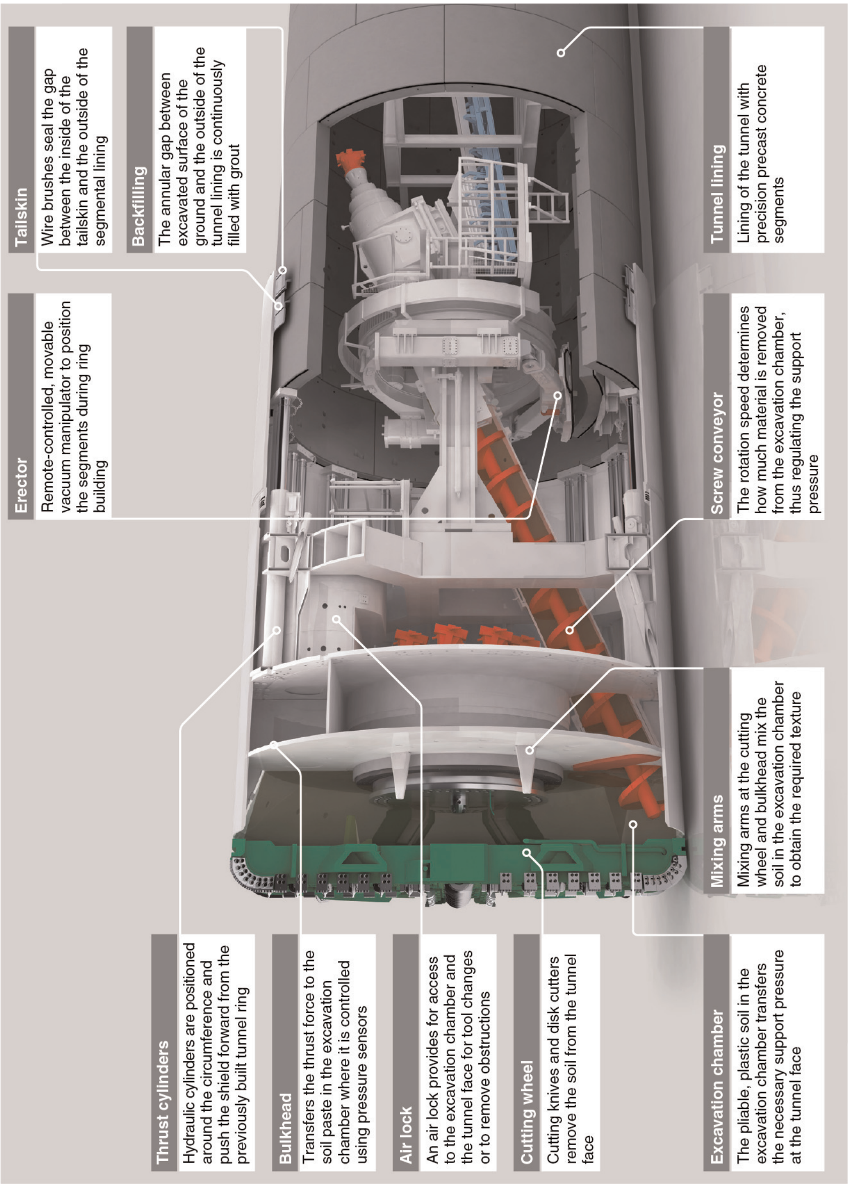
6.10. Combined shield

Encountering variable ground conditions in any tunnelling project is a common occurrence, and this has compelled both contractors and manufacturers to consider

Figure 6.11 (a) Conceptual diagram of an EPB TBM. This is a shield machine with an earth-pressure-balance working face. The soil extraction takes place via the cutting wheel. The tunnel is supported with lining segments (moulded segments of steel-reinforced concrete). (b) EPB TBM with its various components and their functions (courtesy of Herrenknecht AG)



(a)



Thrust cylinders
Hydraulic cylinders are positioned around the circumference and push the shield forward from the previously built tunnel ring

Bulkhead
Transfers the thrust force to the soil paste in the excavation chamber where it is controlled using pressure sensors

Air lock
An air lock provides for access to the excavation chamber and the tunnel face for tool changes or to remove obstructions

Cutting wheel
Cutting knives and disk cutters remove the soil from the tunnel face

Excavation chamber
The pliable, plastic soil in the excavation chamber transfers the necessary support pressure at the tunnel face

Mixing arms
Mixing arms at the cutting wheel and bulkhead mix the soil in the excavation chamber to obtain the required texture

Screw conveyor
The rotation speed determines how much material is removed from the excavation chamber, thus regulating the support pressure

Tunnel lining
Lining of the tunnel with precision precast concrete segments

Erector
Remote-controlled, movable vacuum manipulator to position the segments during ring building

Tailskin
Wire brushes seal the gap between the inside of the tailskin and the outside of the segmental lining

Backfilling
The annular gap between excavated surface of the ground and the outside of the tunnel lining is continuously filled with grout

(b)

Figure 6.11 Continued

Table 6.4 Operational data for an EPB TBM (courtesy of Herrenknecht AG)

Geology, diameter range and technical details	Significant features
Geology: soft ground (clay, silt, loam, low water permeability) *Diameter range*: 1.7–16 m *Excavation*: cutting knives and disk cutters remove the soil *Tunnel face support*: pliable, plastic soil produces active support pressure in the excavation chamber *Removal*: a screw conveyor transports the excavated material to the logistics system at the back *Thrust*: hydraulic thrust cylinders in the shield or jacking frame in the launch shaft push the machine forward *Tunnel lining*: segmental lining or pipe jack	■ High advance rates possible in cohesive soils having a high clay or silt content ■ Geological range of application can be enhanced by soil conditioning ■ No additional support medium required ■ Can be used in heterogeneous soil conditions ■ 750 m of metro tunnels have been completed by Herrenknecht AG using this unit

'combined shields'. Maidl *et al*. (1996) have come up with possible combinations, which include:

1 compressed air and open-faced shield
2 open-faced and slurry shield
3 open-faced shield and EPB
4 slurry and EPB
5 open-faced shield, EPB and slurry shield.

Combinations 1–3, have been tried. Combination 3 was tried at the Channel Tunnel (UK–France). It is worth mentioning that EPB and slurry shields have compressed air support systems. Compressed air support is needed when going into the excavation chamber for the purpose of undertaking repairs, or to deal with any problem at the working face, such as a breakdown, encountering obstacles, etc. Various combinations have been possible due to advancements made in methods, techniques and equipment, and through their consistent review, additions and innovations. This includes advances made in information technology, logistics, surveying, automation, electronics, etc.

6.11. Excavation tools

During shield tunnelling, only the front face can be accessed to deploy cutting tools. A number of tools are available (Kurihara *et al*., 1995; Maidl *et al*., 1996). Their classification is given below:

- Manual tools – in conjunction with shield tunnelling, manual tools are used when special ground conditions are encountered for a short distance and where mechanical excavation is not suitable for the ground encountered. For example, pneumatic hammer drills and excavators find applications in firm ground where there are obstacles at the tunnel face. The common tools are hoe, spade and pneumatic pointed chisel.

- Cutting edges – these are put at the circumference of the shield, and are suitable for homogeneous ground without boulders.
- Cutting knives and teeth – these are put together at the cutting head to loosen firm soil.
- Cutter bits – these are the picks fitted on the spoke of the cutting wheel.
- Rippers – these are placed normal to the tunnel face.
- Cutting disks – these are hard-rock tools.

6.12. Excavation procedure

- Without cutting tools – very homogeneous loose soil with low shear strength can be squeezed through the jacking force.
- Manually – this technique still finds applications in countries where labour is cheap. However, even in developed and developing countries, mechanical excavation is often not feasible, and this technique needs to be applied.
- Partial-face excavators – these excavators move in both the transverse and the longitudinal direction within the shield into which they are fitted or deployed.
- Bucket and teeth – these are employed mainly in cohesive soil, and rotating excavation tools with cutter bits are used in massive cemented ground. When these tools are mounted on a boom, the resultant piece of special equipment becomes known as a roadheader.
- Special rock-cutting machines – the mobile miner produced by Robbins and the continuous miner produced by the Wirth company fall in this category.
- Full-face mechanical excavation – this is an important innovation that has many merits (see Chapter 5 for a full description). Prominent features of the system are that
  - it produces a stable circular-shaped tunnel without overbreak
  - it is claimed that the technique produces a higher advance rate
  - it requires high investment and effective utilisation and availability for a successful operation
  - homogeneous ground is favoured; heterogeneous ground leads to problems and adverse results
  - the technique is considered as non-cyclical, as face cutting, muck removal and face support are achieved simultaneously
  - the cutting wheel is the most important part of the unit – it is equipped with cutting tools of the type warranted by the ground conditions.

6.13. Excavation and transportation techniques

Techniques for mucking/excavating the material and its transport through the shield are summarised in Figure 6.12.

6.14. Supports/linings

An important aspect during shield tunnelling is the support network behind the shield (Anheuser and Braach, 1996). The linings that can be used are classified in Figure 6.13.

Figure 6.12 Classification of excavation and transportation techniques

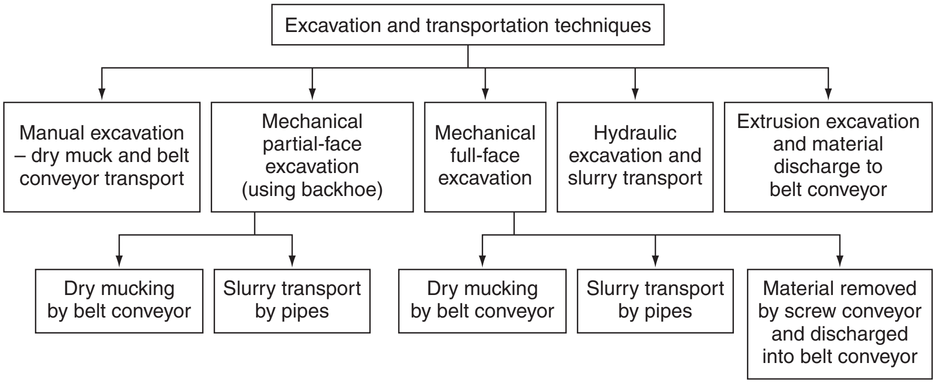
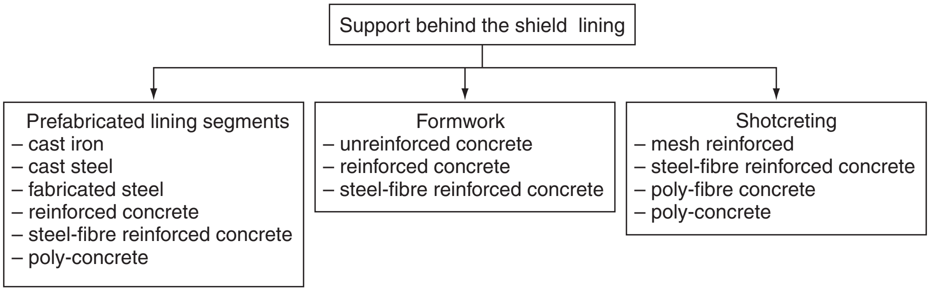


Figure 6.13 Classification of linings



6.15. Health, safety and environment (HSE)

Some of the salient points that should be given due importance during mechanised tunnelling operations are listed below (Kurihara *et al.*, 1995; Maidl and Gipperich, 1996; Maidl *et al.*, 1996):

- In mechanised tunnelling, ergonomics and safe working conditions must be given priority.
- In a TBM system, access to the cutter head is only possible when the machine is at a standstill. However, care must be taken that safe access to the working face can be made by the operating crew, as and when the need arises, for the purpose of inspection, maintenance or operation. A device is provided so that the cutter head can be prevented from unintentional movement.
- Provision must be made for safe handling, fitting and replacement of heavy parts and consumables, such as cutter heads, etc., for TBMs.
- All TBMs must be fitted with protective devices to cut off the power of the motors in the event of abnormal occurrences that are beyond the functional capabilities of equipment/units.

- Handling, fitting and erection devices are an integral part of the back-up system for heavy ground supports at or behind the face. This includes supporting sets and/or their segments.
- Provision of a fire-extinguishing system at the unit and an effective escape mechanism for the crew in the event of fire must be given due consideration. This equipment must be constructed of materials that will not produce toxic fumes in the event of fire.
- Fire-fighting equipment, which could be powder, gas or foam type (automatic or manually operated), should be fitted throughout the entire tunnelling machine. Hydraulic and electrical systems are the areas most vulnerable to fire.
- Effective ventilation means provision for fresh air circulation, dust suppression and/or collection, and withdrawal of personnel in the event of encountering, or a sudden inrush of, flammable gases such as methane beyond the permissible limits. These are aspects that must be looked into.
- A laser guidance system is an integral fitting in modern TBMs; care should be taken that the laser window is fitted in such a way that exposure of the eyes to the laser beam is kept to a minimum.
- Efficient management will give due importance to an efficient communication system, protection against noise, dusts and hazards from compressed air and air contaminants, and accident and incident analysis.
- The safety features listed here are either as laid out in the standard practices set by the governing agencies/bodies of the country of operation (e.g. as detailed in Section 10.5.2), or as prescribed by some specialised agencies or committees.
- Emergency plans or ‘standing orders’ must be formulated and brought into operation in the event of fire, a sudden inrush of flammable gases, abnormal type of water, or a fall or collapse of the ground.

6.16. Selection of the shield

In shield tunnelling, the factors that should be given due consideration according to the recommendations of the Deutscher Ausschuss für Unterirdisches Bauen (DAUB, the German Tunnelling Committee) are listed below:

- Excavation – ground firmness, abrasiveness, geological structure, hardness, grain structure, planes of weakness, presence of boulders (size and quantity).
- Face support – permeability, rock quality designation, shear strength, plasticity and water content.
- Separation – investigation regarding fines generated from mechanical strain, grain structure and natural water content.
- Input from the contractors, process technicians and working engineers results in a practical solution for a given shield tunnelling project.
- Most manufacturers give due importance to hydrogeological conditions when designing their products.

The geological and hydraulic information about the ground is the foundation on which planning for shield tunnelling is based (see Figure 5.2). Important parameters that are looked into are

- water permeability (Figure 6.14)
- grading curve (Figure 6.15)
- consistency limits
- rock/clay mineralogy
- ground quality
- rock strength.

6.16.1 Other parameters

Model parameters:
- ground/formation, soils – types, thickness, structural features
- geological and mineralogical characteristics
- geomechanical conditions – strength, permeability
- hydrological conditions and position of groundwater level.

Design parameters:
- size and shape of tunnel/shield
- methods/technique
- equipment to be deployed
- support types
- size of tail void.

Likely induced conditions:
- disturbance to ground
- disturbance to water regime
- impact of compressed air, slurries injection, digging mechanism, etc.
- time gap and measures to provide supports (primary and secondary), backfilling the tail void.

Measures to guard against:
- collapse, ground lowering/subsidence, water regime lowering, over-excavation, support deformation and failures, water seepage, and accidents of any kind during the construction phase.

6.17. Ground settlement/displacement

When excavating the ground, a ‘subsidence trough’ is formed between the immediate roof of the excavation and the surface ground line. The extent of the damage is a function of the tunnel dimensions, the geomechanical and structural features of the overlying strata, the type of lining and its backfill, the time gap between the excavation and establishing permanent support, water-lowering measures required (if any), and a few other factors. By referring to the relevant literature, ground settlement can be forecast with some degree of accuracy (Makata, 1981; Nomoto *et al.*, 1995; Yamada *et al.*, 1986). This forecast should be made at the planning and design phase so that necessary steps can be taken during the construction phase. In 1981, Makata described ground displacement over five zones, as shown in Figure 6.16, and detailed in Table 6.5.

Figure 6.14 Ground permeability: grading by size distribution, and application of slurry and EPB concepts to keep out groundwater and support the ground at the tunnelling face (courtesy of Herrenknecht AG)

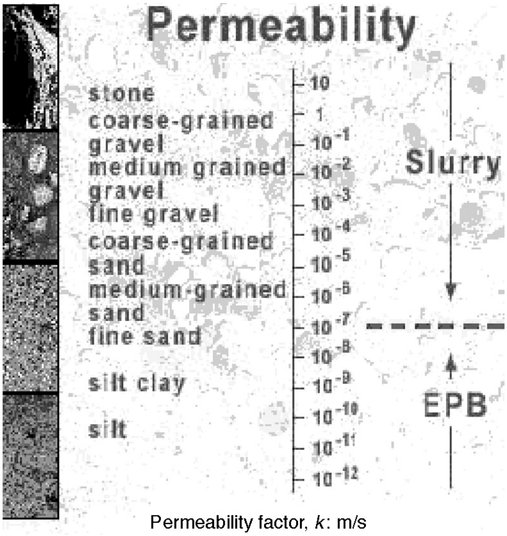
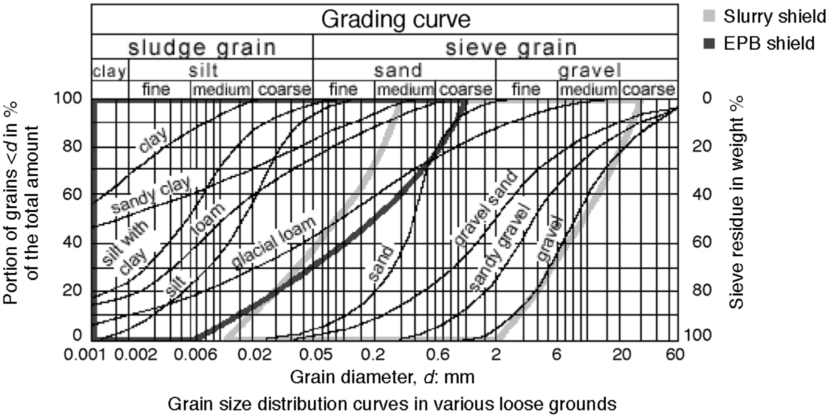


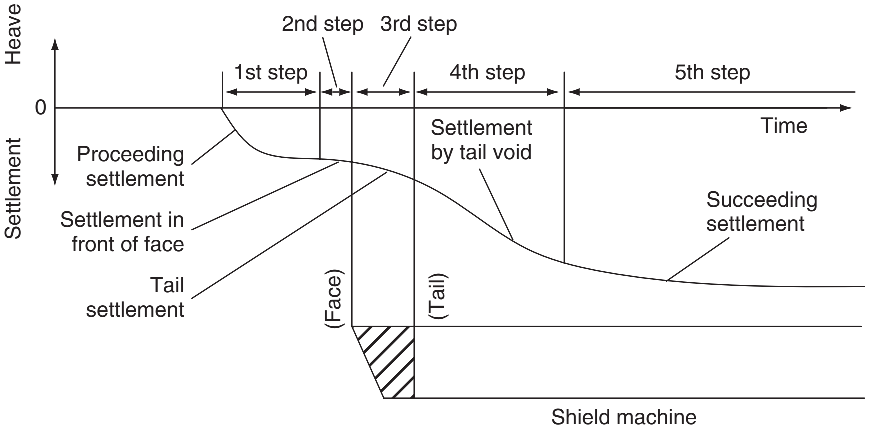
Figure 6.15 Grading curves to identify the application of slurry or EPB shield units. Note the common zone where both shields could be applicable (courtesy of Herrenknecht AG)



6.18. Unique technologies for very demanding underground missions/situations

As described in Section 5.4, in mechanised tunnelling there are basically three different shield types: open-face shields, earth-pressure-balance shields and slurry shields. Each of these proven methods has advantages in its special range of applications, and

Figure 6.16 Ground subsidence caused by shield tunnelling

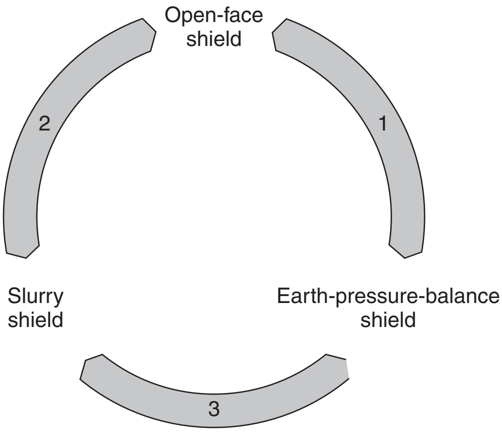


technological advances over the years have enabled their use in ground of a wider geological range. The aim is to use the optimum machine technology for the given geology, thus increasing project efficiency. Many tunnel alignments lead through highly changeable ground conditions where classical methods reach their technical or economic limits. As described in Section 5.4.1.4 Robbins has introduced ‘crossover TBMs’ for these special cases, and Herrenknecht has developed multi-mode TBMs. The basic concept makes it possible to change between slurry support, earth-pressure support and open

Table 6.5 Causes and mechanism of ground displacement

Type of settlement	Causes	Change in ground conditions	Type of settlement
Proceeding settlement (ahead of face)	Lowering of groundwater level	Increase in effective earth cover pressure	Compression, consolidation, settlement
Settlement in front of face	Collapse of face, excessive digging, push-in at the face	Release or disturbance of ground stress	Elastic and plastic deformation
Tail settlement	Agitation at time of pushing of shield tunnelling machine	Disturbance	Compaction
Settlement by tail void	Occurrence of tail void	Release of ground stress	Elastic and plastic deformation
Secondary settlement	All the above causes (residual portions)	–	Compression and creep settlement

Figure 6.17 Options for various combinations of TBMs (courtesy of Herrenknecht AG)



mode (Figure 6.17) within one tunnel alignment, by undertaking a range of conversions. In general, two design variants are possible.

- Multi-mode TBM with a modular basic structure – the tunnelling method is changed in the tunnel by extensive modifications to individual components.
- Multi-mode TBM with components allowing for several tunnelling methods, which are all integrated into the machine – the tunnelling mode can be changed in a relatively shorter time and at relatively lower cost. However, these machines have a considerably more complex technical design.

6.18.1 Combination of EPB and open-face TBM

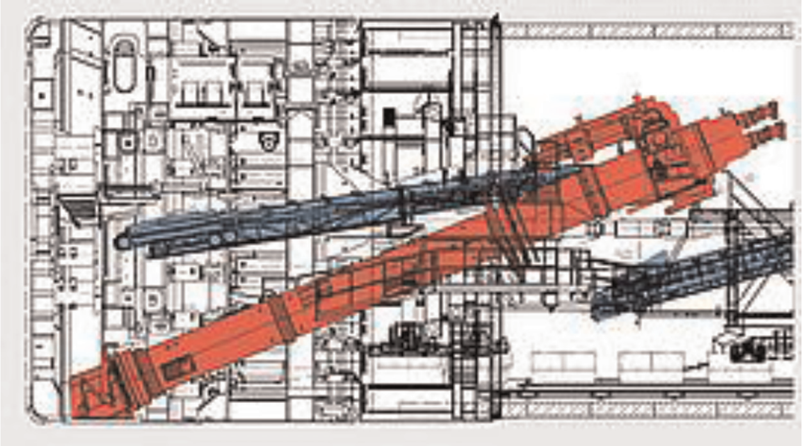
EPB shields with a screw conveyor (Figure 6.18) in the invert section can be driven in both the conventional closed EPB mode and the open mode. In the open mode the excavation chamber and screw are partly filled. No active support pressure against the tunnel face can be built up, and the screw conveyor is used only for removing the excavated material.

Alternatively, a belt conveyor with a retractable muck ring can be installed in the centre. This requires additional conversion measures at the cutter head, and the screw conveyor is partly retracted in the open tunnelling mode. The combination of an EPB shield and an open-face TBM can be designed with a modular basic structure and as a version with a parallel screw and a central belt conveyor.

6.18.2 Combination of open-face and slurry TBM

Multi-mode TBMs capable of both open-faced and slurry-supported modes of operation have been used successfully in many projects (Box 6.1). The greatest challenge when changing the tunnelling mode is to deal with the different ways of removing the excavated material. While the slurry-supported shield has a slurry circuit installed, in the open mode the material is removed using a central belt conveyor with a retractable muck

Figure 6.18 Multi-mode TBM with a screw conveyor and machine belt to change flexibly between closed EPB and open-mode operation (courtesy of Herrenknecht AG)



ring. This means that both conveying systems must be installed on the TBM and the back-up system. Modular and integrated concept machine solutions are available.

6.18.3 Combination of EPB and slurry TBM

Both modes of this combination use a closed pressure system to actively support the tunnel face. The main differences between the modes lie in the composition and characteristics of the support medium, the means of conveying of the excavated material and the excavation chamber design. For large machine diameters (>9 m), parallel installation of a screw conveyor and a slurry circuit in the invert section of the excavation chamber is possible. This configuration is not possible in smaller-diameter machines, which means that changing the tunnelling mode requires time and thus incurs costs. This is particularly true if an additional stone crusher is needed in front of the slurry circuit intake screen. Therefore, the EPB and slurry shield combination is used only if specific project conditions justify the great effort and cost (see Box 6.1).

Box 6.1 Some selected applications of combined mode machines

EPB and slurry
- Socatop Tunnel, France

Slurry and open mode
- Hallandsås Tunnel, Sweden
- Lake Mead, USA

EPB and open mode
- Finne Tunnel, Germany
- Katzenberg Tunnel, Germany
- Tunnel de Sayeme, France

Case study 6.1

Multi-mode (slurry and open mode) TBM – Lake Mead, Nevada, USA

On 10 December 2014, the Herrenknecht TBM S-502 (diameter 7.2 m) reached its target after 3 years on the lake bed. Starting from a 180 m deep shaft it had dug a 4.4 km tunnel under the lake. During this time the machine was subjected to water pressure of up to 15 bar – a new world record for tunnelling under high pressure. The previous record of 11 bar had been set by Herrenknecht on the tunnel project at Hallandsås, Sweden, in 2013.

The tunnel at Lake Mead passes through the so-called Muddy Creek Formation, which comprises alternating layers of hard rock and conglomerates as well as fault zones. The fault zones are full of secondary minerals and are partly filled with water from Lake Mead.

The TBM S-502 is a multi-mode TBM that can be operated in open or closed mode according to the geological conditions and a considerable range of additional equipment is available for the machine. The machine has a flexible design in terms of support and excavation methods. The tunnelling mode can be adapted to changing ground, requiring relatively short conversion times and incurring only low costs. This means that even tunnels with extremely varying geological and hydrogeological conditions can be constructed safely and cost-effectively using this innovative multi-mode TBM, and therefore it was ideally suited for the extreme conditions of the Lake Mead project.

6.18.4 Variable density TBM

A multi-mode TBM with EPB and slurry-supported modes is the most complex form of a convertible machine, and so its use is only cost-effective in very special cases. For this reason, Herrenknecht has developed the variable density TBM which applies a totally unique tunnelling technology. Without major mechanical modifications, the machine can switch between four different tunnelling modes while in the tunnel, and thus it combines the advantages of each method in one machine (Figure 6.19). This means that geological and hydrogeological changes along the tunnel length can be managed with extreme flexibility.

The excavated material is removed from the pressurised excavation chamber through a screw conveyor in both the EPB and the slurry mode. Depending on the mode used, the support pressure is controlled either via the screw conveyor speed and advance rate, or by using slurry that is automatically controlled by an air cushion. The submerged wall opening is replaced by communicating pipes. In the EPB mode, the screw conveyor drops the excavated material onto a belt conveyor. An additional slurryfier box at the end of the screw conveyor makes it possible to drive the TBM with a hydraulic slurry circuit in slurry mode. In the latter case, either a normal bentonite suspension or a high-density suspension can be used. This increases further the range of application of the variable density TBM and makes the machine an all-rounder for loose soils of all kinds.

In all modes the excavated material is removed from the pressurised excavator chamber by a screw conveyor. In the EPB mode, the screw conveyor speed and the advance rate control the face support pressure. The screw conveyor drops the excavated material onto a belt conveyor. In the slurry mode, the face support pressure is automatically controlled by an air cushion. Communicating pipes connect the front part of the excavation chamber, the pressure chamber, with the rear part, the working chamber. For the hydraulic slurry circuit a slurryfier box is used at the end of the screw conveyor.

In addition, in slurry mode it is possible to vary the density of the support medium in the excavation chamber. In cooperation with the Ruhr University (Bochum, Germany), Herrenknecht developed a mixture thickened with limestone dust. The choice between the more fluid low-density support medium (LDSM) and the denser high-density support medium (HDSM) considerably increases the areas where variable density can be used. The high-density mode closes the gap between mix-shield and EPB operation.

Case study 6.2

Variable density TBM – metro system, Kuala Lumpur

The variable density TBM technology proved to be a game changer in Kuala Lumpur, where its karst soil riddled with fissures and crevices is a real challenge for tunnel builders. The variable density TBM (see Figure 6.19) with its four different tunnelling modes adapted well to the different conditions. After nearly 2 years of tunnelling, in mid-April 2015, 9.5 km of tunnel was completed, and this was a major breakthrough both in the construction of the Kuala Lumpur metro and for mechanised tunnelling in difficult soft ground.

Technical details
Six variable-density multi-mode TBMs (see Figure 6.19):

- shield diameter 6620 mm
- cutter-head power 1280 kW
- torque 4239 kN m

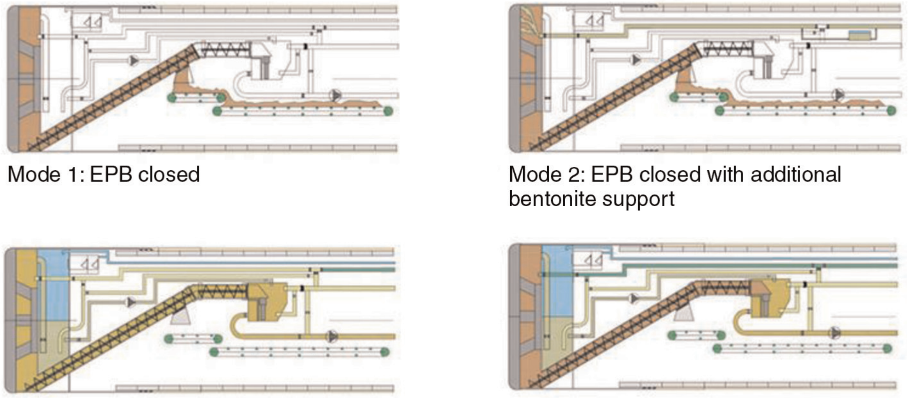
Four tunnelling modes (see Figure 6.19):

- EPB closed
- EPB closed with additional bentonite support
- mix-shield mode with LDSM
- mix-shield mode with HDSM

Two EPB shields:

- shield diameter 6620 mm
- cutter-head power 1280 kW
- torque 4239 kN m

Figure 6.19 Variable density TBM with its four different tunnelling modes – the all-round tunnelling technology for soft ground (courtesy of Herrenknecht AG)



Mode 1: EPB closed

Mode 2: EPB closed with additional bentonite support

Mode 3: mix-shield mode with LDSM (low-density support medium)

Mode 4: mix-shield mode with HDSM (high-density support medium)

Case study 6.3

EPB and mix-shield TBMs – Crossrail, London, UK

Construction of Crossrail, Europe's largest infrastructure construction project, started in 2009 and the opening is scheduled for the end of 2018. The total cost amounts to approximately €20.8 billion, and the project will have involved up to 10 000 workers working at more than 40 jobsites. Crossrail is a new 118 km London underground railway from Reading and Heathrow in the west to Sheffield and Abbey Wood in the east, via central London. The route will connect 40 stations, ten of which will be new. The journey time from London Heathrow to the main financial centre in the City of London (Liverpool Street) will be shortened from 55 to 32 minutes. It is expected that 200 million passengers per year will use the new railway.

The tunnelling phase of Crossrail was completed on 26 May 2015. In just 3 years, construction crews from three UK and European consortia navigated eight high-tech borers through the centre of London, driving 42 km of tunnels at depths of up to 40 m under one of the world's busiest cities.

The eight TBMs used on the project (six EPB and two mix-shield; diameter 7.08 m, length 147 m, weight up to 1000 ton, drive power up to 1920 kW) made their way under some of the most expensive real estate in the world, passing existing underground rail lines, sewerage, supply and disposal channels, as well as building foundations. All the TBMs were equipped with navigation systems for precision targeted control. The machines were driven 24 hours a day, 7 days a week (operated by 12 men on the TBMs, 8 men on the back-up and above ground, in shifts), and an impressive advance rate of up to 72 m/day (45 segment rings) was achieved.

Martin Herrenknecht, the Managing Director of Herrenknecht AG (Schwanau, Germany), which supplied the TBMs and comprehensive service solutions, concluded that it was the close cooperation between individual specialists, contractors and suppliers which enabled this project to be completed within very demanding timelines and binding budget plans, and with maximum safety.

6.19. Terminology

See Herrenknecht AG 2017; Robbins 2017.

Agitator. A motor-driven mixing arm in the bottom section of the shield in front of the suction pipe for stirring the excavated material mixed with bentonite suspension in a mix-shield TBM. It prevents material from settling and cohesive soil from becoming clogged in the shield bottom area in front of the grill and suction pipe.

Air lock. A lock through which people and/or materials can pass from the atmospheric area to the pressurised area of the TBM. It enables access to the tunnel face to control the cutting wheel, exchange tools or remove obstacles.

Annular gap. See *annulus*.

Annulus. A cavity between the surrounding soil and the pipe string or the tunnel lining. It is created by the slightly larger diameter of the cutting wheel or cutter head compared to the diameter of the pipe string or tunnel structure.

Automatic guidance. The automatic control circuit in modern tunnelling machines features systems for steering the shield drive, controlling the overcut, controlling the support pressure, automatic ring building using robots, and automatic grouting and concrete extrusion. All the relevant driving and operational parameters are displayed on the control panel (unlike in the past, when the control panel had only digital displays). Operator intervention is possible via a joystick. The operator sits in the control room where the computer has been installed.

AVN (automatische vortriebsmaschine). An automatic tunnelling machine that also removes slurry material.

Back-loading. A tool mounting that makes it possible to change the disk cutters from a protected position behind the cutting wheel or cutter head.

Bentonite. A highly expansive clay excavated from natural sources. In tunnelling technology, it is primarily used as bentonite suspension. It is used as the transport medium for the extracted material in the flushing circuit, as a support medium (thixotropic liquid) for the working face and as a lubricant for reducing friction (e.g. during pipe jacking). It is also used for the production of a slurry wall.

Blade shield. The shield skin consists of individual boxes mounted on a base frame, and the blades are advanced individually or in groups. The system finds applications in urban areas. The excavation is mechanical, using an excavator or a roadheader. It is even possible to drive tunnel shapes other than circular.

Blind hole. A tunnel that ends in a blind alley in the ground.

Boulder. A geological obstacle (mostly a single large piece of rock encountered in sandy or clayey soils).

Breathing air. Compressed air that has been filtered to be suitable for breathing. Required in man locks and for pressurising maintenance personnel in the excavation chamber for maintenance works.

Bypass. A part of the feed and slurry circuit. By switching the bypass, the feed line is connected to the slurry line so that the flow in the slurry circuit can be maintained when the TBM is stopped without flushing the tunnel face. Thus, the number of repeated starting procedures for the slurry pumps is considerably reduced.

Chisel tool. A specially formed excavation tool on a longitudinal cutting head.

Conditioning. The ground rarely has all the characteristics required for it to be used as the support medium in EPB shield operation mode. The ground should therefore be conditioned to act as a plastic support medium. Depending on the particular geology, conditioning is achieved by adding water, bentonite, polymer or foam.

Cone crusher. The cone-shaped part of a TBM behind the cutter head. Due to its special form, it crushes the excavated material into conveyable grain sizes during the rotation of the cutter head. It is mainly used with AVN machines.

Control stand. The work station of the machine operator. It is located either above ground in the control container (if remote controlled) or directly inside the machine.

Cutter head. The rotating circular structure or front section of a TBM in which the cutters are installed and the spoils are picked up from the tunnel invert.

Cutting head. A rotating extraction tool at the front of the TBM. The term is used in particular for hard rock machines.

Cutting knives. Special cutting tools equipped with a hard metal disk. These soft ground tools are tightened to the support and can be changed from the rear. Soft ground tools are used in heterogeneous ground.

Cutting wheel. A disk-shaped or spoke-type tool carrier, mainly with cutting knives, for the excavation of soft and heterogeneous ground and mixed soils.

DCRM (disk cutter rotation monitoring). A system for the real-time measurement of the rotation and temperature of disk cutters during tunnelling. Monitoring can identify tool wear and the need to replace parts. It is integrated directly in the fastening set of an individual disk cutter.

Digital guidance system. A guidance system that automatically tracks and displays the direction of the TBM and facilitates accurate steering by the TBM operator.

Discharge pipe. A jacket tube at the end of a screw conveyor with an opening for the discharge of the pumping medium. The opening can be completely or partially closed with a mechanical valve. If the material to be conveyed is suitable, the pressure differences can be controlled over the length of the screw conveyor and, as a result, the earth pressure in the extraction chamber is also controlled. The discharge pipe is used with EPB machines and can also be combined with thick-matter pumps.

Double-shield TBM. A shielded machine designed for tunnelling in weak or broken rock conditions. The machine can bore while simultaneously installing a lining from within its shield.

Drive. It comprises a ring-shaped, centre-free drive for the cutting wheel or cutter head of the TBM. A large, ring-shaped bearing with integral teeth equipped with several pinions on the periphery that are operated hydraulically or electrically via planetary gears.

Erector. A manipulator for positioning concrete segments during ring building.

Excavation chamber. A chamber and/or space directly behind the cutter head or cutting wheel.

Excavator. A universal excavation tool for partial face excavation. Depending on the condition of the soil, it can be equipped with an excavation shovel or a bucket tooth hydraulic hammer.

Extension. The external diameter of a micro-tunnelling machine can be upsized by attaching an extension kit. In this way the micro-tunnelling machine can be used to jack pipes both of the standard machine diameter and of the next largest diameter.

Filter cake. An air-impermeable membrane that forms at the interface between the soil and the bentonite suspension in slurry-supported tunnelling methods. It seals the soil against infiltrating groundwater and makes it possible to control the balance between the pressure applied on the bentonite suspension and the earth and groundwater pressure.

Geothermy. The natural heat of the Earth which can be exploited by means of drilling and which can be used to generate electric power or for power–heat coupling.

Gripper shoes. Convex steel structures attached to both sides of a TBM that extend and anchor against the side of the tunnel walls to support the TBM while boring, and react to both the torque and the thrust of the TBM.

Guidance system. A system allowing the position of the TBM to be determined. Depending on the diameter, a system with either a gyrocompass (interval measurement) or laser technology (permanent measurement) is employed.

Inclinometer. Determines the current roll angle of the laser station and transfers this data via the control unit to the computer of the PLC (programmable logic controller) system.

In situ casting. A single-leaf shaft construction method using transferable formwork to complete the final construction of the shaft during the shaft process. The transferable formwork is filled with concrete in situ (in place on the construction site), and once the concrete has hardened it forms the finished shaft construction. The concrete often incorporates steel reinforcement. The concrete hardening process means parallel shaft construction is restricted.

Launch shaft. The start of the excavation work and the setting up of the tunnelling machine. The assembly of the TBM at the construction site usually takes place on a shield cradle. The machine is in the start position. (See Chapter 8.)

Main-beam TBM. An open-type TBM designed for tunnelling in hard, self-supporting rock where shields are not required.

Main drive. The cutting wheel drive. Usually a ring-shaped, free-centre drive for the cutting wheel and/or the cutter head of the TBM. Alternatively, a large, ring-shaped bearing with internal teeth equipped with numerous pinions on the periphery, which are driven hydraulically or electrically via planetary gears. The free centre makes this drive ideal for mix-shield technology.

Main jacking station. A jacking system installed in the launch shaft. Often called the *jacking frame* in pipe jacking.

Man lock. An air lock consisting of two chambers (front chamber/main chamber) that allows access to the excavation chamber under compressed air in order to inspect the cutting wheel, change the cutter or remove obstacles.

Material lock. A lock is provided on the TBM to allow tools and other materials to be passed into the pressurised chamber at the front of the TBM. In order to make the handling of heavy objects easier, the transfer lock is equipped with transport trolleys that travel on rails.

Micro-tunnelling. In the USA, this is defined as a remotely controlled pipe jacking process that does not require personnel. (See Chapter 8.)

Muck bucket. A scoop-shaped part of the front and gage area of the cutter head that picks up the freshly cut rock/soil or ‘muck’ and drops it onto the muck extraction system (on hard rock TBMs this is usually a conveyor belt).

Muck conveyance. Technology (comparable to concrete pump technology) for conveying the extracted material with the help of muck pumps (piston pumps). It is employed with EPB machines.

Muck pump. A piston pump for the stroke-by-stroke conveyance of highly viscous slurries (e.g. grout, bentonite, concrete or conditioned excavated material). It is suitable for high slurry pressures.

Muck ring. A belt conveyor muck hopper that is positioned in the excavation chamber behind the cutter head and transfers the excavated material to the belt conveyor.

Open shield TBMs. TBMs without the option of active tunnel face support. They do not have a closed system for pressure balance at the tunnel face and are generally used in non-aquifers and stable geology. Open shield machines include, among others, hard rock and partial-face excavation machines.

Overcut. Difference between the excavation diameter and the diameter of the shield skin or pipe string.

Pipe arch. A tunnelling construction method for creating, for example, underpasses. A ‘shield’ consisting of several pipes installed next to one another acts as a support structure. Under the protection of the arch large tunnel diameters can be excavated using mining techniques along short routes.

Pipe jacking. A tunnelling construction method for the creation of pipelines consisting of individual product or casing pipes. The TBM and the pipe string behind it are advanced up to the target shaft with the help of a hydraulic jacking frame in the launch shaft. (See Chapter 8.)

Pipeline. Jacking pipes are lowered separately into the launch shaft and, after being jacked with the help of the main jacking station, they form the pipeline. (See Chapter 8.)

Pipe lubrication. A procedure employed to reduce the skin friction between the pipeline and the surrounding earth, as well as to support the annulus by means of injected bentonite suspension. (See Chapter 8.)

Pressure bulkhead. A retaining wall built into the TBM to hold back water. Sealed cutter-head supports act as a barrier against water inflows.

Probe drill. A pneumatic or hydraulic rock drill mounted on a TBM that is used to drill ahead of the machine to determine the ground conditions and water inflows.

Refraction. The deflection of a targeted laser beam as a result of changing air density along the beam path.

Ring beam. Circular steel beams that are erected to support the tunnel where the rock is not self-supporting (otherwise known as ‘bad ground’).

Rockhead. A small boring unit that functions as either a single-shield or double-shield boring machine for long utility tunnels. The machine can be either self-propelled (double-shield rockhead) or thrust forward using a pipe jacking unit (single-shield rockhead). Torque is supplied by a hydraulic or electric drive. The Robbins Rockhead comes in diameters of 1.35–2.0 m.

Rotary coupling. A sealed connection between a stationary and a rotating component. It is used for a number of fluids, such as hydraulic oil for various components, bentonite suspension or foam. The largest rotary coupling on a TBM is located in the transition area to the rotating cutting wheel.

Sea outfall. The general term for the construction of pipelines from the coastline into the open sea.

Segmental lining. A tunnel lining method that utilises individual precast concrete segments. The individual segments are transported through the completed part of the tunnel and assembled by the erector to form closed rings directly behind the TBM. The TBM is equipped with hydraulic thrust cylinders, which push the shield forward from the last built tunnel ring.

Separator. A device that separates solids and liquids in order to prepare a carrier medium for reintroduction to the slurry circuit and the extracted solids for disposal. The separation of the solid particles from the carrier medium takes place in stages, which correspond to the fractions of grain of the loose stone being treated.

Settlement. Sinking of the ground surface due to loosening and disturbance of the natural layering around the void (stress redistribution).

Shield skin. The exterior steel jacket and basic construction of a TBM. It serves as protection against the surrounding earth and groundwater. TBMs without a closed shield (gripper TBMs) are used only in rock.

Single-shield TBM. A TBM with a shield designed for tunnelling in variable geology, from soil to rock. Instead of the gripper shoes found on an open TBM, a shielded machine advances by ‘pushing’ off the concrete lining segment.

Sinking. A process of creating an excavation in the downward direction such as a shaft (vertical or inclined) with or without the aid of explosives. (See Chapter 9.)

Slurry circuit. In the excavation chamber, the excavated ground is mixed with bentonite suspension, which serves as transport medium in the hydraulic slurry system. Slurry pumps (centrifugal pumps) transport the suspension via the slurry line to the separation plant. The separated bentonite suspension is fed back into the circuit via the feed line.

Slurryfier box. A special development for extending the application area of EPB shields. The box connects the outlet of the screw conveyor to the slurry circuit so that the excavated material can be conveyed hydraulically.

Soil conditioning. The process of conditioning soils using additives such as bentonite, surfactants, water and polymers to systematically change the soil properties (e.g. the consistency). Is used in tunnel construction, especially when using EPB technology.

Support pressure. The creation of an overpressure in the excavation chamber to compensate for the earth and/or (ground) water pressure.

Suspension. A mixture of substances consisting of fine particles of solid substance(s) suspended in a liquid. A suspension serves as the support and transport medium and/or flushing liquid in mechanised tunnelling.

Tail shield. A large cylindrical structure mounted on the rear section of a TBM that supports unstable ground. Normally, when the rock is too broken or soft the segments or rock support are mounted inside the tail shield.

Tailskin. The back part of a shield forming a transition to the lining segment.

Tailskin seal. A seal that lies on the exterior contour of the segment or jacking pipe and seals the annular gap between the inside of the tailskin and the outside of the tunnel lining.

Target. An electronic target used to control the position of the TBM. Sensors measure the position of the target relative to the laser beam, and passes the values to the computer in the control panel. This enables the exact position of the machine to be checked at all times.

Telescoping shield. A shield that provides protection throughout the entire propelling stroke of a TBM. It is located between the cutter-head support and the gripper assembly.

Tunnel face. The area where the material is excavated.

Tunnelling. The general term for the construction of tunnels.

Variable-frequency drive. AC current is converted to DC current and then back to AC current to produce variable rotational speeds with an AC motor.

Ventilation. The general term for the supply of fresh air in a tunnel (primary ventilation).

Working air. Compressed atmospheric air (compressed air) for the operation of compressed air machines (e.g. material locks, tools, winches, cranes and pumps) and for feeding to the compressed-air cushion above the bentonite level in the ring area of the tunnelling shield.

6.20. Concluding remarks

The following information is important in the selection of a tunnel-boring (mechanised tunnelling) method:

- grain-size distribution curves, groundwater level (see Figure 6.15)
- bulk/buoyant density, permeability (see Figure 6.14), abrasiveness
- friction angle, cohesion, Atterberg limits (the critical water content of a fine-grained soil: shrinkage limit, plastic limit and liquid limit), quartz content
- uniaxial compressive strength, tensile strength.

6.21. Questions

1 Define a modern shield in the context of tunnelling. Give a brief history of the development of shields. Why is shield tunnelling very popular today?
2 A shield is a mobile safety device. What is its function?
3 Classify shield tunnelling methods based on the techniques used to control groundwater and support the forward end of the tunnel.
4 Why is supporting the tunnel face (forward end) so important?
5 Draw a line diagram to outline the techniques that are currently in use to control groundwater and support the forward end of the tunnel.
6 Differentiate between an open shield and a closed shield. Where are open shields employed?
7 Open shields can be further categorised based on the ground excavation mechanism. List these mechanisms and where the associated shields can be employed. Give the merits and limitations of each type.
8 Draw conceptual diagrams to show natural support and a mechanical shield. Describe a mechanised shield.
9 When is a mechanised shield known as a semi-mechanised shield or a partial-face extraction unit? List the ground excavators that could be installed within the shield. What is the basis for choosing these shields and what advantages do these units offer? Is interchange between these excavators possible?
10 Where can the partial-face shield with a roadheader find and the partial-face shield with an excavator be deployed?
11 Which manufacturer has developed a modular system that allows the exchange between roadheaders and backhoe excavators? Where can such systems be deployed?
12 Give a brief history of holding water pressure under control pneumatically. Describe the concept. Draw a conceptual diagram of a compressed-air shield. Where does such a shield find application? List its limitations.
13 The Japanese are known for their slurry shields. Describe the concept underlying such shields and the process that takes place when undertaking tunnelling using this method. Draw a conceptual diagram of a slurry shield. Why is this technique more popular in coastal areas? List its disadvantages.
14 Classify slurry shields based on the supporting fluid used. What is the application of each shield type? Draw a conceptual diagram for each one.
15 When there is some uncertainty about the type of ground that will be encountered, which design of slurry shield could be deployed? Draw a diagram to illustrate the working procedure of this unit. Describe the operation of the conversion from a mix-shield to a slurry shield.
16 Where can an EPB shield could be used? Draw conceptual diagrams to illustrate this technique. How does an EPB shield differs from other shields in terms of the

support of the working face? How is the material (spoil or muck) that has been extracted removed?

17 The EPB concept is an improvement over slurry shielding, having several advantages. List its advantages. For which materials is the EPB technique most suitable? Does it, in practice, require ground conditioning, and if so how is this achieved? How is transport through the tunnel achieved with this system?

18 What is the concept of a combined shield system? When does a combination of shields become necessary? List the various shield combinations that have been tried out, and give examples of tunnelling projects where they have been used.

19 Listed below are a number of tools that are available for use in conjunction with shield tunnelling. Specify the significance of each one and state where each is attached and used.
(a) Manual tools.
(b) Cutting edges.
(c) Cutting knives and teeth.
(d) Cutter bits.
(e) Rippers.
(f) Cutting disks.
(g) Bucket and teeth.
(h) Special rock-cutting machines.

20 Full-face mechanical excavation is an important development that has many merits. List the prominent features of this system.

21 List the techniques used for mucking/excavating material and its transport through the shield. Draw a line diagram to summarise the techniques.

22 An important aspect during shield tunnelling is the support network behind the shield. Using a line diagram, classify the linings that can be used in this system.

23 How would you address the following issues associated with mechanised tunnelling?
(a) Ergonomics and safe working conditions.
(b) Safe access to the working face by the operating crew.
(c) Provision for safe handling, fitting and replacement of heavy parts and consumables.
(d) Handling, fitting and erection of supporting sets.
(e) Provision for fire-fighting.
(f) Effective ventilation.
(g) Efficient communication system.
(h) Emergency plans or ‘standing orders’.
(i) For shield tunnelling, the German Tunnelling Committee (DAUB) has recommended a few guidelines on the following aspects:
  - excavation
  - face support
  - separation
  - input from contractors, process technicians and working engineers.

  Elaborate on each aspect.

24 Why do the following geological and hydrological parameters form the foundation on which planning for shield tunnelling is based? How would you address them?
   (a) Water permeability.
   (b) Grading curve.
   (c) Consistency limits.
   (d) Rock/clay mineralogy.
   (e) Ground quality.
   (f) Rock strength.

25 List the design and model parameters that must be taken into account when designing a tunnelling project.

26 How would you address the following likely occurrences during a tunnelling project?
   (a) Disturbance to the ground.
   (b) Disturbance to the water regime.
   (c) Adverse impact of compressed air, slurries injection, digging mechanism, etc.
   (d) The need for a time gap and measures to provide supports (primary and secondary); backfilling the tail void.

27 List the measures that can be taken to guard against each of the following in a tunnelling project: (a) collapse, (b) ground lowering/subsidence, (c) water-regime lowering, (d) over-excavation, (e) support deformation and failures, (f) water seepage and (g) accidents of any kind during the construction phase.

28 When excavating the ground a ‘subsidence trough’ is formed, indicating the extent of damage that has been caused due to the subsurface excavations. The extent of the damage is a function of a few parameters. List these parameters.

29 In 1981, Makata described five zones of ground displacement that occur when undertaking tunnelling using shields. Tabulate the details and draw the figure given by him.

30 Define following terms used in conjunction with shield tunnelling: (a) automatic guidance, (b) AVN cutting head, (c) cutting wheel, (d) discharge pipe, (e) launch shaft, (f) separator, (g) tailskin, (h) working air.

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Chapter 7
Special methods

Keeping disturbance to the natural ground setting to a minimum could be considered as directly proportional to cost reduction and the minimisation of problems.

7.1. New Austrian tunnelling method (NATM)

7.1.1 Introduction

The NATM was developed soon after World War II, since when it has been consistently improved. Today, NATM which is also known as the *sequential excavation method* (SEM), is a well-recognised technique due to its success in a variety of conditions ranging from hard to soft rock, and soft stable ground to weak, friable and unstable ground. It has been successfully used in rural as well as urban areas, particularly under some major cities, to construct tunnels for roads, railway and water conveyance. The main advantage of the NATM over conventional drill-and-blast techniques, tunnel-boring machines (TBMs) and shields is its outstanding flexibility. The principle underlying the NATM is illustrated in Figure 7.1 (Sauer and Gold, 1989).

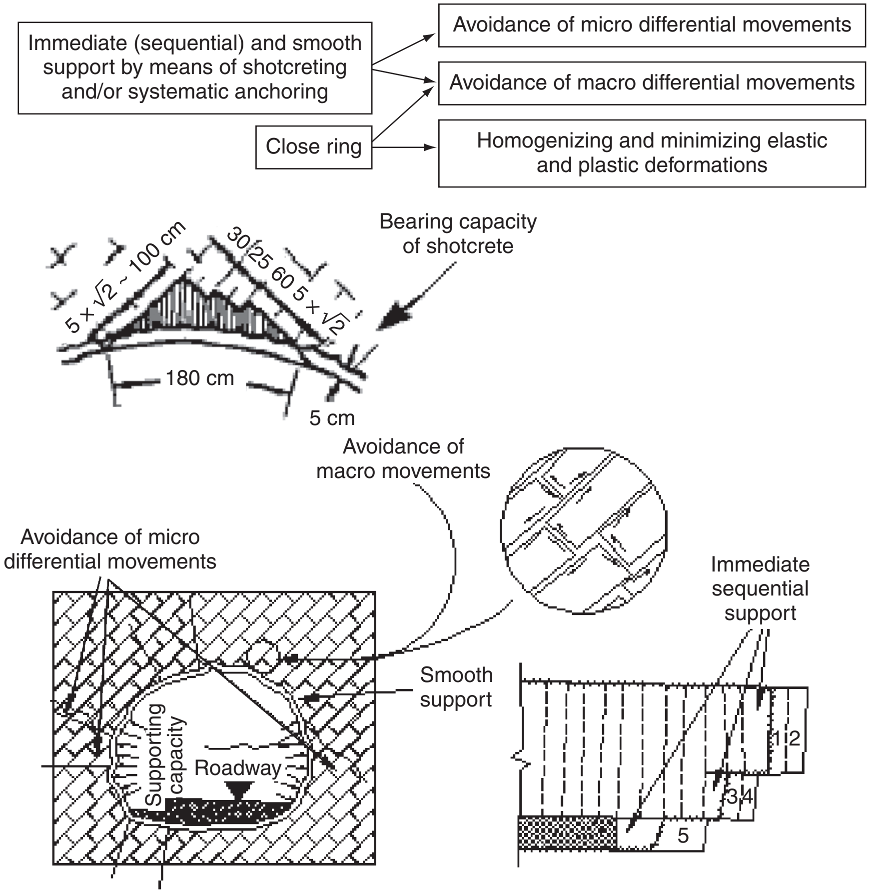
7.1.2 Main guidelines

- The initial tunnel lining should primarily support the immediate layers of the ground surrounding the opening (the loosening zone) and guard them against further deterioration.
- The faster the initial support is put in place and functional, the smaller the loosening zone; the initial lining should, however, not attract additional forces by being tougher than necessary.
- As the 'load-carrying arch' that develops around the opening will be more or less circular in shape, the size of the loosening zone and the burden imposed on the lining can be minimised by adopting this shape for the opening as well; at the very least, abrupt changes along the tunnel perimeter must be avoided.
- The smaller the loosening zone and the unsupported area of the tunnel, the smaller the loads and the actual amount of deformation and surface settlement.

In addition, the salient features of this technique, as described by Heflin and Mohammad (1987), are summarised below:

- The NATM strives to optimise design by harmonising structural, geotechnical and construction considerations.
- The ground around the opening is considered both a load-imparting and a load-carrying ring. The excavation sequence used minimises ground disturbance in

Figure 7.1 The principle of NATM. The method involves immediate sequential support to prevent micro and macro differential movements (Sauer and Gold, 1989)



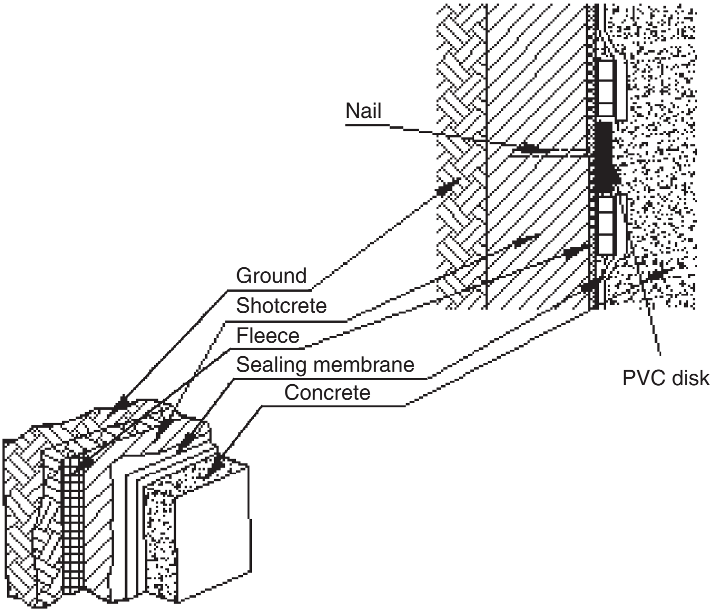
order to preserve the inherent strength of the ground. The excavated area is kept small, and timely installation of initial support is ensured. It is claimed that the immediate sequential support provided by the method prevents micro and macro movements.

- The tunnel shape is selected to minimise flexure and stress concentration, and to ensure stability of the support systems. The lining is kept relatively thin and flexible, and its full contact with the ground is ensured to mitigate further the development of localised excessive bending moments.
- The ground is subdivided into several categories, usually not exceeding six, in accordance with the geological conditions, and structural support systems are designed accordingly.
- The NATM, unlike conventional designs, treats the initial lining as an integral part of the overall design. The finite-element method (FEM) is used extensively to

perform structural analysis of both the initial and the final lining systems, and to check stresses and deformations in the surrounding ground. Calculations are done to simulate the various excavation sequences.

- The NATM design approach for soft ground emphasises minimal ring-closure time as related to ground stand-up time. As the lining cross-section, at a given location, is installed in several stages, as dictated by the excavation sequence, splice bars or mesh are used between various initial lining segments to ensure structural continuity.
- When applicable, hydrostatic pressure is considered in the lining design. In the NATM, water inflow needs are controlled to ensure that the pore-water pressure is within tolerable limits. The installation of piezometers at critical locations is specified during the design phase. Within the tunnel excavation, all seeping groundwater is collected and pumped out using perforated drainage pipes. Where necessary, relief holes are drilled to collect perched groundwater. Under difficult conditions, it sometimes becomes necessary to seal the excavation face with shotcrete and then use vacuum pipes to relieve the water head. Excavation can then continue only after the effectiveness of the dewatering procedure has been demonstrated by the drilling of additional exploratory holes. These guidelines are in line with those specified by the Washington Metropolitan Area Transit Authority (WMATA) to control water inflow during tunnelling operations. A schematic diagram of the waterproofing details is given in Figure 7.2.
- Auxiliary means of initial support are also employed depending on the ground conditions and other factors, such as the presence of nearby structures and

Figure 7.2 Waterproofing details in NATM



utilities. For NATM to be performed safely in soft ground, flowing ground conditions must be prevented, and even limited running ground situations must be adequately guarded against. Ground stability must be ensured by effecting an adequate drawdown, with grouting also used where necessary. Auxiliary means of initial support, such as spiling of various kinds, poling plates and similar methodologies, may somewhat reduce the ground movement at and near the face under marginal conditions, but they cannot control the flowing ground and may provide only scant help in running ground.

- Depending on the ground conditions (described above) and a need to protect surface installations, where applicable the following range of initial support systems have been incorporated in the design:
  - (i) sealing shotcrete
  - (ii) lattice girders
  - (iii) soil anchors
  - (iv) welded wire fabric
  - (v) rebar splices for initial shotcrete lining
  - (vi) structural shotcrete in layers, as specified
  - (vii) reinforcing rod spiling
  - (viii) perforated pipe spiling to be used for pre-grouting short distances ahead of the face, generally 3–4.5 m
  - (ix) plastic sleeve pipes to be used for pre-grouting for longer distances ahead of the face, generally 15–21 m
  - (x) steel poling plates.

  Items (i)–(v) are considered standard means of initial support when installed in a timely manner in good-to-excellent ground conditions. (Table 7.1 illustrates the use of some of these items.) Items (vi)–(x) may be looked upon as supplementary support systems needed in fair-to-poor ground conditions or where additional support is needed for other purposes, as described earlier.
- With regard to instrumentation, the initial support needs are based on the actual geological conditions encountered during construction and the response of the excavated ground. For NATM to be applied correctly and efficiently, design assumptions must be verified by means of in situ instrumentation. The designs identify the critical cross-sections where monitoring is required. A wide range of instrumentation is used for this purpose, including shallow settlement indicators, extensometers, sliding micrometers, convergence points within the tunnel to measure movement in all directions, pressure cells to measure earth pressures, load cells to measure stresses in shotcrete lining, and piezometers to monitor variations in pore-water pressure and water heads.
- In NATM construction, the excavation procedure and the initial support is varied to optimally accommodate the different ground conditions and thus to optimise cost savings.

7.1.3 Ground categories and tunnelling procedures

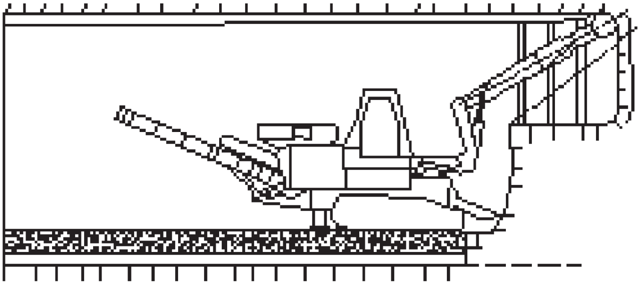
The NATM can be applied to soil and rocks having a uniaxial compressive strength (UCS) up to ~40 MPa and tunnel a cross-section up to 60 m^2 or more (see Table 7.1 and Figure 7.3) (Sandtner and Gehring, 1988).

Table 7.1 Application of the NATM to cover soil and rocks with a UCS up to 40 MPa and a cross-section up to >60 m^2: the percentage of operation time covered by the NATM using an AMT 70 roadheader (Sandtner and Gehring, 1988)

Excavation sequence	Approx. % time of overall time of one cycle of advance											
	Soil cross-section						Rock (UCS ~40 MPa)					
	40 m^2		40–60 m^2		>60 m^2		40 m^2		40–60 m^2		>60 m^2	
Excavating roof section (including mucking)	9.0	●	9.0	●	8.0	●	10.5	●	11.0	●	12.0	●
Placing of roof arch	4.5	■	4.5	■	5.5	■	4.5	■	5.0	■	5.5	■
Placing of wire mesh in roof section	6.5	○	6.0	○	6.5	○	5.5	○	5.5	○	5.5	○
Shotcreting in roof section	13.0	■	12.0	■	12.0	■	10.5	■	11.0	■	12.0	■
Excavation of bench (including mucking)	9.0	●	9.0	●	9.5	●	10.0	●	11.0	●	11.0	●
Placing of steel arch (lateral)	6.5	○	5.0	○	4.0	○	4.0	○	3.0	○	2.5	○
Placing of wire mesh (lateral)	4.5	○	3.5	○	3.0	○	4.0	○	3.5	○	3.0	○
Shotcreting of side wall	13.0	●	12.5	●	12.0	●	11.0	●	10.0	●	9.0	●
Excavating of floor arch (including mucking)	4.5	■	5.5	■	6.0	■	7.5	■	8.0	■	8.5	■
Placing of floor segment (steel arch)	6.5	○	7.0	○	7.0	○	6.0	○	6.5	○	6.5	○
Concreting of floor arch	6.5	○	7.0	○	7.0	○	6.5	○	6.5	○	7.0	○
Refill of floor arch	4.0	○	4.5	○	4.5	○	4.0	○	4.0	○	3.5	○
Driving of steel piles	12.5	○	14.0	○	15.0%	○						
Placing of rock bolts							16.0	■	15.0	■	14.0	■
% of operation time with AMT 70 system	66.4		67.0		56.0		70.0		71.0		58.0	

●, basic function; ■, already existing, or planned additional function; ○, not planned for integration.

Figure 7.3 An AMT 70 roadheader



Excavation with short advanced roof section using a roadheader

7.1.4 Techniques

The driving techniques include

- tunnel heading by manual mining using conventional tools and appliances
- tunnel heading with the aid of explosives (drilling and blasting)
- tunnel heading using an excavator, boom-mounted excavator or roadheader.

7.1.5 Excavation sequence

The excavation sequence used minimises ground disturbance in order to preserve the inherent strength of the ground. The excavated area is kept small, and timely installation of initial support is required. Typically, the full excavation sequence consists of the following operations:

- crown excavation
- bench excavation
- excavation of invert.

7.2. Applications of NATM

7.2.1 Typical NATM

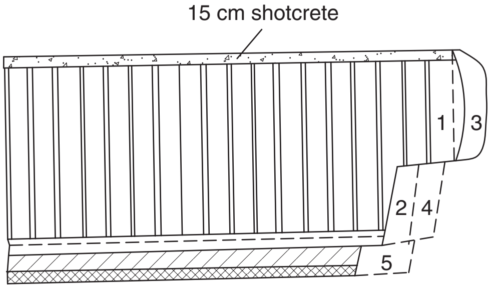
A typical excavation procedure was followed for the Frankfurt Metro Tunnel (Figure 7.4) (Babenderede, 1980; Whittaker and Frith, 1990).

7.2.2 NATM with roadheader

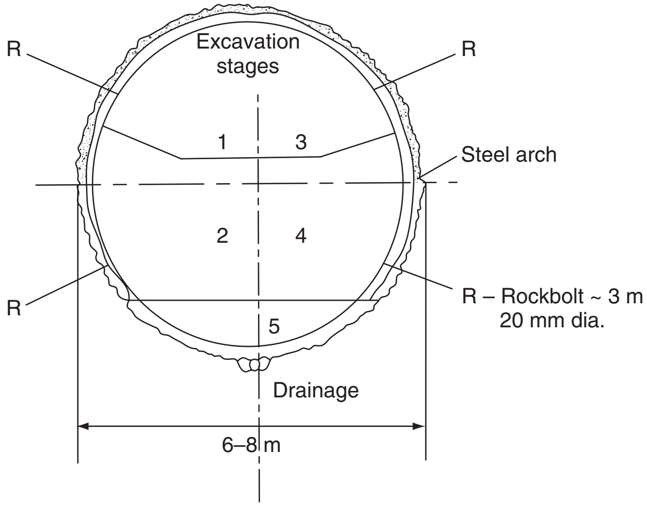
Sandtner and Gehring (1988) outlined to what extent the individual steps that are required during tunnelling using the NATM can be mechanised (see Table 7.1). They estimated that most of the operational steps can be mechanised for 55–70% of the overall operational time. They also compared the application of NATM with rock fragmentation by blasting (drilling-and-blasting method) with the use of an AMT 70 roadheader (Voest Alpine, Linz, Austria) (see Figure 7.3) by assuming a tunnelling project with the following details:

- rock quality: moderate, with a UCS of 20 MPa

Figure 7.4 Application of NATM while driving the Frankfurt Metro Tunnel



Application of NATM at Frankfurt Metro



- depth of round, or single advance: 2 m
- cross-section: roof 20 m^2, bench 35 m^2, floor arch 5 m^2 (total 60 m^2).

The work cycles of using a jumbo for drilling (together with blasting) and of using a roadheader for excavation were calculated, and it was found that by using a roadheader a time saving of 20% could be achieved (Sandtner and Gehring, 1988). In addition to using the roadheader for the rock fragmentation, it should also be used to perform peripheral operations, particularly those relating to rock support. To expedite the whole work cycle the roadheader can be used with an attachment for the placing of steel arches and for other auxiliary operations. The roadheader can negotiate gradients up to ±12°.

An AMT 70 (see Figure 7.3) roadheader was used in the NATM project to construct the Karawanks Tunnel, which links Austria and Slovenia. The 8.5 km long and 100 m^2 cross-section road tunnel had to pass through mainly limestone, dolomite and sandstone.

7.2.3 NATM in fissured and heavily watered formations

Deacon and Hughes (1988) described the application of NATM to construct two surface drifts through water-bearing strata at a gypsum mine at Barrow-upon-Soar, UK. The NATM was selected due to its flexibility to accommodate a variety of ground conditions. In this project, grouting from the surface and the use of NATM were helpful in solving the problems associated with water, the main problem being the presence of a fissured hydraulic limestone series, which was heavily water-bearing and under sub-artesian pressure. Out of the total 1000 m of tunnelling, some 400 m was difficult and wet.

According to the principles of the NATM, the project was divided into three segments: portal, hydrostatic and non-hydrostatic. The rocks were classified into five groups and, due to the ground conditions, the length of the round (drilling and blasting in one go) was restricted to 0.5–3.0 m.

7.2.4 NATM variants

The principles of the NATM are fundamental to modern-day tunnelling, and the method fundamentally involves specifically addressing the specific soil conditions encountered. As the use of the NATM has spread, new terms have arisen and alternative names for certain aspects of the method have been adopted. This is partly due to the increased use of this tunnelling method in the USA, particularly for shallow tunnels in soft ground.

Other names have been used for the NATM. For example, the names *sequential excavation method* (SEM) or *sprayed concrete lining* (SCL) are often used for its use in shallower tunnels. In Japan, the terms *centre dividing wall NATM* or *cross-diaphragm method* (both abbreviated to CDM), and *upper half vertical subdivision method* (UHVS) are used.

The Austrian Society of Engineers and Architects defines the NATM as ‘a method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-like support structure. Thus the supporting formations will themselves be part of this supporting structure.’

Some engineers use the name NATM whenever proposing the use of shotcrete for initial ground support in an open-face tunnel. However, the use of the name NATM can be misleading in relation to soft-ground tunnels. As noted by Brown (XXXX), NATM can refer to both a design philosophy and a construction method.

Two projects where NATM has been utilised are described in Case Studies 7.1 and 7.2.

Case study 7.1

NATM – Heathrow Express rail link, London, UK

Balfour Beatty was contracted to build 8.8 km of shield-driven running tunnel and various NATM caverns, including the underground station complexes at the central terminal area (CTA) and Terminal 4, on the Heathrow Express rail link project. Geoconsult was the specialist NATM design engineer to Balfour Beatty. The NATM was specified for the design of the stations following a successful trial of the method in London Clay at Heathrow in 1992. That had been the first use of the NATM in London Clay, and the method was subsequently adopted for the Waterloo and London Bridge stations on the Jubilee Line Extension of the London Underground.

A 10 m diameter crater formed during driving of the Heathrow Express tunnel on 21 October 1994 (*Ground Engineering*, 2000; HSE, 1996, 2000; ICE, 1998, 1999).

Background
NATM in London Clay.

Possible causes of failure
Possible causes include a series of design and management errors combined with poor workmanship and quality control (Wallis, 1999).

Consequences
- Differential settlement induced at adjacent buildings.
- Services at Terminal 4 halted for 1 month.
- Remedial measures caused chaos at Heathrow Airport.
- Recovery cost £150 million (three times the original contract sum).
- Remedial measures: backfilled with 13 000 m^3 concrete.

Lessons learnt
- Measures to ensure safety must be planned.
- Do not lose sight of critical technical issues in the pursuit of time and cost reductions.
- While a number of factors contributed to the collapse, half of them were matters of management.
- However much engineers are pressured to build quickly and cheaply, the industry will be judged by its failures.

The Health and Safety Executive, in its report on the safety of NATM tunnelling in London Clay (HSE, 1996), stated that NATM is a safe and appropriate tunnelling method in London Clay ‘provided enough care is taken’ and that the Heathrow NATM structures, which opened to the public in mid-1998, are safe.

Case study 7.2

NATM combined with other methods – Beacon Hill Station, Seattle, WA, USA

A combination of the methods described in this chapter were used to construct the station at Beacon Hill over the period 2000–2007. The station is a tunnel station, located about 49 m (160 ft) under South Lander Street, with an entrance located at the south-east corner of Beacon Avenue South and South Lander Street.

Technical data
A light-rail station located 46 m (150 ft) beneath the surface. The station complex includes a central elevator and access shaft, a concourse, opposing platform tunnels and cross-passages.

Platform tunnel section: 36 ft wide × 31 ft high

Platform tunnel area: 925 ft^2 (86 m^2)

Total station excavation area: 63 000 ft^2 (5853 m^2).

Geology
Overconsolidated glacial clay and till with fractured zones. Intermittent sand and silt layers with perched groundwater. Thus, a soft-ground geology.

Construction methods and techniques

- Methods: cut and cover, NATM SEM and TBM
- Special techniques: barrel vault method, ground water control, jet grouting, slurry wall, vacuum dewatering.

7.3. Lee's tunnelling method

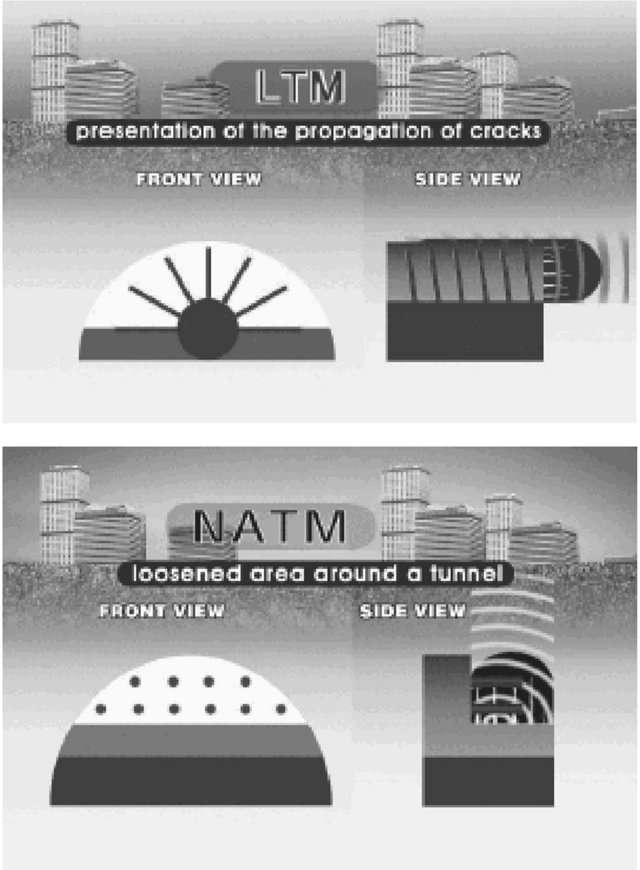
7.3.1 Introduction

Lee's tunnelling method (LTM), developed by the LTM Corporation (Seoul, Korea), is a combination of NATM (Figure 7.5) and blasting, and mechanised tunnelling using a TBM (Johnson, 1982; Lee, 2002). In the LTM, drilling and blasting for enlargement of the pilot tunnel and the construction of concrete linings can be carried out simultaneously with the excavation of the pilot tunnel by the TBM. The LTM Corporation claims that this technique can reduce the construction period by 30% or more and also reduce costs by 10% or more (Figure 7.6), due to the minimisation of loosened areas around the tunnel face (see Figure 7.5).

7.3.2 Technique

During conventional drilling and blasting, because the charge holes are drilled longitudinally the loosened area around a face increases during blasting, whereas in LTM the major direction of crack propagation due to blasting is to the front of the face (see Figure 7.5). This could allow the loosened area around a face to be reduced considerably, thereby resulting in a reduction in the consumption of support materials (such as shotcrete and rock bolts), vibrations and noise.

Figure 7.5 Comparison of the LTM and NATM techniques (courtesy of LTM Corporation)



7.3.3 Equipment for LTM

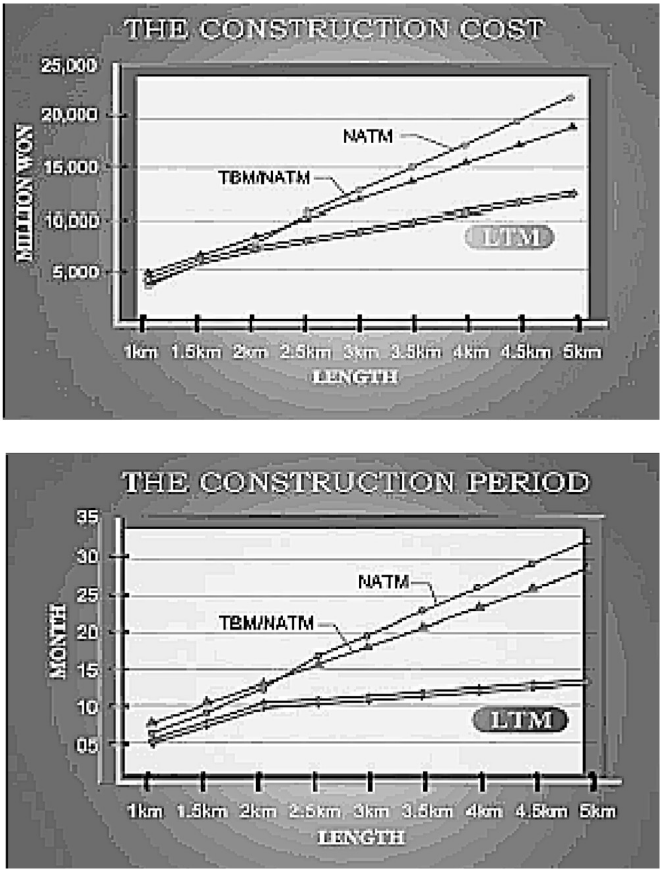
An LTM equipment fleet includes a TBM, a drill jumbo, a mobile loader, carriers to dispose of muck, mobile ladders and auxiliary equipment for various services. The carriers are categorised as the bottom carrier, the deck plate carrier and the ladder carrier, in addition to the main carrier, which can transport a large amount of muck.

7.3.4 Sequence of operations

The following steps are taken when using LTM to undertake a tunnelling project.

1. The jumbo drill mounted on the back-up trailer of the TBM drills the oblique blasting holes simultaneously with the TBM excavation. The muck generated by the TBM is loaded onto the trolley via the conveyor belt.
2. On completion of the drilling of the oblique blasting holes in the pilot tunnel, holes are drilled in the upper and lower half sections of the tunnel. Mobile ladders are used to move the drill jumbos.

Figure 7.6 Comparison of the construction cost and time period for LTM and existing methods (courtesy of LTM Corporation)



3. Drilling at the rear of the tunnel face then follows. After finishing the drilling work, the holes drilled at various sections are charged with explosives and stemmed.
4. Prior to blasting, the carriers are removed from the blasting site. The ventilation duct is decoupled, and all equipment and workers, including the TBM operators, are evacuated. The blasting of the upper and the lower half sections is carried out simultaneously.
5. Ventilation is resumed after the blasting, and muck transfer is begun at the various sections. As soon as all the muck has been disposed of at one side of the tunnel face, the ventilation duct for the TBM is re-coupled, and TBM excavation is resumed. Drilling operations, as described in preceding sections, are also resumed.
6. The rolling stock that has been used to carry muck away from the tunnel are loaded with the support materials, so that the lining can be constructed

simultaneously at the rear, several hundreds of metres distant from the face. The service lines for utilities are also installed simultaneously.

7 After finishing the TBM excavation and the blasting for enlargement, all facilities related to the TBM excavation are dismantled sequentially, and transverse blasting of the lower half section of the centre of the tunnel can be undertaken. At this time, the lining can be protected from the blasting by installing a steel shell composed of several segments.

8 The California switching system can be installed in three lanes by utilising the enlarged final section of the tunnel, enabling the trolley for the TBM and other carriers to move freely.

7.4. Semi-mechanised methods

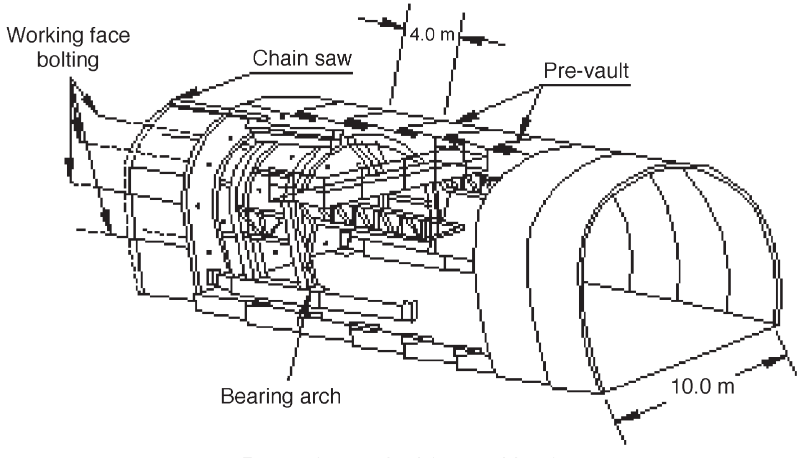
7.4.1 Pre-vault method (mechanical pre-cutting tunnelling method)

The pre-vault method (mechanical pre-cutting tunnelling method, MPTM) was developed in the 1970s. It has seen wide application in recent years, both in rocks and in soft-ground tunnelling projects (Cazenave and Le Goer, 1996; Dias and Kastner, 1998; Singh, 1993). The method allows for advance or pre-support of the section to be excavated by

- sawing a small slit (or slot) (15–20 cm thick, 3–4 m long) along the outer line of the section to be excavated (Figure 7.7) (Cazenave and Le Goer, 1996; Dias and Kastner, 1998)
- shotcreting the slit
- excavating under the protection of a thin vault.

This method, the use of which was initially confined to the upper half section of tunnels, progressively came to be used for the full tunnel section, even for very large tunnels up to

Figure 7.7 Pre-vault tunnelling method



150 m^2. The method finds applications as described below (Walsum, 1993):

- *Tunnel cross-section*. The minimum radius that the standard cutter can cover is 2 m, which limits the minimum MPTM tunnel diameter to 4 m. Such machines have been built but they leave little room for other equipment to pass under the MPTM portal. It is recommended, therefore, to use the MPTM for tunnels having an excavated cross-section of at least 30 m^2 or an equivalent diameter of 6 m. The third-generation machines can be used on cross-sections larger than 70 m^2.
- *Tunnel length*. The tunnel length should be at least 300 m and not more than 2000–4000 m when two tunnel headings are feasible. When multiple headings are feasible, the MPTM becomes competitive with TBMs, in terms of both time and cost. Practice has shown that the MPTM is particularly competitive in the urban environment.
- *Geology*. The ground cover over the tunnel should preferably be in excess of one tunnel diameter, although tunnels have been successfully driven with less cover. Soils suitable for the MPTM are sands and silts, clayey sands and silts, sandy and silty clays, plastic to stiff clays, and marl.
- *Tunnelling beneath the water-table*. It is feasible to use the MPTM for tunnelling under the water-table as long as the ground mass surrounding the tunnel has a permeability coefficient k of less than 10^{-5} m/s. A perched water-table ahead of the face can sometimes be lowered by means of drains drilled ahead of the face.
- *In rock*. The current state of the art allows tunnelling using the MPTM in rock with unconfined compressive strengths up to 70 MPa. Research is in progress to develop cutters capable of operating in harder rocks.

7.4.1.1 Scope and comparison with other construction methods

It is claimed that MPTM results in better safety, quality of the end product and economy. The last of these greatly depends on the tunnel's cross-section and length. Listed below are some of salient features of this technique (Walsum, 1993):

- One great advantage of the MPTM is that it can be used side by side with all sorts of conventional tunnelling equipment.
- The flexibility of the MPTM pays off in heterogeneous ground. The method allows switching from tunnelling with to tunnelling without a pre-lining. If hard rock is encountered, conventional drill-and-blast tunnelling can be used without affecting the rhythm of advance of the tunnelling operation. The MPTM can be kept in readiness to be put into service when required.
- From an environmental point of view, both the MPTM and TBMs avoid excessive noise and vibration, even when the MPTM is combined with blasting. When it comes to surface settlement, however, particularly in soft ground, the MPTM is superior as a result of the pre-lining (i.e. the tunnel lining precedes rather than follows the excavation). When compared with conventional drilling and blasting, the MPTM eliminates overbreak, and results in reductions in temporary support, noise level and consumption of explosive.
- The more effective ground control, typical of the MPTM, translates directly into greater safety. Shotcreting into a pre-cut slot is a much cleaner operation than the

shotcreting of a tunnel surface, as rebound is virtually eliminated. The MPTM also lends itself to full mechanisation of the shotcreting operation. The result is a clean, hygienic underground operation.

- The MPTM provides the opportunity to adapt the tunnel cross-section to requirements imposed by the geology, tunnel use or both, unlike tunnels created using TBMs which have to be circular. TBMs are made in diameters of up to about 12 m, whereas the MPTM can be applied to larger cross-sections.
- For large-span tunnel openings (i.e. in excess of 8 m), the cost of an MPTM is of the order of 10% of that of a TBM. When comparing the MPTM with a TBM purely on the basis of cost, two MPTMs can do better than one TBM for tunnel lengths up to 3000–4000 m. Therefore, for the majority of urban tunnelling projects the MPTM can compete successfully with TBMs. However, for longer tunnel lengths, the TBM has a time advantage, unless tunnel excavation can proceed on more than two headings simultaneously.

7.4.1.2 MPTM with pre-lining versus jet-grouted pre-lining

On some projects (e.g. on the high-speed railway line between Rome and Florence, Italy), an effort has been made to construct a pre-lining using the jet-grouting technique. While with jet-grouting one can reach further ahead of the face than with the MPTM, it has been shown that the quality of the pre-lining so obtained is not as good (Walsum, 1993).

The use of the MPTM on a railway tunnel at Březno, Slovakia, is described in Case Study 7.3.

Case study 7.3

MPTM – railway tunnel, Březno, Slovakia

The Březno railway tunnel is the longest rail tunnel on the Slovak railway network. The project was undertaken during the period 2000–2007 (ITA-AITES, 2017b). The owner chose a mechanical pre-cutting method (MPM) for the excavation and installation of the primary lining. This method was assumed to be well suited to the existing geotechnical conditions – unstable and squeezing ground, low-strength clayey rock and relatively shallow overburden. The excavation passed through fine-grained medium plastic to fat clays and black chalk, with transitions to claystone.

In addition, according to pre-project investigations it was likely that remnants of undocumented mining activities would to be encountered in the area. These predictions were confirmed during the excavation to a much larger extent than expected. A coal seam dipping in the direction of the excavation under the tunnel bottom was encountered at the Březno portal, where the excavation was begun.

These findings necessitated an additional survey, the filling of the abandoned mine workings within the required area, the installation of additional anchors for primary support and a new assessment of the final lining of the tunnel, which had the character of a longitudinally acting beam.

The cutting for the pre-vaults was carried out using a Perforex 3713. A PG-115 drilling set was used to drill boreholes for 16 m long glass-fibre reinforced plastic (GRP) anchors. The pre-vaults, which were created by filling the cut slots with shotcrete, formed 5 m long and 200 mm thick splayed arches ahead of the tunnel. The pre-vaults were allowed to overlap each other by 0.5–2.5 m. Rock breaking at the face and muck loading were performed using a Schaeff 312 excavator.

The excavation of the initial 308 m long stretch was made more difficult by the abandoned mine workings encountered, which had to be filled. The construction of pre-vault segments was also very difficult. In addition, the stability of the primary lining had to be improved by means of radial anchors and bracing concrete sills. An invert was installed under 11 of the pre-vaults.

In the second stretch, which was 370 m long and ended at chainage 1.920 km, the excavation encountered the geotechnical conditions that had been anticipated in the survey, and progressed satisfactorily, with monthly advance rates of nearly 100 m.

Excavation of the next stretch, beyond chainage 1.920 km, encountered highly unfavourable and unexpected geotechnical conditions (weathered and fractured rock, stiff consistency claystone). A series of measures was adopted to stop the increase in deformations (radial anchors, closing of the profile and bracing of the pre-vaults). Despite all these measures, the tunnel collapsed at chainage 2.082 km, along a length of about 85 m, on 5 May 2003. The pre-vault machine was buried by the collapse.

The tunnel excavation was eventually finished by counter-heading from the other portal, using the sequential excavation method (SEM). The recovery of the collapsed tunnel and the pre-vault machine required extraordinary measures (for more detail see Barták, 2007). The fact that no one was injured either during the collapse event or during the recovery operations is a great positive.

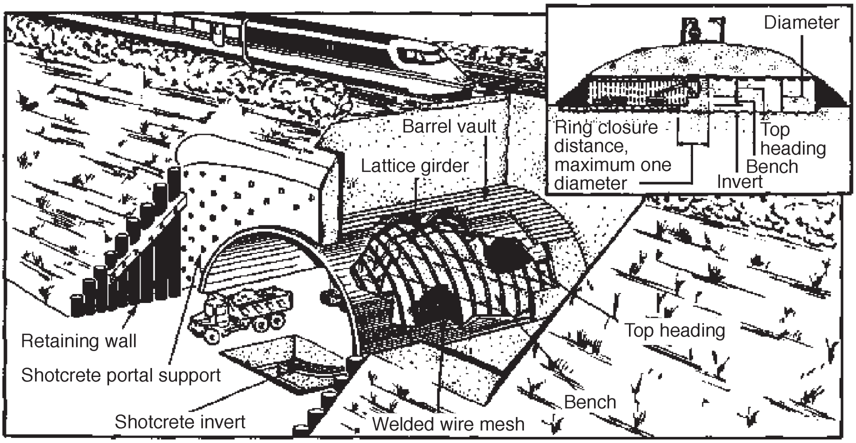
At the beginning, the final (secondary) lining was erected concurrently with the excavation; with a lag behind the excavation face of over 400 m. The concrete invert was cast under a steel bridge structure, which allowed access to the face; it was moved ahead along with the excavation face proceeding. Then the installation of the waterproofing system and casting of the upper vault followed. The rail line was opened to traffic on 1 April 2007.

7.5. Barrel vault method

The barrel vault method (basically, the construction of horizontal piles by jet grouting) falls into the category of reliable options for tunnelling under special conditions (e.g. underpasses under highways, railways, airport runways, buildings or rivers, and tunnelling in groundwater) (Sauer and Gold, 1989). For this reason this technique is popular in Europe, where it is used to ensure safe mining operations under railway embankments and expressways, and wherever settlement must be kept at the observational limit (Figure 7.8).

The method consists of placing metal grouting pipes horizontally along the tunnel perimeter, above the upper part of the crown and ahead of the tunnel heading. After the

Figure 7.8 Barrel vault method



high-pressure grouting has been completed, the cylindrical masses of cement grout, reinforced with the steel pipes, in effect create horizontal piles, arranged in a way that resembles the form of a barrel. This outer shell longitudinally bridges the unsupported area between the undisturbed ground in front of the excavation area and the completed initial tunnel lining behind it. The method is designed to increase the stand-up time and prevent ravelling.

The use of the barrel vault method on the Channel Tunnel rail link and on an urban highway tunnel and service areas in Boston, MA, USA, is described in Case Study 7.4.

Case study 7.4

Barrel vault method – some projects

Channel Tunnel rail link
Owner: London and Continental Railways

Service performed: preliminary design of NATM alternatives for a road under crossing and barrel vault tunnel alternative for railway line under crossing.

Project period: 1997–2003.

Location: Kent, UK.

Technical data: three twin-track railway tunnels, approximately 12 m span, oblique to a 35 m wide chalk spine; one 7 m span access tunnel, 35 m long.

Geology: weak rock, upper chalk and chalk/clay fill embankment.

Special construction techniques: barrel vault method.

Urban highway tunnel and service areas, Boston, MA, USA
Project period: 1995–2003

Technical data: tunnel, four lanes, length 1200 m (3940 ft)

Geology: glacial till (cohesive and granular) and weathered to unweathered argillite bedrock.

Categories: urban highway tunnel, service areas.

Construction techniques: NATM with various pre-support and groundwater cut-off measures, including barrel vaulting and cut-off walls.

Special construction techniques: barrel vault method.

(Dr. Sauer & Partners, 2017)

7.6. Ground improvement

For shield tunnelling, particularly in soft rocks and difficult ground conditions, it is essential to improve the ground through some type of treatment before the start of the tunnelling operation. Soft ground conditions could be any, or a combination of, the following ground types: firm, ravelling, squeezing, running, flowing or swelling (see Section 1.8 and Table 1.7) (Whittaker and Frith, 1990). The techniques used to treat soft ground are summarised in Table 7.2. It should be mentioned that chemical grouts, which include cement and other chemicals, find applications in most of the conditions noted.

Ground can be treated before, during or after the driving of tunnels and caverns. Different alternatives for treating ground are available, and the selection of any one of them

Table 7.2 Ground treatment measures and techniques for treating water problems

Technique/treatment measures	Characteristics and applications
Compressed air to hold back water	■ Prevention of seepage of water at the face (sandy soil, cohesive soil) ■ Retaining the soil at the face (cohesive soil) ■ Increasing ground strength by means of dewatering
Groundwater lowering	■ Lowering the water level (sandy soil)
Chemical grouting, using cement, clay or bentonite, and liquids (usually colloidal solutions that set into a gel)	■ Preventing seepage of water at the face (sandy soil) ■ Increasing adhesion of the soil (sandy soil) ■ Reducing the air permeability of the ground (sandy soil) ■ Increasing the strength of ground (sandy soil, cohesive soil)
Freezing	■ Preventing the seepage of water at the face ■ Increasing the strength of ground

depends on the magnitude of the problem, the site conditions, and the judgement and experience of the engineers.

- *Reinforcement*. Bolting, anchoring and surface coating can be used to reinforce rock. Rock bolting is the established practice for reinforcing rocks. Lining the ground by spraying concrete (shotcreting), guniting or the use of prefabricated concrete blocks in the form of supports of different kinds are the usual methods. The application and other details of these techniques are dealt with in Chapter 4.
- *Lowering the water-table/groundwater*. Treatment that tackles the problems caused by the presence of water (see Table 7.2).
- *Grouting*. Grouting is an expensive way of reducing the inflow of water when undertaking subsurface excavations and operations. It also delays the work. It should, therefore, be used only when drainage and pumping, which are cheaper and faster, are impractical; when seepage must be reduced substantially in the long term as well as the short term; or when both the strength and the watertightness of the rock mass need to be improved (Johnson, 1982). Grouting also can be beneficial in underground mines where water inflows would otherwise lead to difficult and unsafe mining conditions.

An example of the use of grouting at subsea tunnel at Xiang'an, China, is given in Case Study 7.5.

Case study 7.5

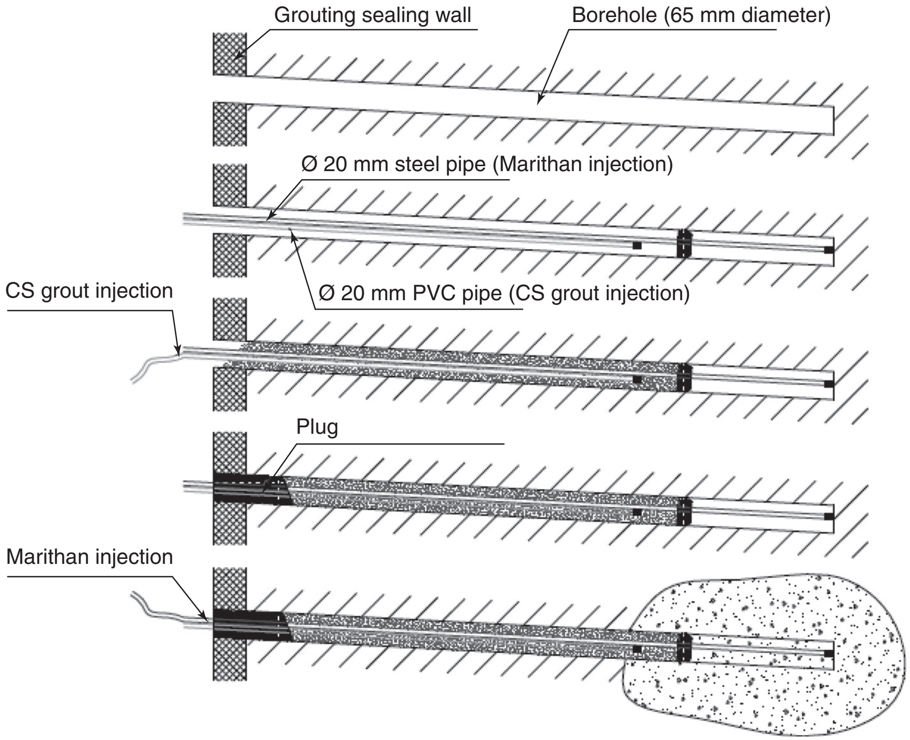
Grouting – subsea tunnel, Xiang'an, China

Zhang *et al*. (2014) studied grouting techniques for the unfavourable geological conditions (highly weathered rock) faced when driving a tunnel under the seabed at Xiang'an, China. They considered five stages of a typical grouting process: backfill and permeation grouting, compaction grouting, primary fracture grouting, secondary compaction grouting and secondary fracture grouting. A cement grouting was used to reinforce and seal the rock, and the permeability was further reduced by the injection of Marithan (Figure 7.9).* This reinforcement technique significantly reduced the permeability, strengthened the ground and guaranteed the stability of the excavation.

It is noted that due to the uncertainties with regard to the geotechnical and geological conditions, and the complex interactions between the ground and the grouting material, the grouting parameters (e.g. grouting pressure, grouting material and amount of grouting) employed during construction were mainly determined from field tests. Zhang *et al*. recommended that some further studies should be performed to determine the grouting parameters.

*Marithan is a chemical grout mixture composed of ordinary Portland cement (P O 42.5R) and sodium silicate ($Na_2O{\cdot}3SiO_2$, 30–45 degrees Baumé). Marithan is a two-component polyurethane product, which has high adhesive strength and outstanding mechanical properties. It can create a bond with the rock and can remain intact throughout the lifetime of the project. When the product is injected into the ground, the low-viscosity mixture remains liquid for several seconds and penetrates easily into the fissures, where it expands, sets and seals the threaded zone.

Figure 7.9 Injecting grout in a borehole



7.7. Use of shotcrete during tunnelling

The ground can be lined by spraying concrete using the techniques of ‘shotcreting’ and ‘guniting’. This is a common procedure when driving tunnels and caverns (Hack, 1996). The salient points that should be considered when adopting these techniques include

- supporting agents/elements in face zone
- lining thickness
- safety of the crew
- working conditions and health protection of crews
- degree of mechanisation
- degree of standardisation
- danger of breakage/collapse/failures
- construction time and cost – short tunnels, long tunnels.

7.8. Cut-and-cover tunnelling

For shallow depth tunnels, the cut-and-cover technique is the fastest method. In this method, a trench is created at the tunnel site using the conventional methods of rock fragmentation and ground digging. In soft ground, the sides are supported using piles (Megaw and Bartlett, 1983). In the *bottom-up method*, the whole width of the tunnel is excavated first, and then the sides and roof are supported. In the *top-down method*, first the sides are dug, and then concrete is placed or some other form of support is built at both sides. The tunnel is covered with a roof slab, and excavation of the ground enclosed by the two sides follows. The top of the roof slab is backfilled to restore the surface. The ground can then be used in the same manner as before or in an even better way. The top-down method is also used to construct portals, particularly in hilly terrain.

The original parts of the London Underground network, the Metropolitan and District Lines, were constructed using the cut-and-cover method. A major disadvantage of the technique is the widespread disruption generated at the surface level during construction. This, and the availability of electric traction, brought about London Underground's switch towards the end of the 19th century to bored tunnels at a deeper level, and this model (concept) has been adopted the world over for undertaking such constructions at subsurface levels.

7.9. Submerged (immersed) tubes/tunnels

Submerged or immersed tunnels are tunnels built under water bodies. There are two methods of building such tunnels (Megaw and Bartlett, 1983).

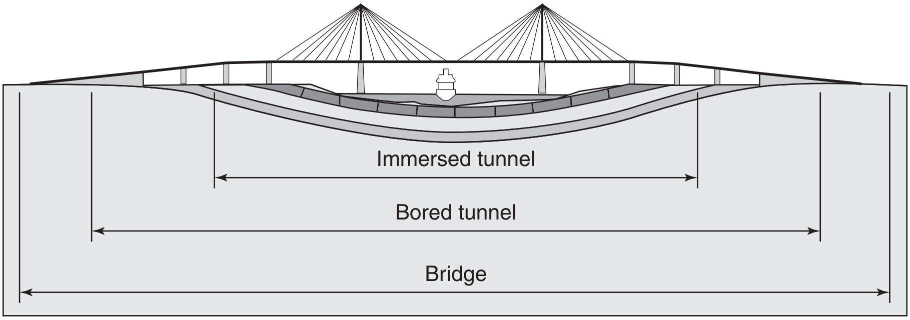
In the first method, which leaves a sufficient cover of ground between the floor of the water body and the back of the tunnel, the tunnel is driven by the use of borers.

In the second method, a trench is dug below the floor of the water body, and the trench floor covered with sand or gravel. The tunnel, which can be circular or rectangular in cross-section, is then built by assembling prefabricated steel tubing or reinforced-concrete elements. The tunnel elements are constructed in the dry at any place of convenience, and the ends of each element are temporarily sealed with bulkheads. The elements are transported to the tunnel site, usually by floating, and occasionally on a barge or assisted by cranes. The elements are sunk into the tunnel trench using pontoons or other floating craft. Care is taken to perfectly join the elements of the tunnel to ensure watertightness. The trench sides are backfilled with suitable sand and gravel, and fill is also pumped over the area where the tunnel has been built. Approach structures can be built on the banks before, after or concurrently with the immersed tunnel, depending on the conditions.

Immersed tunnels can be a suitable alternative to bored tunnels where a waterway needs to be crossed. Manufacturers that advocate this method state that it works out to be cheaper. This concept is not new but more than 100 years old, and more than 150 immersed tunnels have been constructed worldwide. The technique involves suspending a tunnel within the waterway.

Immersed tunnels can be placed immediately beneath a waterway. In contrast, a bored tunnel is usually only stable if its roof is at least its own diameter beneath the water. This allows immersed tunnels to be shorter and/or approach gradients to be flatter – an

Figure 7.10 Longitudinal cross-section of an immersed tunnel (ITA, 1999)



advantage for all tunnels but especially so for a railway tunnel. These tunnels can be constructed in ground conditions that preclude bored tunnelling or render it prohibitively expensive, such as in the soft alluvial deposits that are characteristic of large river estuaries. They can also be constructed in earthquake-prone areas (Figure 7.10).

They need not be circular in cross-section. Almost any section can be accommodated, which makes this option very attractive for road, rail and other purposes.

A comparison of the advantages and disadvantages of immersed tunnels, bored tunnels and bridges for crossing waterways is given in Table 7.3.

Examples of immersed tunnels are given in Case Study 7.6.

Table 7.3 Comparison of immersed tunnelling and other options for crossing waterways (courtesy of Ramboll)

	Immersed tunnel	Bored tunnel	Bridge
Economical shape	+	–	+
Economical length	+	–	–
Vertical clearance	+	+	–
Seabed depth	–	–	+
Hard ground conditions	–	+/–	+
Soft ground conditions	+	+/–	+/–
Seismic conditions	+	+/–	+/–
Environment	+	+	–
Construction costs	–	+/–	+
Maintenance costs	+	+	–

(+) Advantages and (–) disadvantages compared with other techniques.

Case study 7.6

Immersed tunnels

Given below are few examples of immersed tunnels that have been built in the recent past.

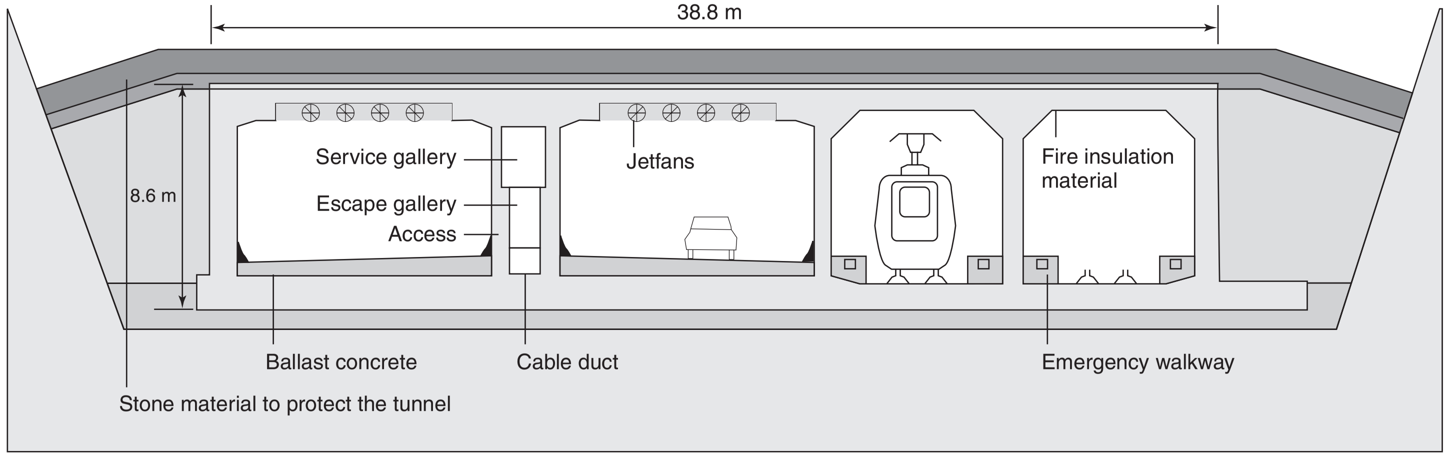
- The fixed link between South Korea's coastal city of Busan and Geoje Island was inaugurated in December 2010. It is one of the world's deepest immersed road tunnels (48 m below mean water level). The link includes two major cable-stayed bridges.
- The new crossing at Frederikssund, Denmark, 2008–2009.
- The Söderströmstunneln is part of the Citybanan project in Stockholm, Sweden, which began in 2006. An approximately 6 km long tunnel running beneath central Stockholm contains two railway tracks and three new underground stations. When finalised the new line will double the capacity for rail traffic through central Stockholm.
- The Fehmarn Belt Fixed Link will be an immersed tunnel connecting the Danish island of Lolland with the German island of Fehmarn. The assignment is currently under tender. The tunnel will have four tubes: two will carry road traffic and each will have two lanes and an emergency lane; two tubes will each have one rail track. The tunnel cross-section will be rectangular, approximately 40 m wide and 10 m high. Galleries (2.0 m wide) containing technical installations will be located between the road tubes.
- The Øresund fixed link (Figure 7.11) comprises a 16 km long fixed motorway and railway link across Øresund. It has four major elements: an artificial peninsula from the Danish coast at Kastrup, a 3.5 km long immersed tunnel, a 4 km long artificial island (Peberholm) south of Saltholm, and a 7.8 km long bridge from Peberholm to Lernacken in Sweden. The consultants Ramboll constructed a complete illustrative design of all four components. The project was commissioned during 1993–2000 and is currently progressing smoothly.
- Work is under way to build a fixed link between Hong Kong and mainland China (Hong Kong–Zhuhai–Macao). The structure is considered to be China's most important infrastructure project, both technically and politically, and will include the world's longest immersed tunnel for road traffic. Construction began in 2009, and is expected to open for use in December 2017.

7.10. Box jacking

Box jacking is similar to pipe jacking (described in Chapter 8), but instead of jacking tubes, a box-shaped tunnel is used. Jacked boxes can have a much larger span than a pipe jack, with the span of some box jacks being in excess of 20 m (66 ft). A cutting head is normally used at the front of the box being jacked, and spoil removal is normally by excavator from within the box (TerraSolutions UK, 2012).

Reinforced concrete box jacking process. First, the box section is designed and cast, either at the site or offsite and then transported to the site, depending on the requirements. The

Figure 7.11 Cross-section of the 4 km immersed tunnel at Øresund Fixed Link, Denmark (courtesy of Ramboll)



foundation boxes, which are designed to carry the dead and the live loads, are jacked into the ground. Then, high-capacity jacks are placed at the back of the box and the box is pushed into the ground. A purpose-designed tunnelling shield is provided in the front end. The box is then jacked carefully through the earth. Excavation and jacking are done in small increments of advance. Measures should be taken to prevent the soil being dragged towards the box.

Problems encountered during jacking. Settlement of the ground above, seepage of ground water and caving in of soil, etc., are some of the problems that are encountered during the jacking process. The technique of ground freezing is used to deal with these problems. The technique involves circulating a brine solution maintained at −30°C through the tubes/pipes that have been fixed in the soil at suitable intervals. This results in freezing of the ground, which then behaves like an ice block. To avoid the ground upheaving; the whole process should be carefully designed and executed. As an example, the Southern Boston piers transit way was to pass below the 100-year-old Russia Wharf Building, and this technique was adopted to freeze 2 m thick soil; underpinning was also done using mini piles.

Merits and demerits of the box jacking process. The process enables timely completion of the project without disruption to traffic, and it complies with all European directives relating to the protection of the environment. Some of the demerits of the process are higher costs and the need for skilled crews and the observance of proper safety precautions. However, box jacking will undoubtedly continue to be the most advantageous method of installing underground infrastructure for whatever purpose it is intended.

7.11. Concluding remarks

The success of any tunnelling technique lies in keeping disturbance to the natural ground setting to a minimum. This results in reduced costs and the minimisation of problems. Techniques for achieving this have been described in this chapter.

- Flexibility is the main advantage of the NATM over other tunnelling methods. The method involves immediate sequential support to prevent micro and macro differential movements.
- Unlike conventional methods, the NATM treats the initial lining as an integral part of the overall design. The finite-element method (FEM) is used to perform a structural analysis of both the initial and the final lining systems. In the NATM water inflow needs are controlled to ensure that the pore-water pressure is within tolerable limits.
- In NATM construction, the excavation procedure and initial support is adjusted to optimally accommodate the ground conditions encountered, in order to achieve cost savings.
- The LTM Corporation claims that the use of LTM reduces the time of construction by 30% or more and costs by 10% or more, due to the minimisation of the loosened area around the tunnel face.
- The MPTM provides the opportunity to adapt the tunnel cross-sectional shape to meet the requirements imposed by the geology, tunnel usage or both, whereas

tunnels created using TBMs are always circular. For large-span tunnel openings, the cost of an MPTM is of the order of 10% of the cost of a TBM for tunnel lengths up to 3–4 km. However, for longer tunnel lengths, the use of a TBM has a time advantage, unless tunnel excavation can proceed on more than two tunnel headings simultaneously.
- The barrel vault method is a reliable option for tunnelling for underpasses under highways, railways, airport runways, buildings or rivers, and tunnelling in groundwater.
- Ground can be treated before, during or after driving tunnels and caverns. Chemical grouts, which are composed of cement and other chemicals, find applications in most of the conditions that are encountered.
- Cut-and-cover tunnelling is the fastest method for shallow tunnels, and it is also used to construct portals, particularly in hilly terrain.

7.12. Questions

1. Is it true that keeping disturbance to the natural ground setting to a minimum could be considered as directly proportional to the cost reduction and the minimisation of the problems?
2. What does NATM stand for? Give a brief history of the origin of this method. What is its main advantage over other methods?
3. Draw a diagram to illustrate the principle of the NATM. List its main guidelines.
4. Do you agree: The sooner that the initial support is put in place and functional the better it is?
5. What is the usual shape of the ‘load-carrying arch’ that develops around an opening? List the salient features of the NATM as described by Heflin and Mohammad (1987).
6. Is it true that the excavation sequence used in the NATM minimises ground disturbance in order to preserve the inherent strength of the ground?
7. What criteria are used to select the tunnel shape?
8. Into how many categories is ground subdivided, and on what criteria is this division based?
9. Is it true that NATM, unlike conventional methods, treats the initial lining as an integral part of the overall design?
10. What is the use the finite-element method (FEM) in the NATM system?
11. In the NATM, why is the installation of piezometers at critical locations specified during the design phase? What guidelines are followed to control water inflow during tunnelling operations?
12. For NATM to be performed safely in soft ground, what precautions should be taken?
13. Depending on the ground conditions and the need to protect surface installations, wherever applicable, the initial support systems listed below can be incorporated in the NATM design:
    (i) sealing shotcrete
    (ii) lattice girders
    (iii) soil anchors

(iv) welded wire fabric
(v) rebar splices for initial shotcrete lining
(vi) structural shotcrete in layers, as specified
(vii) reinforcing-rod spiling
(viii) perforated-pipe spiling used to pre-grout short distances ahead of the face, generally 3–4.5 m
(ix) plastic sleeve pipes used to pre-grout longer distances ahead of the face, generally 15–21 m
(x) steel poling plates.

Specify the ground conditions where systems (i)–(v) are considered the standard means of initial support.

Specify the ground conditions where systems (vi)–(x) should be considered.

14 In the NATM, the design identifies the critical cross-sections where monitoring is required. A wide range of instrumentation is used for this purpose. Make a list of this instrumentation.

15 In NATM construction, why is the excavation procedure and the initial support varied?

16 Give the uniaxial compressive strength (UCS) and tunnel cross-section size ranges for which NATM can be applied.

17 List other names that are used for the NATM.

18 List the excavation sequence that is followed in the NATM to minimise ground disturbance.

19 Could the NATM be applied in fissured and heavily watered formations?

20 Describe briefly Lee's tunnelling method (LTM). Who developed this method and how does it compare with other methods, as claimed by its developers? You can present your comparison with other methods as a graph.

21 Why in the LTM is the major direction of crack propagation due to blasting to the front of the face, contrary to what occurs when using conventional drilling and blasting, where the charge holes are drilled longitudinally?

22 List the sets of equipment that make up an LTM equipment fleet.

23 List the steps that are taken when undertaking a LTM tunnelling project.

24 Describe the pre-vault method (mechanical pre-cutting tunnelling method, MPTM). Mention its scope of application. Is this method applicable for large tunnels having cross-sections up to 150 m^2?

25 List the applications of the MPTM, covering the following aspects:

- tunnel cross-section
- tunnel length
- geology
- tunnelling under the water-table
- in rocks (mention the UCS limit)

26 It is claimed that the MPTM results in better safety, quality of end product and economy. Give your comments on this claim. List the salient features of this technique.

27 In what way is the MPTM a flexible method?

28 Why are both the MPTM and TBMs better options than other techniques from an environmental point of view?

29 Why is shotcreting in the MPTM cleaner than in the conventional tunnelling methods?

30 Is it true that the MPTM provides the opportunity to adapt the tunnel cross-section to meet the requirements imposed by the geology, tunnel use or both, unlike tunnels bored using TBMs, which are circular? Also, is it true that TBMs are made in diameters of up to about 19 m, whereas the MPTM can be applied to larger tunnel cross-sections?

31 Is it true that for large-span tunnel openings, (i.e. in excess of 8 m) the cost of an MPTM is of the order of 10% of that of a TBM? Why can the MPTM compete successfully with the use of TBMs for the majority of urban tunnelling projects?

32 Describe the barrel vault method. Is it a reliable option for tunnelling under special conditions? Can you list those conditions? Why is this technique popular in Europe?

33 Why is ground treatment usually essential prior to shield tunnelling? What do you understand by the term ‘soft ground conditions’? Describe these conditions.

34 Why do chemical grouts find applications in most soft ground conditions?

35 When can ground be treated? What alternatives are available to treat ground, and what needs to be taken into consideration when selecting a treatment?

36 Describe the following techniques, mentioning their applications:
(a) reinforcement
(b) grouting
(c) lowering the water-table/groundwater level.

37 List the salient points that should be considered when adopting the techniques of shotcreting and guniting.

38 When should tunnelling by the cut-and-cover method should be selected? Describe this method. Is this method also utilised to construct portals, particularly in hilly terrain? Distinguish between the top-down method and bottom-up method versions of this method.

39 Why could immersed tunnels be a suitable alternative to bored tunnels where a waterway needs to be crossed? Can immersed tunnels be placed immediately beneath a waterway? What features of immersed tunnels make them highly attractive for road, rail and other purposes?

40 List the options for crossing waterways. Compare the various aspects of these options using + or – signs to show where one option is advantageous or disadvantageous compared with the others.

41 Describe box jacking. What problems are usually encountered in this technique? List its merits and demerits.

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Chapter 8
Microtunnelling

The trenchless technology revolution is in its full swing due to its inherent features: economy, convenience and lack of disturbance. It has huge potential.

8.1. Introduction

The concept of trenchless technology came into use in the UK in the 1950s, in Japan in the 1960s, in Germany in the 1970s and in the USA in the 1980s (Thomson, 1985). The social and economic significance of this technology is widely appreciated the world over, and its use is in full swing, as evidenced by the projects that are underway in different parts of the world. Applications vary from country to country but the dominating microtunnel size is $>$100 mm. Trenchless technology is chosen for reasons of economy, convenience and lack of disturbance. One can foresee a potentially huge market for this technique.

In conventional and mechanised methods of trenching (described in Chapter 3), trenches are dug from the surface. The trenches are used for many purposes, and involve indirect costs and public concerns (e.g. road damage, damage to adjacent utilities, disruption of traffic and collateral damage to local businesses that lose customers due to the works). The public has accepted these shortcomings in the past because there was no other way to install or repair some essential services.

In general, the term 'microtunnelling' refers to the driving of subsurface small-sized openings or trenches to lay down pipelines for water and gas, cables for power and telecoms, and sewer lines. This is also known as *trenchless technology*. As there is now no size limit for microtunnelling, the technology has reached a stage where it is difficult to distinguish between this method and other tunnelling methods. The market for microtunnelling is expanding continuously due to the advantages of this method over trenching, particularly in terms of public acceptance due to the far reduced inconvenience and annoyance associated with it compared with the traditional methods and techniques.

There is no universally accepted definition of microtunnelling. However, the definition accepted in the USA is (Nicholas, 2002): a remotely controlled, laser-guided pipe jacking process that does not require entry into the tunnel of personnel; it is a 'trenchless construction method' that has no size limitations. This definition may not be applicable everywhere but will be followed in this chapter.

A tunnel may be considered a microtunnel if all the following are used during construction:

- Remote control: the entry of personnel is not required for operation.
- Guiding: this normally refers to the use of a laser beam to guide the operation. This factor enables the installation of gravity sewers at the required tolerance for line and grade.
- Pipe jacking: the pipeline is constructed by consecutively pushing pipes using a jacking system. The pipe is installed as the spoil is continuously excavated and removed.
- Continuous support: continuous pressure is provided to the face of the excavation to balance the groundwater and earth pressures.

Microtunnelling can be used to install any size of pipe (within the practical limits described in the following paragraphs), and it can be used successfully under a variety of ground conditions, ranging from soft soils to rock, including mixed face conditions, and above or below groundwater.

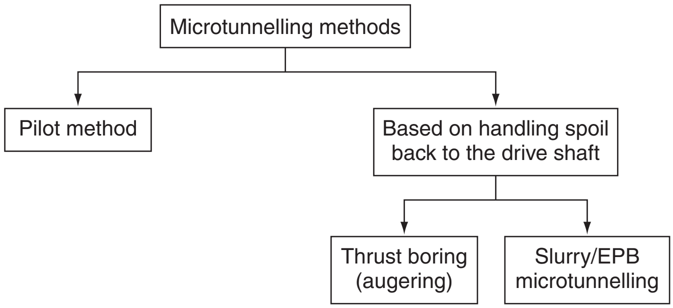
8.2. Pipe jacking

The pipe jacking technique utilises a set of systems that provide integration of the tasks required to build a tunnel. It can be described as a process that encompasses the horizontal thrusting of prefabricated elements (pipes) through the earth to provide a structurally stable opening. When building microtunnels, pipe jacking is an integral and dominant operation. Pipe jacking and microtunnelling really have the same meaning, as they refer to a process in which the soil is removed by the machine and transported by a conveying system specifically adapted to that particular technique. The hydraulic thrust jacks installed in the launch shaft drive the jacking pipe in the direction of the reception shaft. The tunnel extends pipe by pipe right up to the breakthrough.

The following operations need to be carried out when constructing microtunnels in soft ground:

- control of the soil at and around the working face

Figure 8.1 Classification of microtunnelling methods



- excavation of the soil from the working face
- loading of the spoil or ‘muck’ onto a haulage system and its removal from the microtunnel for installation of the required earth support systems.

A classification of microtunnelling methods is given in Figure 8.1 (Boyce and Gray, 1996; Herrenknecht, 1999; Nicholas, 2002).

8.3. Pilot method/horizontal directional drilling

The pilot method requires two shafts, one of which is known as the *launch* and the other as the *reception*. At a predetermined position, a pilot hole is driven from the launching shaft; later, it joins the reception shaft. The drill bit is then replaced with an enlargement head and the pilot hole is enlarged; subsequently, the pipes to be fitted (known as product pipes) are jacked. This method is also known as *horizontal directional drilling* (HDD). HDD involves drilling a small-diameter (50–200 mm) pilot hole, the alignment of which can be controlled horizontally and vertically. The pilot hole is reamed to a larger diameter (depending on the final diameter of the pipe) and the pipe pushed into place. HDD installations can be up to 1700 m in length. The operational details and data of with this technology are given in Table 8.1 and described below.

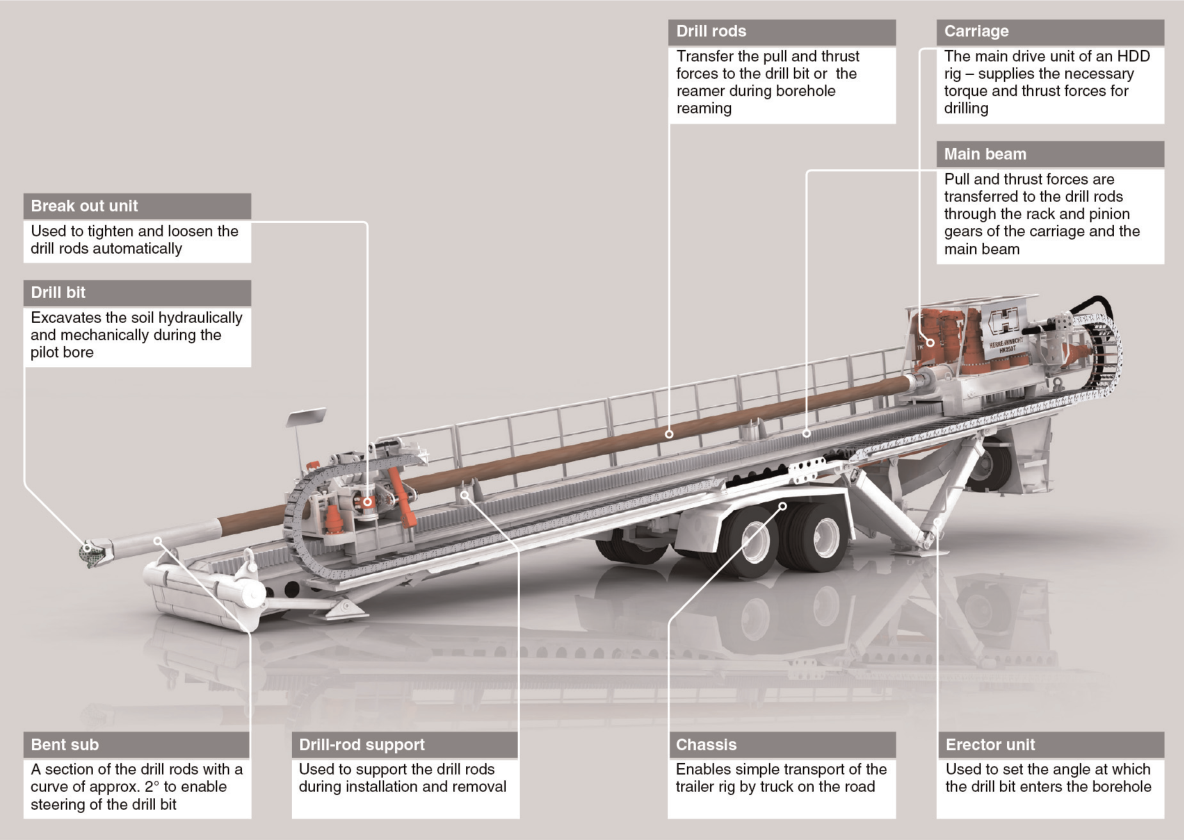
HDD technology is simple but functional. Pipelines are installed in three steps.

1 The HDD rig (Figure 8.2) is used to bore a pilot hole from the launch point towards the reception point. The rotating drill rods are precisely guided along the

Table 8.1 Operational data for an HDD rig (courtesy of Herrenknecht AG)

Operational details, geology and diameter range	Significant features
Geology: soft ground, rock (relatively stable ground is a prerequisite) *Diameter range*: 0.2–2 m (8–80 in.) **Functionality** *Excavation*: a drill bit excavates the soil in a pilot hole; subsequently, a reamer widens the borehole *Borehole support*: hydraulic support using a bentonite suspension *Removal of material*: hydraulic conveyance of the excavated material through the annular gap using a bentonite suspension *Thrust*: the carriage thrusts the rotating drill rods forward and pulls them back during reaming *Tunnel lining*: pipeline	■ Economical and environmentally friendly method for installing pipelines ■ Broad geological range of application: stable loose soils and rock ■ Four basic rig types available for different ranges of implementation ■ Using the pipe thruster the available thrust and pull force can be increased (by up to 750 ton)

Figure 8.2 An HDD rig with its various components and their functions (courtesy of Herrenknecht AG)



desired alignment by means of a surveying system located directly behind the drill bit. In soft geologies the soil is excavated hydraulically using high pressure, while in rocks the excavation is done mechanically with the use of a mud motor. Bentonite is mixed with the excavated material and the mixture flows back to the starting point through the annular gap between the drill rods and the borehole wall. A suspension plant separates the liquid from the solid components and supplies the recycled suspension back to the bentonite circuit.

2. After exiting at the reception point, the pilot drill bit, including the surveying system, is removed from the drill rods and replaced by a reamer. Using the excavation tools and bentonite, the soil is excavated both hydraulically and mechanically while pulling back the drill rods through the pilot borehole. The water–bentonite mixture supports the expanded borehole, removes the soil and at the same time cools the components. Reaming is performed in several passes until the final borehole diameter (which is about 30–50% larger than the actual pipeline diameter) is achieved.
3. The pipeline is installed by connecting the prefabricated pipeline to the drill rods. Lifting the front end of the pipeline creates a so called ‘over-bend’, and the angle of entry of the pipeline is adjusted to the angle of entry of the borehole, while maintaining the minimum radius. The pipeline is then attached to the reamer and a swivel joint, and is pulled back to the entry point by the HDD rig until it reaches the final position. During this process the bentonite minimises the friction between the pipeline skin and the surrounding soil.

In situations where there are long crossings, large pipeline diameters or difficult ground conditions, a pipe thruster is used to give an extra force of up to 750 ton at the exit point.

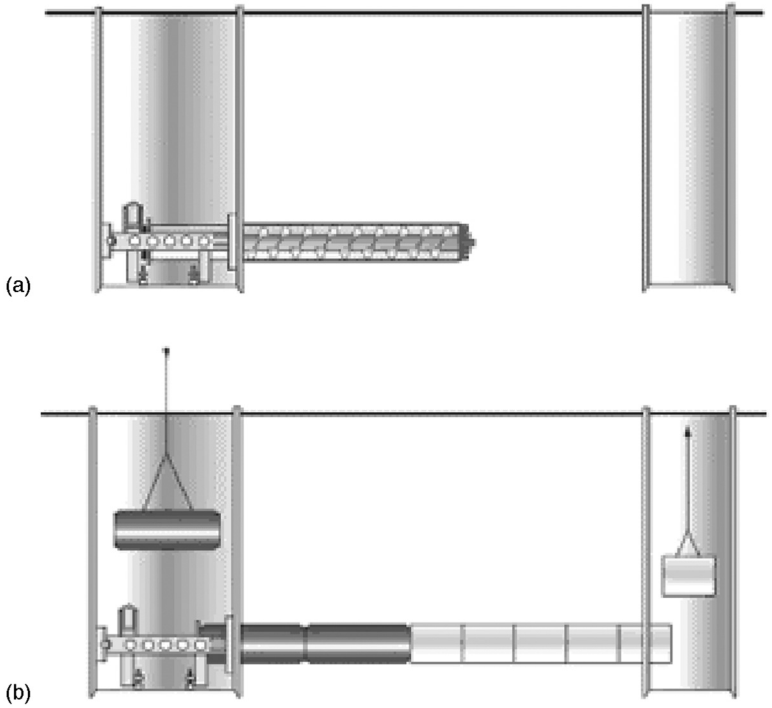
8.4. Thrust boring

In this technique, the cutting wheel cuts the material, which is then carried to the launching shaft by an auger and removed by cranes or other means. Pipes are jacked into the ground. The method is suitable for short distances. A laser guidance system is used for direction, positioning and monitoring. Data are displayed on the operator’s control panel. Conceptual diagrams of thrust boring and a boring machine are shown in Figure 8.3.

An auger boring machine uses auger flights (Figure 8.4) to transport the spoil back to the drive shaft (Herrenknecht, 1999; Hunt *et al.*, 2001; Mathy *et al.*, 1999). The power required to physically turn the auger flights restricts the maximum pipe size to 1400 mm. The typical installation length is 60–75 m. As the installation length approaches 107 m, the power required to physically turn the auger increases to a point that there is insufficient available power to turn the cutting head to cut the soil at the face of the microtunnel. Therefore, for longer lengths the cutting head is hydraulically or electrically driven and the auger flights are driven from the drive shaft, allowing bore lengths of up to 120 m.

With all these machines the material that has been excavated at the working face is removed by the augers. The augers transfer the moment of torsion from the drive to the extraction tools and convey the material. Hollow drilling augers can be pressurised

Figure 8.3 (a, b) Conceptual diagrams of thrust boring (augering). (a) For automatic drilling, the exact alignment of the machine is of utmost importance. The longer the shaft, the more exact the drill hole, with the result that longer tunnelling pipes can be deployed. (b) When drilling from a launch shaft to a target shaft (open–open), after reaching the target shaft with the product pipes, the steel protection pipes, including the auger conveyors, are jacked into the target shaft and removed from there. (c) Auger boring machine, showing the various components and their functions (courtesy of Herrenknecht AG)



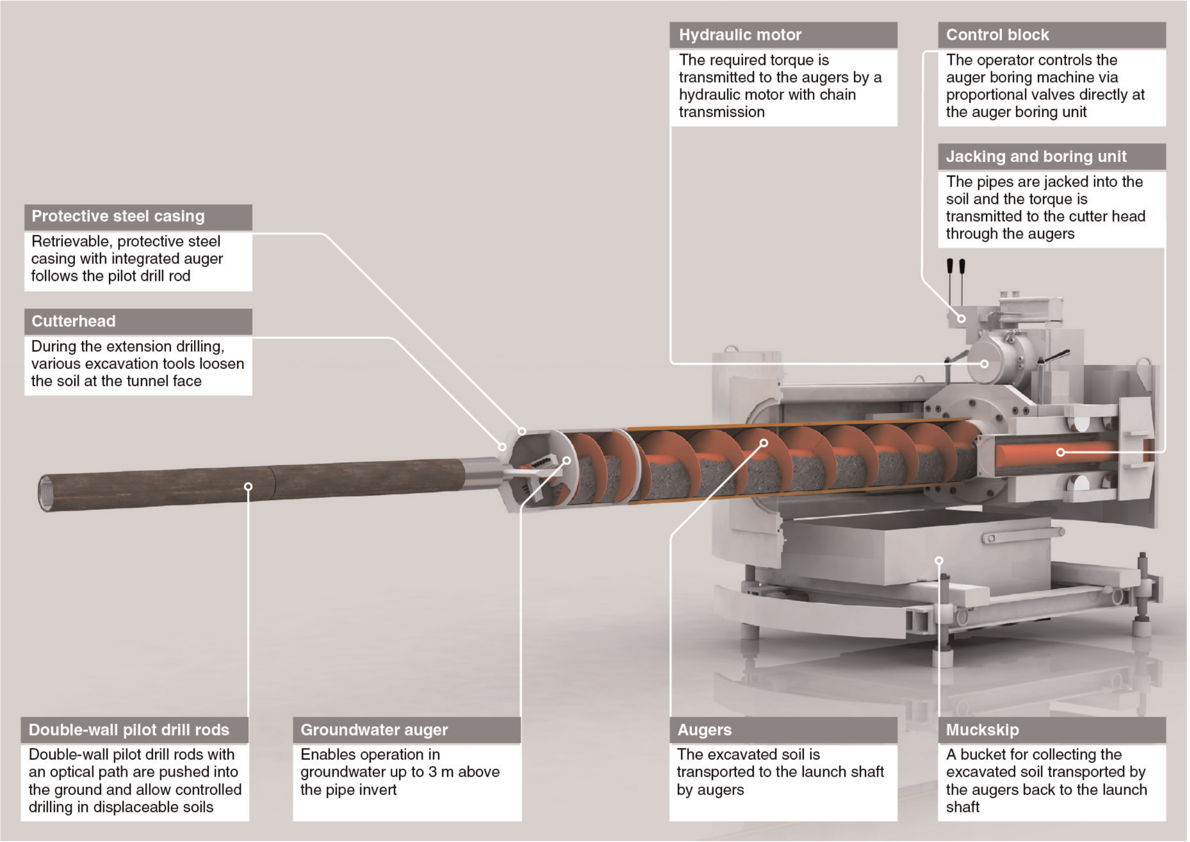
with air or water, and when a measuring system is deployed the drill hole serves as an optical lane.

The auger boring machines manufactured by Bohrtec Gesellschaft für Bohrtechnologie mbH (Alsdorf, Germany) and Herrenknecht AG (Schwanau, Germany) are claiming their place worldwide. The operational data and significant features of these machines are summarised in Table 8.2.

The following are well-known microtunnelling machine manufacturers whose equipment is in use the world over:

- Iseki Poly-Tech Inc., Tokyo, Japan
- Wirth Soltau GmbH, Geilenkirchen, Germany
- Herrenknecht AG, Schwanau, Germany
- The Robbins Company, Solon, OH, USA.

Figure 8.3 Continued



(c)

Figure 8.4 Clay pipes with auger and casing units inserted, and ready for jacking

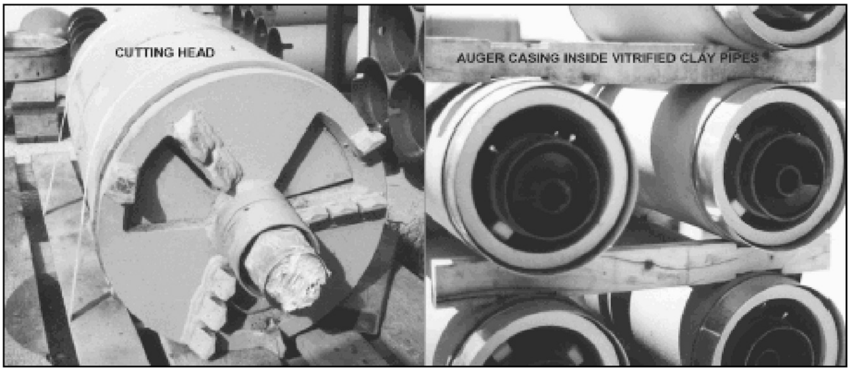


Table 8.2 Operational data for an augur boring machine (courtesy of Herrenknecht AG)

Operational details, geology and diameter range	Significant features
Geology: soft ground, heterogeneous ground, rocks *Diameter range*: 0.1–1.4 m *Excavation*: various excavation tools remove the soil *Removal of material*: augers transport the excavated material to the launching shaft *Thrust*: the jacking and boring unit in the launch shaft pushes the cutter head forward through the jacking pipes *Lining*: pipe jacking	■ Manufactured by Herrenknecht in cooperation with Bohrtec ■ Due to the simple tunnelling principle and expanded range of application, these machines can be used to install pipelines and house connections quickly and safely at low cost, and with minimum impact on the environment ■ 300 000 m of pipe has been installed underground using these units

8.5. Slurry microtunnelling machines

Slurry microtunnelling machines use a pressurised fluid to transport the cuttings to the drive shaft. The cuttings are separated from the slurry, which is then recirculated. Pipe sizes range from 250 to 3000 mm; jacking distances of up to 152 m can be achieved. Longer drives are possible if intermediate jacking stations are used.

The excavation cycle of the slurry microtunnelling machine is as follows:

1. The cutting head excavates the face and concurrently injects it with slurry to counterbalance the earth pressure.
2. The excavated soils are mixed with the slurry and pumped from the face to the settling tank to separate the soil from the slurry, which is then pumped back to the cutting head.

3 At the control panel, the operator uses a computer program and laser guidance system to direct the cutting head to replace excavated soil and jack the steel pipe into the excavated area.

8.6. Iseki Poly-Tech – Unclemole

The Unclemole is a pressurised-slurry tunnel-shield machine manufactured by Iseki Poly-Tech, Inc. (Iseki, 2017). The machine automatically counterbalances the earth pressure at the tunnel face by mechanically coordinating the excavation speed, cutting-face pressure and jacking thrust. The groundwater pressure is balanced by adjusting the pressure, flow and density of the slurry. All machine functions are controlled by one operator using a control panel located at the surface. The soil is excavated using a spoke-type cutter head with four arms, and the forward movement of the shield squeezes the soil into the crushing chamber where an eccentric rotating crusher breaks it into smaller pieces. The crusher then compacts and crushes the soil perpendicularly to the shield axis and it is transferred into the slurry chamber, from where it is transported to the slurry tank at the surface. The operation of the Unclemole is monitored continuously by means of a remote TV camera that transmits pictures to the operator at the control panel. The major components of the Unclemole include:

- the Unclemole shield
- the Molemeister (two-stage thrust jacking system)
- the slurry circulation system
- the soil separation equipment
- the operation console panel.

The Unclemole Super does everything that the Unclemole does but in addition it can be used in harder ground. In this unit, behind the roller-cutter clad head there is a crushing arrangement similar to the one in the Iseki Unclemole. This equipment has been used to install many kilometres of pipe, with internal diameters (IDs) in the range 300–2400 mm, around the world within last decade. It is claimed that this unit is more flexible than any other with regard to ground variability.

8.7. Herrenknecht microtunnelling system

The Herrenknecht microtunnelling system (AVN), is a miniaturised automated tunnel-boring machine (TBM) and slurry soil removal system. It is laser guided and computer controlled (Herrenknecht, 2017).

Face support is maintained by means of slurry pressure balanced by water used for hydraulic spoil transportation. The tunnel drive takes place in an equilibrium, with the amount of soil displaced being equal to the volume of the tunnel diameter displaced, thus causing neither surface settlement nor upheaval. The AVN machines excavate using a high-speed rotational cutting head on the leading edge of the machine. The head is hydraulically driven. It has enough power to handle any change in conditions that may be encountered. A horizontal rotary ‘coffee mill’ crusher reduces the excavated material to a maximum aggregate size of 20 mm (0.75 in.). An articulated section at the front end

Table 8.3 Operational data for an AVN machine (courtesy of Herrenknecht AG)

Operational details, geology and diameter range	Significant features
Geology: soft ground, heterogeneous ground, rocks *Diameter range*: 0.4–4.2 m *Excavation*: cutting knives and disk cutters remove the soil *Tunnel-face support*: hydraulic support using the slurry suspension *Removal of material*: hydraulic conveyance of excavated material through a closed slurry circuit *Thrust*: a jacking frame in the launch shaft or hydraulic thrust cylinders in the shield push the machine forward *Tunnel lining*: pipe jacking or segmental lining	■ Usable in almost all ground conditions and with high water pressures ■ An ideal technology for the non-man-entry diameter range (*microtunnelling*) ■ Very long pipe jacking stretches (even >1000 m) are possible with the use of intermediate jacking stations ■ Herrenknecht has delivered 950 of these machines worldwide

of the machine controls the steering correction for deviations in grade and alignment. (See Table 8.3 and Figures 8.5 and 8.6.)

AVN machines (see Figure 8.6) belong to the category of closed, full-face excavation machines with a hydraulic slurry circuit. In soft soils and mixed geologies, standard or mixed ground cutter heads are used, while a rock cutter head with disk cutters is used for tunnelling in stable rock formations. A cone-shaped crusher inside the excavation chamber crumbles stones and other obstructions to a conveyable grain size while the machine is tunnelling and advancing. The material falls through openings similar to a strainer in front of the suction port and is then removed through the slurry line together with the suspension. The excavation diameter can be enlarged using an upsize kit and a modified cutter head. This means that an AVN machine can be used to tunnel different diameters and bore tunnels for different types of pipes.

A range of surveying technologies is available to control the AVN machines. The universal Navigation System can be used in all diameter ranges. Various gyro systems and electronic water-levelling systems allow for exact positioning. The interaction between the articulation joint and the steering cylinders in the front section of the shield keeps the AVN machine precisely on course even in the presence of three-dimensional curves and tight radii.

An additional access door behind the cutter head in AVN machines allows personnel to access the tunnel face. In some tunnelling operations obstructions such as sheet-pile

Figure 8.5 Surface and subsurface layouts and schematic presentation of the terminology used for microtunnelling (courtesy of Herrenknecht AG)

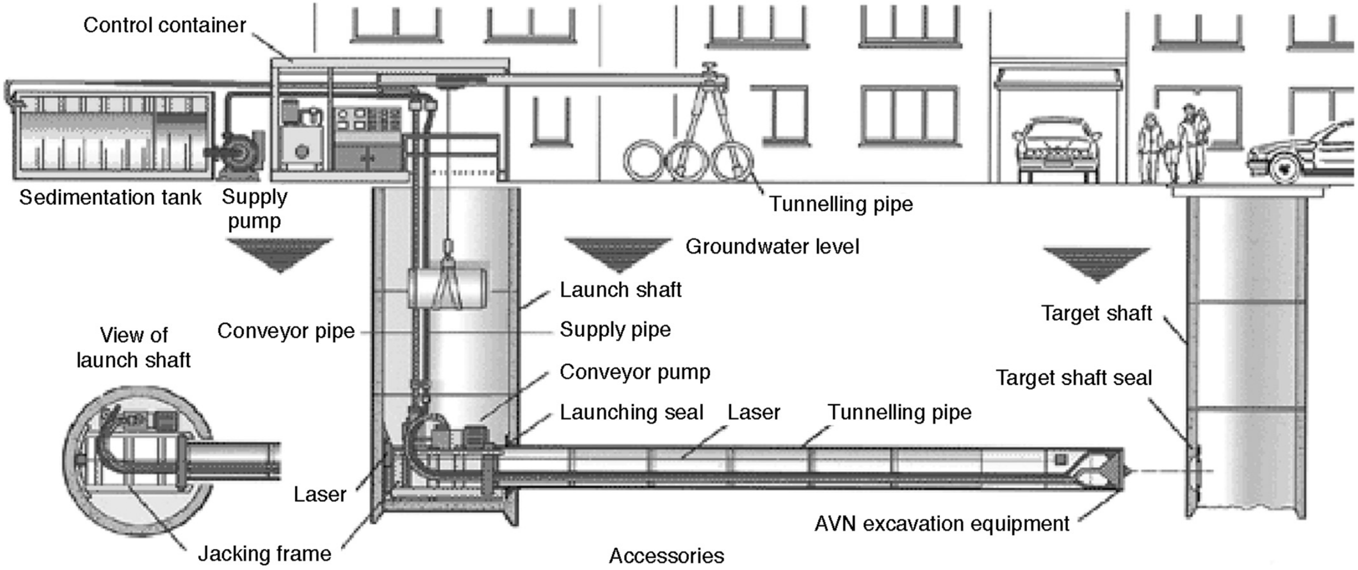
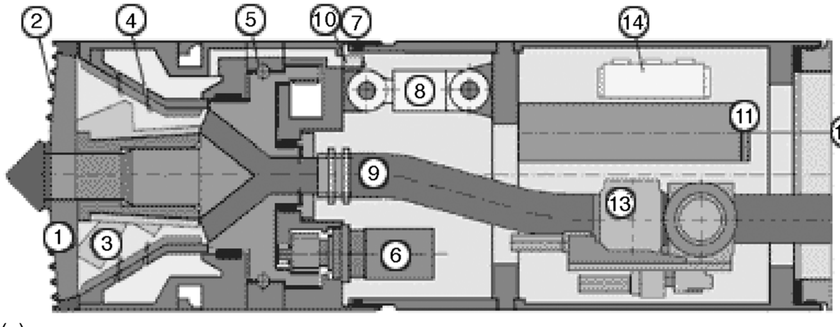


Figure 8.6 (a) An automatic tunnelling machine: 1, cutting wheel; 2, extraction tool; 3, crusher space; 4, nozzles; 5, main bearing; 6, rotation drive; 7, shield articulation seal; 8, steering cylinder; 9, conveyor pipe; 10, supply pipe; 11, electronic laser system target; 12, laser beam; 13, bypass; 14, hydraulic block. (b) An AVN1200T microtunnelling machine, showing its various components and their functions (courtesy of Herrenknecht AG)



(a)

walls, steel girders or large boulders are expected to occur from the very beginning. In these cases, AVN machines equipped with an additional door behind the cutter head are often preferred.

8.7.1 Tunnelling without reception shaft

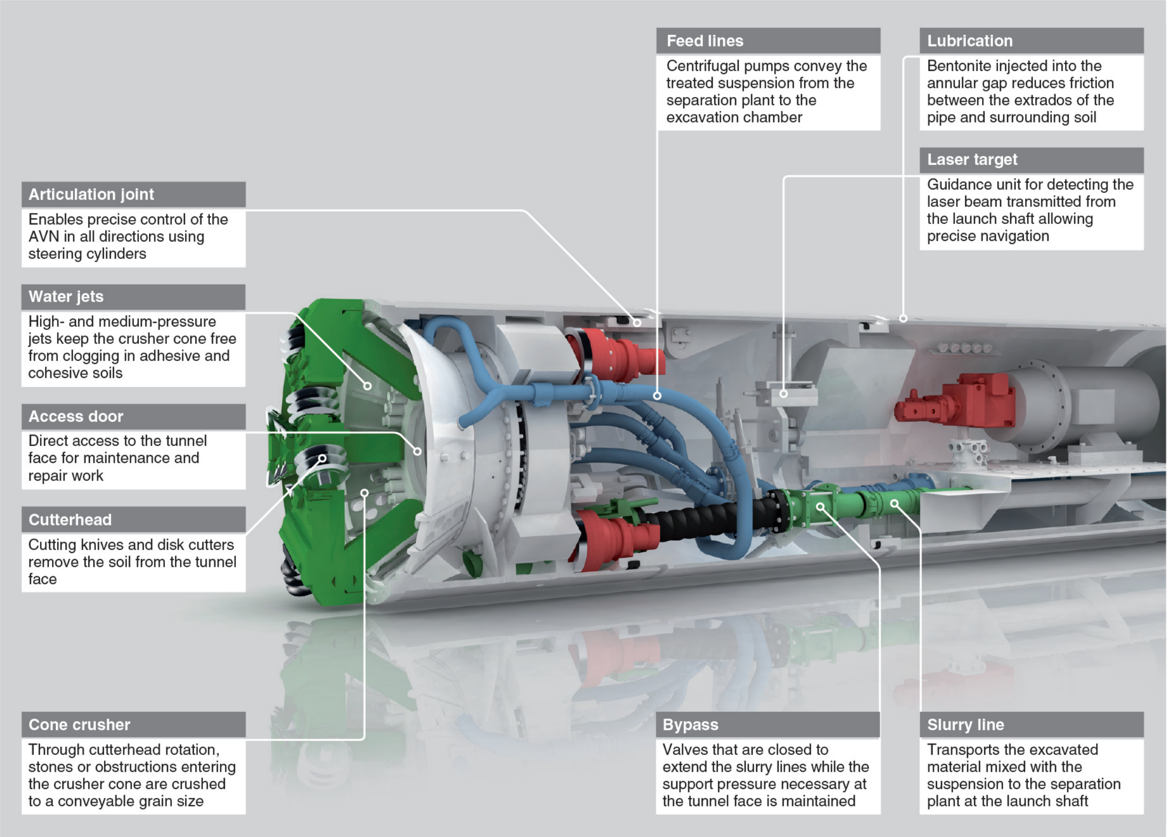
So-called ‘blind-hole tunnels’ are a special challenge, especially in non-accessible microtunnelling diameters. Blind-hole tunnels end directly in the ground, making conventional recovery of the machine impossible. Herrenknecht has developed special cutterheads with a fold-away mechanism for this very special application. When the required drive length has been reached, the microtunnelling machine can be pulled back to the launch shaft with its cutterhead folded away. The jacking pipes remain in the soil. A typical project application of blind-hole tunnels is for pipe arches. Steel pipes are installed side by side in the ground to form a pipe arch. Protected by this arch, the actual tunnel diameter is then excavated using mining techniques. In this way crossings beneath railway lines can be excavated and metro stations can be built safely. A further application of blind-hole tunnels is the installation of house connections or tunnelling operations in which the reception shaft has not yet been completed for logistical reasons.

8.8. Direct pipeline installation in one step

This technique is a combination of microtunnelling and HDD. It involves the installation of a prefabricated pipeline in a borehole that is created simultaneously, making the pipe installation process faster and more economical for pipelines lengths exceeding 1500 m.

In this technique two technologies have been combined (Figure 8.7). From the launch pit, the soil is excavated using a slurry-supported AVN microtunnelling machine. The excavated material is pumped through a slurry circuit inside the prefabricated pipeline,

Figure 8.6 Continued



Articulation joint
Enables precise control of the AVN in all directions using steering cylinders

Water jets
High- and medium-pressure jets keep the crusher cone free from clogging in adhesive and cohesive soils

Access door
Direct access to the tunnel face for maintenance and repair work

Cutterhead
Cutting knives and disk cutters remove the soil from the tunnel face

Cone crusher
Through cutterhead rotation, stones or obstructions entering the crusher cone are crushed to a conveyable grain size

Feed lines
Centrifugal pumps convey the treated suspension from the separation plant to the excavation chamber

Lubrication
Bentonite injected into the annular gap reduces friction between the extrados of the pipe and surrounding soil

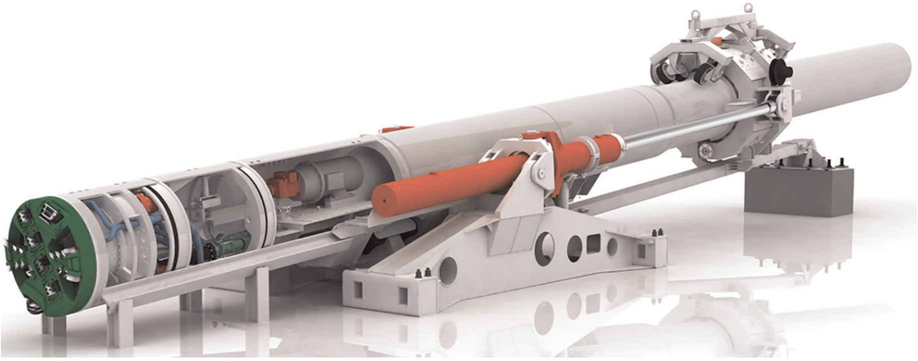
Laser target
Guidance unit for detecting the laser beam transmitted from the launch shaft allowing precise navigation

Bypass
Valves that are closed to extend the slurry lines while the support pressure necessary at the tunnel face is maintained

Slurry line
Transports the excavated material mixed with the suspension to the separation plant at the launch shaft

(b)

Figure 8.7 'Direct pipe' pipeline installation (courtesy of Herrenknecht AG)



to a separation plant located above ground. The pipeline, which is laid on the surface of the rollers and welded to the end of the microtunnelling machine, is pushed into the borehole at the same time as excavation takes place. The necessary thrust force is provided by the pipe thruster, which pushes the microtunnelling machine forward together with the pipeline – with a thrust force of 750 tonnes in increments of 5 m. The push force is transferred to the pipeline through the clamping unit on the pipe thruster and then to the cutter head. During excavation the tunnel face can be controlled consistently and safely using slurry-supported tunnelling technology, even in heterogeneous, water permeable soils. Uphill and downhill slopes as well as curved drives along the alignment can be managed precisely by the guidance system. The operational data and significant features of this technology are summarised in Table 8.4.

Table 8.4 Operational data for 'direct pipe' pipeline installation in one step (courtesy of Herrenknecht AG)

Operational details, geology and diameter range	Significant features
Geology: soft ground, heterogeneous ground, rocks *Diameter range*: 0.8–1.5 m (30–60 in.) *Excavation*: the excavation tool of the AVN machine removes the soil *Support*: hydraulic support using slurry suspension *Removal of material*: hydraulic slurry circuit through slurry pipes installed inside the pipeline *Thrust*: the pipe thruster advances the AVN machine through the pipeline *Lining*: pipeline	■ The borehole is created and the pipeline installed in a single continuous step ■ Permanent support for the borehole ■ Very high installation speed ■ No expensive shaft construction required; close to the surface the launch and target pits are sufficient ■ Direct installation of a pre-welded and pre-inspected pipeline is possible ■ Precise steering is possible on upward and downward slopes and round curves ■ With a 4 m overburden, 1400 m of drilling has been done using HDD by Herrenknecht

8.9. Developments and challenges in microtunnelling

The microtunnelling technique involves many components that are related to hydraulic, electrical, electronic and mechanical systems (Boyce and Coss, 1997; Nicholas, 2002; Zollman, 1985). The technology of these systems has developed tremendously, and this trend is continuing. Experience from three decades of the use of microtunnelling techniques has led manufacturers, contractors and researchers to redouble their efforts, and pay attention to some of the issues (see below) that could hinder performance, and thereby affect the productivity and costs of a project. This is the reason why microtunnelling systems today are more flexible, powerful, reliable and productive than the early systems. Some of the developments that have been achieved are discussed in the following paragraphs.

8.9.1 Digital control and the use of computers

The following are the key developments with respect to the use of computers in microtunnel boring machines (MTBMs):

- Like TBMs, most MTBMs are fitted with fully integrated digital control systems rather than analogue systems.
- MTBMs incorporate automatic fault warning and redundancy. A number of other functions such as gas detection, etc., could be also added.
- The new guidance systems, such as those from Tacs GmbH (Munich, Germany) and VMT GmbH (Bruchsal, Germany), have a three-dimensional graphical representation of the MTBM showing the roll and future position of the machine with reference to the laser. This is achieved by double plate targets and the latest digital cameras and processing systems.
- Features include the ability to download software and receive technical assistance on fault finding without the need for a site visit by a technician. Normally these systems are user-friendly.

8.9.2 Guidance systems

Conventional tunnel surveying methods are impracticable in microtunnelling. In the latter technique proper instrumental guidance is essential unless the tunnel is very short or accuracy is not critical. The operator needs continuous and accurate information about the positioning and attitude of the machine in order to reduce friction, to save the need for intermediate jacking stations, and to avoid costly time-wasting corrections and stoppages. Guidance systems could be for

- straight pipe jacking on straight drives up to 250 m
- pipe jacking on straight drives over 250 m – special provision is made
- pipe jacking on curves – flexible pipe is used and special features are incorporated in the machine (Camp, 2001).

The Universal Navigation System (UNS) developed by Herrenknecht, for example, can be used on straight routes up to 200 m; the UNS with additional features can be used on straight routes up to 400 m or more and even for curved routes. Microtunnelling has been completed successfully using this system to navigate both horizontal and vertical curves in 14 projects in Japan and at many other locations (Camp, 2001).

As mentioned previously, the features of a guidance system include

- Laser technology, or reference prisms and total survey stations – generally the system used on curved drives having diameters of 2 m and larger.
- Gyrocompasses with hydrostatic grade correction – used for smaller diameters (up to 600 mm ID).
- Generally, the minimum curvature radius that can be handled with standard equipment is 100 m.
- Smaller radii (20 m) have been completed using special microtunnelling equipment and pipes.
- The latest models have laser technology that is effective over 600 m. They can achieve a usable 'spot' at this distance by having the ability to focus the spot electronically as the distance increases.

8.9.3 Developments in pumps and motors

One reason why MTBMs have become so successful is the improvement in hydraulic pumps and motors. Machines can now work in variable ground conditions and deal with rocks and obstructions. Today, a 3025 mm outside diameter MTBM can have a 222 kW power pack, giving over 1 246 000 N m of torque and up to 3 rpm on the cutter.

8.9.4 Water jets

The problems of using slurry machines in plastic clays are well documented. These ground conditions lead to low output and cause high wear and tear to the equipment. In 1997, high-pressure water jets were added to the front of MTBMs. Since then, manufacturers have developed a range of water jet options that can cope with different geological situations. High-pressure jets integrated in the cone (see Figure 8.6) inject additional water to clean the system. The jets cut the clay or loam in the excavation chamber and thus prevent clogging. Medium sized jets use the standard slurry ports. The size of the nozzles can be changed to alter the suspension pressure and optimise the material flow.

8.9.5 Rock cutters

Driving microtunnels in hard formations began on an experimental basis in the 1980s, but success was limited to shorter drives in moderately soft rock. In the mid-1990s, the development and use of rock disks diverged (Boyce and Coss, 1997; Friant *et al*., 1994; Nicholas, 2002). Cutterheads of 900 mm and more are now common, and these have been used successfully in mixed ground with large boulders. For hard rock stronger than 100 MPa, the MTBM generally needs to have an outer diameter (OD) of 1320 mm or larger. Small-diameter rock heads (400–600 mm ID) can be used for sedimentary rock with rock strengths of less than 80 MPa, but the cutter heads like the one manufactured by Herrenknecht, among others, can cope with any geology, including harder formations, and any diameter range.

In soft soil and mixed geology, standard or mixed cutter heads are used, while rock cutter heads with disk cutters are used for microtunnelling in stable rock formations. A cone crusher (see Figure 8.6) inside the excavation chamber crumbles the stones and other obstructions to a conveyable size at the same time as tunnelling and advancing. The material falls through openings similar to a strainer in front of a suction port, and is removed through the slurry line together with the suspension.

8.9.6 Cutterheads for excavating in rock and mixed-face conditions

One of the problems with slurry MTBMs is that the cutters cannot be changed during driving, but this becomes essential particularly on longer drives. However, it is now possible to change cutters in MTBMs having an OD of 1800 mm. These machines typically have a central access of about 550 mm, and may have the facility to pressurise the cutter face with compressed air to allow disk changes below the water-table in unstable ground conditions. These machines have been developed for use in very mixed ground conditions, including solid rock.

8.9.7 Slurry lubrication and slurry pumps

The use of bentonite and polymer chemicals to reduce jacking loads has been routine for a long time. An electrohydraulic bentonite pump is used to lubricate the outside of the pipe to ease the thrust loads between the pipe and the ground. For example, the EH2250 (a product from the Akkerman, Brownsdale, MN, USA) is one such pump: it has two tanks of 946 l (250 gallons) each and pumps bentonite at up 207 bar (3000 psi). In slurry MTBMs, the usual circulating slurry is water, as its high flow rate keeps the material moving. There have been continuous improvements in the ratings and performances of slurry pumps.

8.9.8 Pipe materials and improvements

- Reinforced concrete pipes were the first pipes to be used in microtunnels. Since then there has been steady improvement, with the introduction of spun concrete and steel-banded bell and spigot joints. Thus, concrete continues to be the most common material as a primary lining for pipe jacking, with the largest standard range having diameters of 450–3000 mm or greater if required.
- Use of clay to manufacture pipes was a surprise when it was first introduced but today the majority of pipes having IDs in the range 150–700 mm are made of vitrified clay. In the USA, these pipes are available in diameters up to 1200 mm and lengths of 1.2–2.5 m. The use of clay pipes is growing rapidly the world over due to the corrosion and chemical resistance properties of clay.
- Centrifugally spun fiberglass-reinforced polymer mortar pipe was developed in Europe primarily as an open-cut water pipe. It has become the dominant type of pipe used for microtunnels of all sizes in many countries, including the USA. The fiberglass pipe provides smooth interior and exterior surfaces, which reduces jacking loads and enables higher interior flow rates per diameter. The pipe can be designed as both a gravity and a force main pipe. The quality is very high.
- Since the 1990s, the use of polymer concrete pipe, which was developed in Germany, has increased around the world.

- The use of steel pipes is limited. In the mid-1990s, the Permalok (Northwest Pipe Company, Vancouver, WA, USA) was developed in the USA. This is a bell and spigot wall joint for steel pipe which pushes together so welding is not required. It is a good product for use in very difficult ground conditions where the ability to 'pull back' is important.

It is these developments in pipes that have made possible the execution of microtunnelling projects.

8.10. Advantages of microtunnelling compared with conventional methods

A large range of projects have been done using this techniques: at one extreme are the large-diameter microtunnels up to 3.6 m (even up to 4 m) OD for long drives of over 1000 m in mixed ground conditions, and at the other are small-diameter microtunnels of 150 mm OD in rock. Other features of this technology include the following:

- While a microtunnel is being driven at the subsurface (underground), life above ground goes on as normal. Traffic by rail, road and water is virtually unaffected.
- Trenchless technology leaves agricultural land and the natural landscape intact.
- Microtunnelling allows pipe-installation and cable-laying tasks to be completed with precision and safety, and is economical in general, even where space is scarce and valuable.
- The process is flexible as it can be used for a variety of pipe lengths and diameters.
- The process is not affected by weather and no lowering of the groundwater is required.
- Disturbance of the natural ground setting is minimal. The debris/muck generated is minimal compared with conventional trenching techniques in which a huge amount of muck handling is essential. This aspect is illustrated in Box 8.1.

Box 8.1 Microtunnelling – the reduction of waste production compared with conventional methods

Two pipelines of 600 mm ID (760 mm OD) and 1200 mm ID (1450 mm OD), each 100 m long, were installed at a depth of 4 m below the surface datum. With the conventional method it required 136 and 220 of 20 ton lorries of muck handling, compared with 8 and 21 of 20 ton lorries of muck handling, when the trenchless pipe-jacking technique was used. The excavated volume of ground per metre of pipe line was 6.1 m^2 and 0.5 m^2 for the 600 mm ID pipe and 10.28 m^2 and 1.65 m^2 for the 1200 mm ID pipe for the trenchless and conventional methods, respectively. Thus the ground disturbance when using the trenchless technology at the working site was minimised (i.e. this is a sustainable practice).

Case study 8.1

Microtunnelling – examples of the experience in North America

- Diameter ranges vary between 250 and 3000 mm, but for large-diameter tunnels conventional methods are used. Microtunnels of 250 mm diameter are the smallest ones in North America.
- Microtunnelling techniques are typically applied for drive lengths of 30–300 m. Other trenchless methods are used for distances shorter than 30 m.
- The maximum possible drive length is determined by the pipe diameter. For microtunnels having diameters in the range 150–700 mm the ability of the pipe materials to withstand the jacking forces also controls the drive length. For the smaller-diameter pipes, drive lengths can approach 100–160 m.
- The pumping capacity of the slurry systems and the inability to install intermediate jacking stations limit drive lengths for machines in the 600–900 mm diameter range. The drive lengths for these machines are 160–200 m.
- As machines having a diameter exceeding 900 mm have increased power, there is more room for the slurry pumps and, therefore, they can use intermediate jacking stations. In such cases, drive lengths can approach 300 m, but drive lengths cannot exceed 400 m for the larger-diameter machines because of limitations on the jacking systems, jacking forces and loss of production. At long lengths, it becomes easier to stop and start a new tunnel drive rather than to continue with the existing one.

Robbins MTBMs

- Available with diameters nominal (DN) of 250–3000 mm.
- Can be deployed in soft ground, mixed ground or rock formations.
- Can operate below the water-table. Standard systems can operate at a hydrostatic head of up to 3 bar.
- Machines having DN 1100 mm and larger can be manufactured with face access, which allows back-loading cutting tools to be safely changed and inspected from within the MTBM.
- Equipped with both analogue and digital guidance/data logging systems.
- Custom-sized machines can be manufactured.

8.11. Design and construction of microtunnels

The design and construction of microtunnels is not within the scope of this book. The reader is referred to the American Society of Civil Engineers (ASCE) Standard ASCE/CI 36-15, *Standard Design and Construction Guidelines for Microtunnelling* (ASCE, 2015). A wide range of publications are available in this subject area, including excellent ones from the Pipe Jacking Association, UK.

8.12. Current status of trenchless technologies

Trenchless construction includes mainly the construction methods described in the preceding sections. Construction methods for large-sized tunnels are covered in

Chapters 4–7. It is the size of the tunnel (passage) which demarcates the difference between the trenchless and conventional systems. Trenchless techniques require consideration of soil characteristics and the loads applied above them. In cases where the soil is sandy, the water-table is at shallow depth, or heavy loads like that imposed by urban traffic are expected, the depth of excavation has to be such that the pressure of the load on the surface does not affect the bore, otherwise there is danger of the surface caving in.

In the last decade, some of the leading manufacturers of TBMs have entered into the microtunnelling arena, and better products at competitive prices are now available. Currently, an MTBM can be successfully used for any geology and for tunnel diameters up to 3 m or even more.

Microtunnelling is not the only method of installing small-diameter pipelines. Horizontal directional drilling (HDD), as described in Section 8.3, is another method that can be used with microtunnelling.

The auger boring machines made by Bohrtec and Herrenknecht (see Section 8.4), have a simple working principle, and can be used to install pipelines in the diameter range 0.1–1.4 m and house connections quickly and safely, at low cost and with minimum impact on the environment.

Blind-hole tunnels end directly in the ground, making conventional recovery of the machine impossible. This used to be a real challenge, but Herrenknecht has developed special cutter heads with a fold-away mechanism for this very special application.

One-step direct pipeline installation (see Section 8.8) is a combination of microtunnelling and HDD. Pre-fabricated pipeline is installed in a borehole that is created simultaneously, making the installation process faster and economical for pipelines lengths exceeding 1500 m.

The main costs associated with the microtunnelling technique are the cost of the equipment and special pipes and the cost of shaft construction. While these costs are offset by the benefits that such driving allows, much still needs to be done to reduce costs further. The success of a microtunnelling project depends on good coordination and cooperation between contractors, equipment manufacturers, pipe suppliers and the public at the site location.

8.13. Terminology

ELS (electronic laser system). An active target unit with a built-in dual axis inclinometer. It reacts to a striking laser beam and delivers the following values to the controlling PC:

- the current horizontal and vertical position of the laser point in relation to the zero point of the ELS (middle of the target table)

- the angle of the rolling effect, the inclination and the yaw angle (deflection angle to the laser beam)
- the current location, height and attitude of the MTBM.

Intermediate jacking stations. These are deployed to enable the piping segments to be moved individually. Their use is recommended when tunnelling exceeds 100 m and for tunnelling in rock. The resistance to the tunnelling advance, which arises from the friction of the pipe cladding, is divided over the jacking extensions, and so the permissible advancing force of the concrete pipe is not exceeded.

Laser target. The electronic laser target of an AVN machine is used to steer the machine. Sensors measure the position of the laser beam and send the values to a computer in the control panel of the container. This enables the exact position of the machine to be checked at all times.

Launch shaft. The shaft used at the start of the excavation work and for setting up of the tunnelling machine. The assembly of the MTBM at the construction site usually takes place on a shield cradle. The machine is in the start position.

8.14. Conclusion

- Trenchless technology is chosen for reasons of economy, convenience and least disturbance. It can be used for a variety of ground conditions, ranging from soft soils to rocks, including heterogeneous ground, and above or below the groundwater. It allows pipe installation and cable-laying tasks to be completed with precision, safety and economy in general, even where space is scarce and valuable.
- This technology can be used to create boreholes of 0.1–4.2 m diameter.

8.15. Questions

1. What is trenchless technology? List its inherent features. Briefly review its history. In what way is it better than conventional ‘trenches’ dug from the surface?
2. In general, the term microtunnelling refers to what? Why is the market for this technology expanding day by day? List the ground conditions for which this technique can be used. How is microtunnelling defined in the USA?
3. Describe the pipe jacking technique. Do ‘pipe jacking’ and ‘microtunnelling’ have the same meaning? List the operations that need to be carried out when constructing microtunnels in soft ground.
4. Draw a line diagram to classify microtunnelling methods.
5. Describe the pilot method of microtunnelling. What is horizontal directional drilling (HDD)? Up to what length have HDD installations been successfully undertaken?
6. Describe the thrust boring method of microtunnelling. What are its limitations? Up to what length has this technique been used successfully?
7. List the well-known microtunnelling machine manufacturers.
8. Describe slurry microtunnelling machines and their excavation cycle.

9 Describe the Unclemole, giving its working principle. What is the Unclemole Super?
10 Describe Herrenknecht's microtunnelling system (AVN). List the outstanding features that the manufacturer claims for this system. Draw the system configurations used for surface and subsurface operation; include the terminology used.
11 Briefly summarise the developments that have taken place in microtunnelling technology within the last decade.
12 Why are conventional tunnel surveying methods impracticable in microtunnelling? Why does the operator need continuous and accurate information about the positioning and attitude of the machine?
13 How are improvements in hydraulic pumps and motors making MTBMs successful? What are the problems of using slurry machines in plastic clays? Since 1997, high-pressure water jets have been added to the front of MTBMs. How are these jets helpful in overcoming the problems in plastic clays?
14 List the latest developments in rock cutters. What are mini-disk cutters? How do they work? Do these developments allow microtunnelling through rock and mixed-face conditions?
15 Today the majority of pipes in the ID range 200–600 mm are made of vitrified clay. What is the quality of this material that makes its use very fast growing the world over?
16 What are the unique features of fibreglass pipes that make them suitable for microtunnels and the dominant pipe type used for all sizes of microtunnels in many countries?
17 Where do steel pipes find application in microtunnels?
18 List the challenges faced with regard to the following: (a) diameter; (b) length; (c) the ability of the pipe material to withstand the jacking forces; (d) the pumping capacity of slurry system; (e) the cost of equipment, special pipes and shaft construction, which are the main costs associated with microtunnelling.
19 Briefly summarise the current status of trenchless technology.
20 Define the following terms: (a) ELS (electronic laser system); (b) intermediate jacking stations; (c) laser target; (d) launch shaft.

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Chapter 9
Raising, sinking and large subsurface excavations

Creating any opening (shaft, tunnel or raise) is known as a ‘development’. It is a difficult and challenging task, as a new set of conditions is met at every step of advancement.

9.1. Introduction

The preceding chapters dealt with horizontal and inclined openings driven in various environments. This chapter describes the techniques that are used to drive vertical openings, such as raises and shafts, and large-sized excavations. In this chapter, these openings are referred to as ‘caverns’, ‘large-sized openings’ and ‘subsurface and underground excavations’.

Underground excavations have some unique features (Sterling and Godard, 2002). These excavations are naturally protected from severe weather (hurricanes, tornadoes, thunderstorms and other natural phenomena), and can also resist structural damage due to floodwaters, although special isolation provisions are necessary to prevent flooding of the structure itself. Moreover, underground structures have several intrinsic advantages with regard to resisting earthquake motions; they tend to be less affected by surface seismic waves.

In urban areas, underground solutions enable several levels of transport facilities to be brought together at important city transport hubs. They also allow building in close proximity to existing facilities, thus offering better services to the surrounding community.

The underground location provides isolation from the surface climate. The temperature within the soil or rock offers a moderate and uniform thermal environment compared with the extremes of surface temperatures. These moderate temperatures and the slow response of the large thermal mass of the Earth provide a wide range of energy-conservation and energy-storage advantages. Thus, the underground location both provides protection from adverse climates and can provide substantial energy savings; a concept in line with sustainable development (see Section 10.13).

9.2. Raising

In an underground situation one of the important openings is the *raise*, which is driven in the upward direction (Alimkak, 2017; Svensson, 1982; Tatiya, 1979). It can be vertical or steeply inclined. Opposite to a raise is a *winze*, which is driven in the downward direction. Usually, winzes exceeding 4 m in diameter, or equivalent cross-section, are termed *shafts*. When driving raises, after a blasting round the crew has to approach the non-scaled back (i.e. loosened rocks that are not dressed). With a winze/shaft there is no problem of this kind, but in most cases the working crews' feet are in water. During raising, gravity assists in drilling and mucking, thereby making the process faster and cheaper; but in winzing/sinking gravity slows down the drilling speeds and the blasted muck needs hoisting. Thus, driving a winze or sinking a shaft is a slow, tedious and costly affair but provides better safety to working crews than raising. Raising used to be considered one of the most hazardous mining operations but with the advent of new techniques the process has become safe and more economical than winzing. However, winzing or sinking is an indispensable operation in gaining access to the deeper horizons (levels); raising is an established practice to join lower horizons to the upper ones.

Shaft sinking is a specialised operation that requires a trained and skilled crew. Among the different types of opening that are driven for mining and civil engineering purposes, the inclined or vertically down 'sinking operation' is the costliest to drive, as this task is slow and tedious. Decisions with regard to size, shape and positioning are taken based on the purpose a shaft is intended to serve. Circular shafts are preferred in almost all situations due to their stability characteristics. When strata are competent, rectangular or elliptical shafts give the advantage of proper use of their cross-sectional areas.

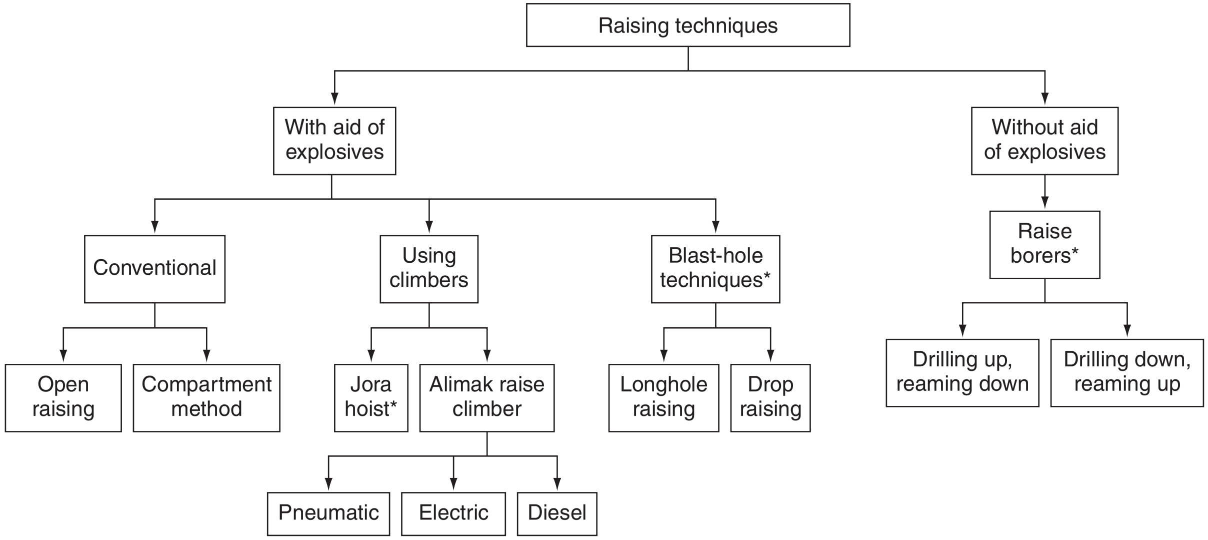
Raises are one of the most important structures in many civil and construction projects and find applications as follows (Singh, 1993):

- Hydroelectric projects:
  - surge chamber
  - ventilation shaft
  - elevator shaft
  - pressure shaft
  - cable shaft.
- Water supply:
  - access or service shaft
  - ventilation
  - supply riser
  - up-take or down-take shaft.
- Waste water shafts:
  - drop shafts.
- Tunnel projects:
  - ventilation
  - accelerator housings
  - access.

9.2.1 Raise driving techniques

For the purpose of driving, raises can be classified as either blind or those that have two levels (horizons) available to access them. The former is more difficult to drive than the latter. Raises can be driven with or without the use of explosives. Figure 9.1 presents a

Figure 9.1 Classification of vertical/steeply inclined raise driving techniques based on the rock fragmentation mechanism and the availability of access to the intended raise site at the time of drivage



*Two levels/horizons must be available

classification of raise driving techniques based on both these criteria. It should be mentioned that the use of stoper or parallel raise feed drills is made while driving all types of raises, except those driven by the use of blast-hole drills and raise borers, in which conventional explosives are also used.

9.2.2 Conventional methods

The open raising technique still finds application in driving short-length raises up to 10 m, and in the compartment method (but not beyond 25 m) (Tatiya, 1979). Use of long-hole drilling can be made for raises up to 40 m, and this is a popular method at mines where the same drifter drills are also used for the production drilling. The same crew can undertake the drilling and raising operations.

9.2.3 Raising by mechanical climbers: Alimak raise climber

The Alimak Hek Group AB (Stockholm, Sweden) introduced this technique in 1957, and even today it is indispensable for driving blind raises of longer lengths (Alimak, 2017; ASCE, 1989; Svensson, 1982). The Alimak raise climber is designed to drive raises up to 100 m long, or even more. Pneumatic, electric and diesel (hydraulic) driven climbers are available. The salient features of this technique are listed below.

- Using this technique it is possible to drive very long raises – vertical or inclined, straight or curved, and mostly rectangular in shape. Even today, this method is almost mandatory for driving blind raises having these features.
- The raise climber can be driven into a safe position using backward guiderails. The guiderail curves also offer the possibility of quick communication between the bottom and the work platform by a special service hoist, known as an Alitrolley or Alicab, which is ready for operation on the guiderail all the time.
- All work is performed at the platform, which is easily adjusted for height and angle.
- The workers travel in the cage (Figure 9.2(a)) under the platform when ascending to the face or descending. All open exposure below the blasted face is thus eliminated.
- Because of its design features for blowing air and water at the face after blasting, risks of foul gases are eliminated and the time required for ventilation is reduced (Figure 9.2(b)).
- An additional extension piece can be connected to the platform to allow the driving of raises of large cross-sectional area or shafts. In order to achieve a large area, two parallel or opposite climbers can also be used.

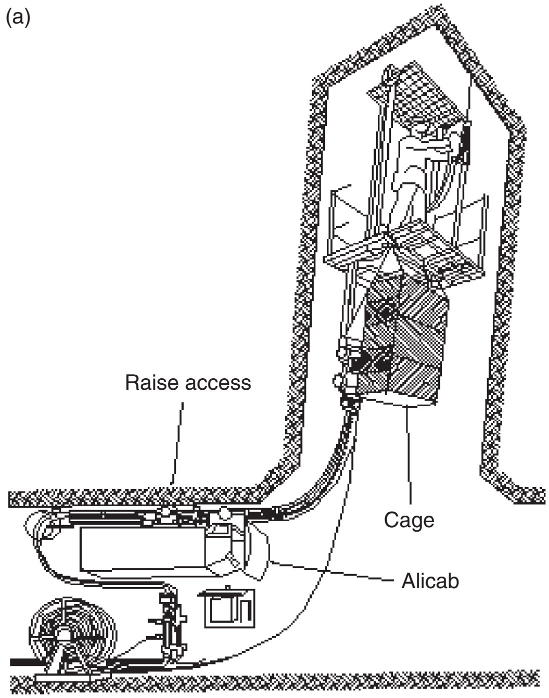
9.2.4 Blast-hole raising method: drop raising

The advanced version of the long-hole raising technique is drop raising, in which large-diameter and longer holes are used to drive the raises (Figure 9.3(a)). This technique is based on the vertical crater retreat (VCR) concept (Svensson, 1982).

9.2.4.1 VCR concept

When creating a surface cavity in a rock mass by detonating an explosive charge that has been placed in the bottom of a hole, the *crater theory* is applied. This blasting concept

Figure 9.2 (a) Alimak raise climber; (b) cycle of operation using an Alimak raise climber



Alimak raise climber

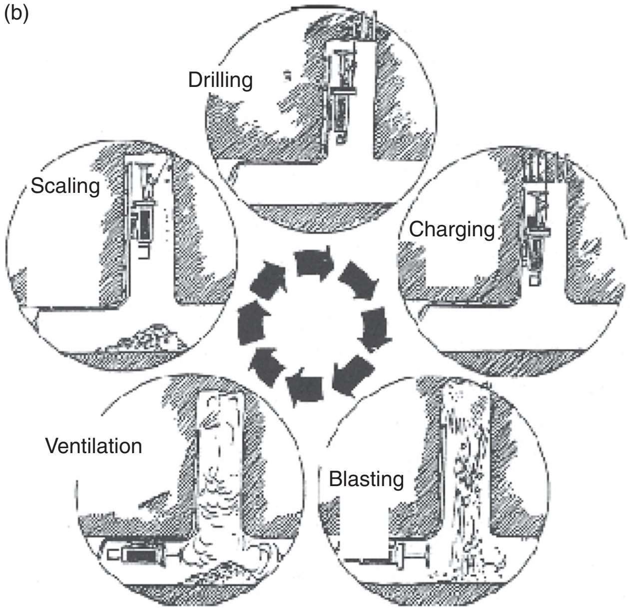
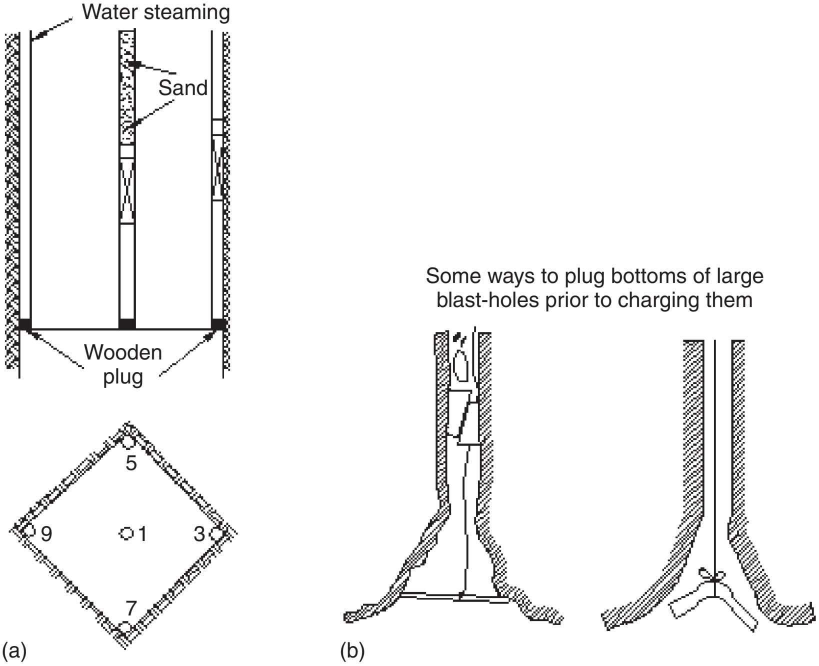


Figure 9.3 Drop raising: (a) drilling with large blast-hole drifters, hole length 25–100 m and diameter 100–200 mm; (b) some practices used to seal (plug) the bottom of a hole prior to charging



was initially used as a tool to evaluate the capability of an explosive. It gained importance in surface blasting operations and, in the recent past, in underground blasting operations too.

The explosive charges used in the crater theory are spherical or a geometrical equivalent. In blasting practice, a spherical charge is defined as having a length to diameter ratio L/D of $1:4$ or less, and up to, but not exceeding, $L/D = 6:1$. Thus, for holes of 165 mm diameter, a charge 990 mm in length would constitute a spherical charge.

The crater consists of five holes, one at the centre and the remaining four at the corners of the raise. Crater theory is valid for the central hole only; for the other of the holes the charge depth increases by 10–20 cm between each hole. The charge length can be determined by using the following formulae:

$$l = 6 \times d \tag{9.1}$$

where l is the charge length and d is the large blast-hole diameter (mm). The optimum charge depth L_{opt} is 50% of the critical depth L_{crit}:

$$L_{\text{opt}} = 0.5L_{\text{crit}} \tag{9.2}$$

$$L_{\text{crit}} = S \times Q^{1/3} \tag{9.3}$$

where S is the strain energy factor, which is usually 1.5 but depends on the explosive and the type of rock, and Q is the charge weight.

$$Q = 3d^3\pi\frac{p}{2} \quad \text{(in kg)} \tag{9.4}$$

where p is the explosive density (g/cm^3). Thus

$$L_{\text{opt}} = 0.5 \times S \times Q^{1/3} \tag{9.5}$$

In this technique, down-the-hole (DTH) drills (see Chapter 2) are used to drill parallel holes in the intended direction in which the raise is to be driven. All holes are drilled to get through into the next lower level to which the raise is to be driven. Holes are blasted in stages, as per the length calculated using Equations 9.1–9.5. Before charging, the holes are plugged using a special technique (see Figure 9.3(b)). Raises of longer lengths (up to 150 m) can be drilled using this method.

9.2.5 Raising by the application of raise borers

This is another technique (Figures 9.4–9.6) that can be applied to drive a raise between two levels. Raises have been drilled successfully even in relatively poor ground. A circular configuration is obtained by this technique without the application of drilling and blasting. The machine is set up at the top and a 225–250 mm diameter pilot hole is drilled down to get through into the lower level. Then a large reamer bit is put on at the bottom of the drill rod and the raise is reamed to the desired diameter up to the upper level. The pilot hole also provides information about the type of strata to be encountered and helps in driving the raise accurately. The reverse procedure can be also adopted (i.e. first driving the pilot hole upward from the lower level towards the upper level and then reaming it from the upper level towards the lower one), but this option is less popular.

Figure 9.4 Driving a vertical raise using a raise borer (courtesy of Atlas Copco AB)

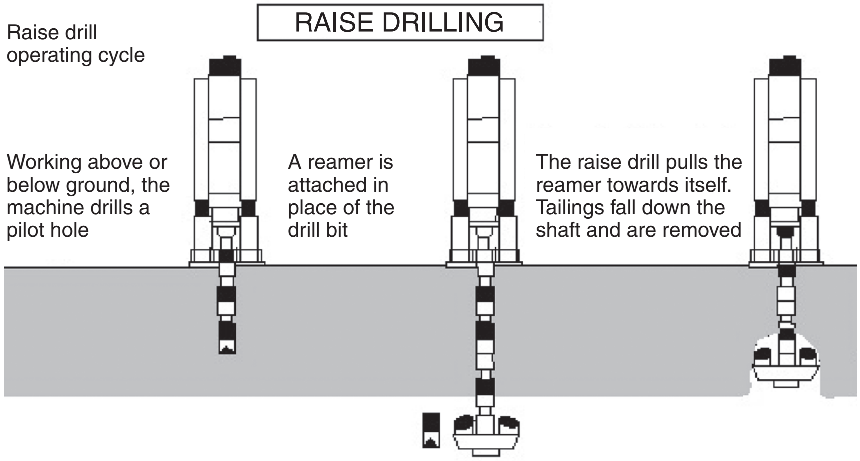


Figure 9.5 Driving an inclined raise (box hole) using a raise borer (courtesy of Atlas Copco AB)

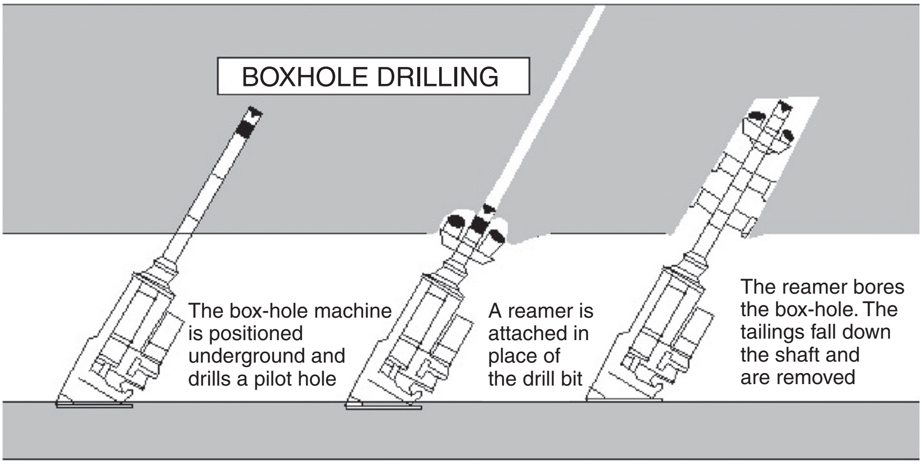


Figure 9.6 The most popular and widely-used model, the Robbins 73RM is considered a reliable workhorse for virtually any raise-boring application. It is a medium-sized raise drill, 1.8–3.1 m in diameter (courtesy of Atlas Copco AB)

Raise borers are available for driving in soft as well as hard ground, and such units are useful to drive raises and shafts up to 6 m diameter. A properly matched unit can provide the following advantages:

- faster rates
- better safety for the working crews
- minimal disturbance to the strata (rock structure).

All these factors ultimately lead to cost savings.

Over the years, manufacturers such as The Robbins Company (Solon, OH, USA) have developed raising equipment which, together with its associated technology and powerful systems, has already achieved milestones. These include

- a shaft length of 1000 m
- diameters of 0.6–6 m
- box holes (blind raises, see Figure 9.5) of length 200 m and diameter 1.8 m.

Since the development of the first production raise borer, the Robbins 41R, more than 35 different raise borer models have been designed and built by Robbins to suit the needs of many different applications. Models are available that could suit multiple purposes such as down-reaming, upward box-hole boring and conventional raise boring. The applications and features of some important models of borer are given in Table 9.1, and Tables 9.3(a) and 9.3(b) gives guidelines for executing raising operations.

Atlas Copco AG (Stockholm, Sweden) has introduced a few variants of its models, as tabulated in Table 1.9. For example: model 34RH C is produced in the variants 34RH C ORS and 34RCC Wide; model 44RH C is available as the 44RH C Low Profile and 44RH C Rail variants; model 73RH C is available as 73RH C High Torque and 73RVF C; and model 123RH C is available as the variant 123 RVF C. These variants are produced to meet the specific need of the user while having almost identical operational details and working range parameters.

9.3. Shaft sinking

Shafts are required for the following purposes:

- mining mineral deposits
- temporary storage and treatment of sewage
- bridge and other deep foundations
- hydraulic lift pits
- wells
- in conjunction with a tunnelling system or network, for the purpose of lifts, escalators, stairways and ladder ways, ventilation, conveyance of liquid, carrying pipes and cable in river crossings, drainage and pumping (particularly from subaqueous tunnels).

Table 9.1 The development of important Atlas Copco Robbins raise borer models and their important features

Robbins model	Diameter: m		Depth: m		Features	Applications
	Nominal	Range	Nominal	Max		
34RHC	1.2	0.6–1.5	340	610	Low-profile, small-diameter raise drill	Slot raises, backfilling and narrow-vein mining
44RHC	1.5	1.0–1.8	250	610	Small-diameter raise drill with higher torque and thrust	Smaller-diameter raises
53RHC	1.8	1.2–2.4	490	650	Low-profile and medium-diameter raise drill	Boring ore passes and ventilation shafts
73RHC	2.4	1.5–3.1	490	650	Any raise-boring application (see Figure 9.6)	Raises of 1.8–3.1 m diameter
91RHC	4.0	2.4–6.0	600	1010	A high power and low profile raise drill	For mines and civil sites with size and weight restrictions
123RHC	5.0	3.1–6.0	920	1100	Most powerful raise-boring machine available in the Atlas Copco Robbins raise boring series	Very large diameter raises, ranging from 3.1 m up to 6.0 m

The techniques used to sink shafts are classified in Figure 9.7 (Douglas and Pfutzenreuter, 1989). The operations can be divided into three groups:

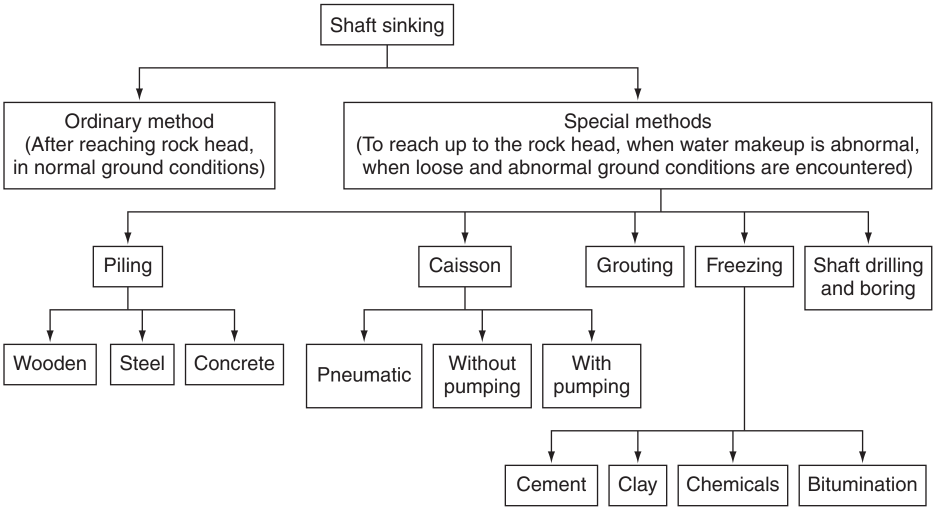
- reaching up to the rock head
- sinking through the rock
- sinking through abnormal or difficult ground, if any, using special methods.

9.3.1 Sinking through the rock

A sinking cycle consists of the following unit operations:

- drilling
- blasting
- mucking and hoisting
- support or shaft lining
- auxiliary operations
  - dewatering
  - ventilation
  - lighting or illumination
  - shaft centring.

Figure 9.7 Classification of shaft-sinking methods/techniques



9.3.1.1 Drilling

Sinkers are used to drill holes of 32–38 mm diameter and shaft jumbos (equipped with a number of drifters) are used to drill holes of 40–55 mm diameter (Unrug, 1992). The hole length varies between 1.5 m and 3 m if sinkers are used and can be up to 5 m if shaft jumbos are used. The common drilling patterns adopted are wedge cut and step cut (Figure 9.8(a)) and pyramid cut (Figure 9.8(b)). The wedge cut pattern is more popular in rectangular shafts, whereas the pyramid cut pattern is more popular in circular ones. The step cut pattern is adopted if the water level is high and the shaft has a large cross-section, so that the face can be divided into two portions to allow for continuous dewatering. The number of holes in a pattern is a function of the hole diameter, the shaft diameter and the type of strata. When drilling holes in the diameter range 45–55 mm using a shaft jumbo, the number of holes can be determined using the following formulae (Hendricks, 1985):

$$N = 0.234A + 22 \tag{9.6a}$$

$$N = 2.55A_1 + 22 \tag{9.6b}$$

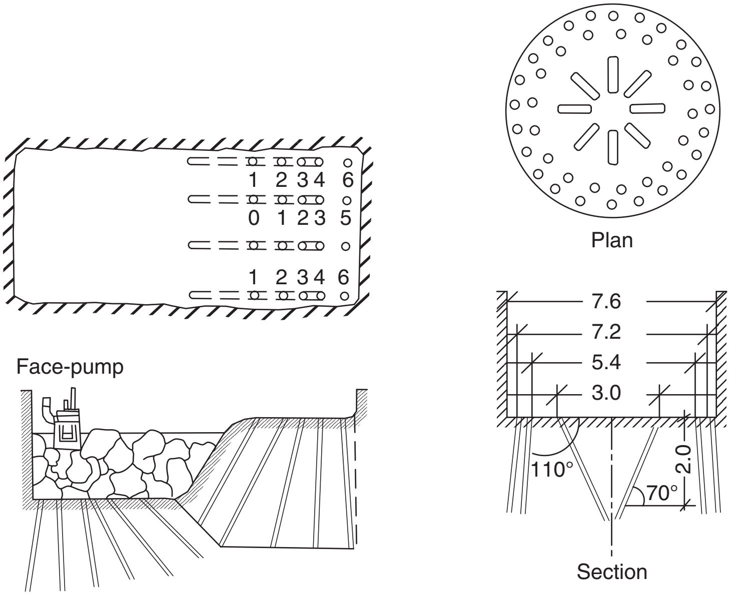
where A is the cross-sectional area in ft^2 and A_1 is the cross-sectional area in m^2.

In the *powder factor method*, depending on the type of rock, a suitable powder factor is selected based on previous experience and the data available. To achieve this powder factor, the number of holes required is calculated and arranged in a particular pattern.

9.3.1.2 Blasting

In practice, during sinking the shaft bottoms are usually full of water, and therefore high-density water-resistant explosives (such as nitroglycerine-based explosives) are used

Figure 9.8 Hole patterns used in shaft sinking: (a) step cut pattern in watery conditions in a rectangular shaft; (b) pyramid cut pattern in a circular shaft (the number of holes shown is for medium-hard rocks)



(a) Step cut (b) Pyramid cut

to charge the holes. Water or a sand–clay mixture can be used as a stemming material. Usually, series–parallel connections are made to connect the detonators at the face and this circuit is then connected to the blasting cable, which is suspended in the shaft and leads right up to the surface. After taking due precautions, the face is blasted. Aluminium-based water gel explosives and high-frequency electromagnetically initiated detonators have been very successfully used in some of the South African shafts, and these have a promising future (Björk, 1981).

The latest development, claimed by Nitro Nobel AB (Sweden), is the use of emulsion explosive with booster and Nonel detonators (Goyal *et al.*, 1988). Hydraulic drills are used to drill 50 mm diameter holes with a cut hole of 0.2 m diameter in the cylindrical cut (parallel hole cut) pattern. A round depth of 5 m has been successfully driven.

9.3.1.3 Lashing and mucking

Lashing is the arrangement that is made for the loading of blasted muck onto a conveyance for its disposal. Thus, a lasher is the person who lashes it, and the lashing unit is a mechanical device incorporating a hoisting, slewing and radial traversing mechanism for the handling of the cactus grab (or any other mucking equipment), which completes the lashing system.

The presence of water, limited space and the time required to install the mucking equipment makes this operation a time-consuming activity. It occupies about 50–60% of the sinking cycle time. The mucking efficiency depends on the size of the rock fragments, the hoisting depth, the shaft cross-section and the water inflow rate. The most commonly used mucking units are arm loaders, some of which are listed below:

- riddle mucker
- Cryderman mucker (Figure 9.9(b))
- cactus grab mucker
- backhoe mucker
- rocker shovel.

Some of the arm loaders listed find their applications mainly during shaft sinking or driving in the downward direction (Björk, 1981). Their use is, therefore, confined to these operations only.

9.3.1.4 Support or shaft lining

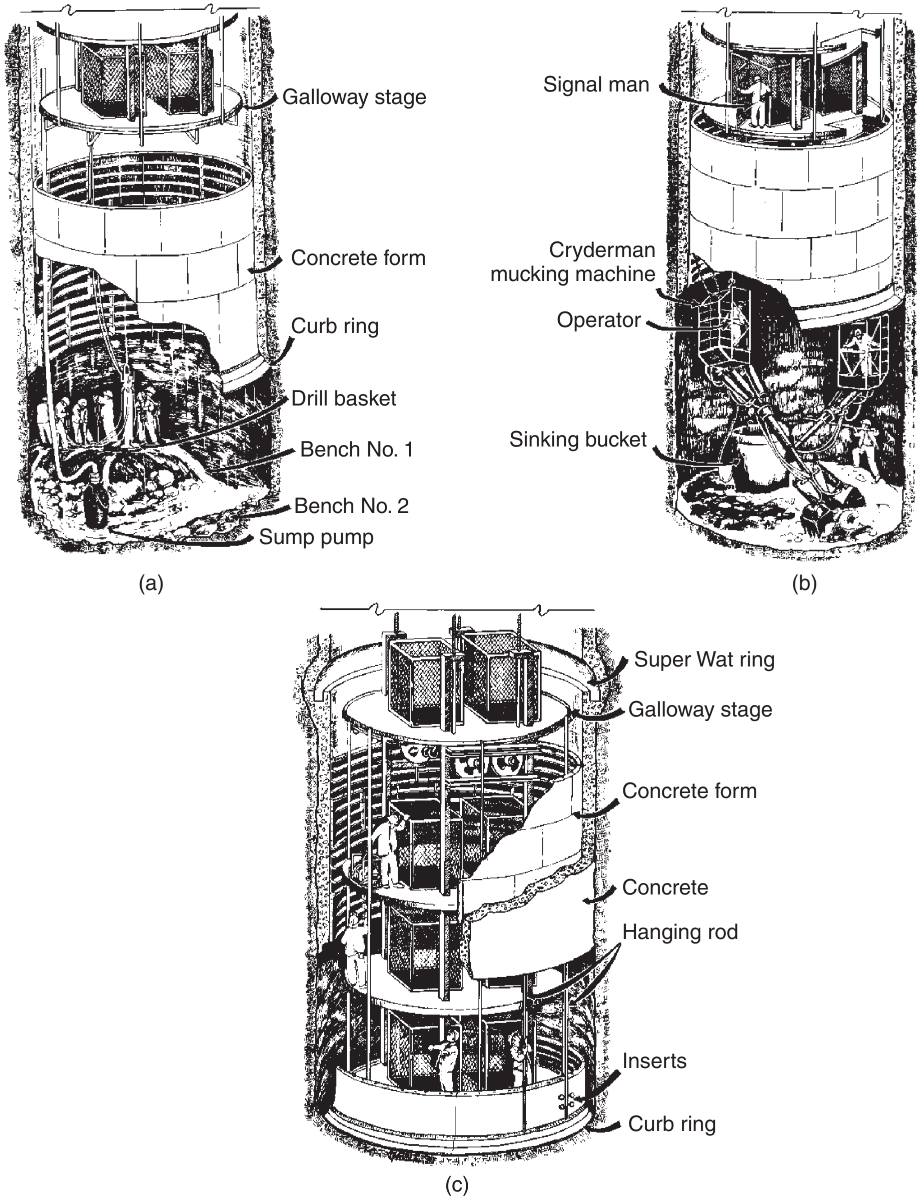
Basically there are two types of lining: temporary and permanent (Unrug, 1992). The type of water and the strength of the strata through which the sinking operation is to be carried out govern the choice. In some situations, no temporary support is required, whereas in others it is essential to protect the crew and equipment from any side fall. Depending on the conditions, the length of temporary supports can range from 6 m to 40 m. Once this length is covered by the temporary lining, and before advancing further, the permanent lining is installed. If feasible, the temporary lining can be removed before installing the permanent lining, otherwise it may be left in place. The permanent lining can be composed of bricks, concrete blocks, monolithic concrete (Figure 9.9(c)), shotcrete or cast iron tubing. In the past, bricks and concrete blocks were used in dry and shallow depth situations, but nowadays monolithic concrete of the desired strength is commonly used. Steel tubing is used in conjunction with the freezing methods of sinking.

9.3.1.5 Auxiliary operations

Dewatering. During sinking, once the shaft has reached the water-table or below it, water inflow is unavoidable. Therefore some arrangement has to be made depending on the water inflow rate to be dealt with. The present practice is to use face or sinking pumps.

- *Face pumps*. If the water inflow is limited, the water can be hoisted out using kibbles or water barrels. To fill these barrels, pneumatically operated membrane face pumps are most suitable, as they can deal with muddy, silted and dirty water.
- *Sinking pumps*. If the water inflow is beyond the handling capacity of the face pumps, then hanging pumps are used. These can be suspended in the shaft together with the electric cables, motor, suction and delivery ranges. The pumps used are of the turbine type, to which impellers can be added as the water head increases. Adjusting the valve on the delivery side can also regulate the quantity.
- *Provision for intermediate sump and pumps*. When the shaft depth increases and water inflow is sufficient, it is always preferable to have intermediate pump chambers with sumps at an interval not exceeding 250 m (Boky, 1967).

Figure 9.9 (a) Drilling using the benching technique (Björk, 1981); (b) mucking using a Cryderman mucker; (c) supporting using concrete



Ventilation. Fresh air, supplied by a forcing fan installed at the surface, is provided at the face through rigid and flexible ducts which are suspended at the side of the shaft. The rigid ventilation duct range terminates at least 6 m above the shaft bottom to avoid damage due to blasting. Thereafter, in order to have fresh air at the face, flexible canvas ducting is joined to it. The whole shaft (excluding the rigid duct) acts as a return. In many sinking projects nowadays, the practice is to install a contra-rotating fan at the surface so that immediately after the blasting it is switched on to act as an exhaust, and once the fumes are cleared it is re-switched to act as a forcing fan. A sufficient quantity of air with a water (pressure) gauge up to 0.3 m is required to ventilate the face.

Illumination. A pneumatically operated light, consisting of a cluster of 4–6 bulbs fixed in a suitable watertight fitting, is used to provide illumination at the working face during drilling, mucking, lining and other operations.

Shaft centring. Using the reference points, which are fixed before commencing the sinking operation to fix the shaft centre, the shaft's centre and inclination (i.e. verticality, in the case of a vertical shaft) are checked from time to time by means of a centring device installed at the surface.

Guidelines for executing shaft sinking and winzing operations are given in Table 9.3.

9.3.2 Special methods of shaft sinking

In the process of shaft sinking, it becomes necessary to adopt a special method/technique if the ground through which the shaft is to be sunk is loose or unstable (e.g. in sand, mud, gravel or alluvium), or when an excessive amount of water is encountered which cannot be dealt with by the sinking pumps. In some situations, both sets of these conditions may be encountered. Listed below are special methods that can be used to deal with these types of situation (Hendricks, 1985; McKinstry, 1983):

- piling system
- caisson methods
- cementation
- freezing method.

Detailed descriptions of these methods are beyond the scope of this book.

9.3.2.1 Shaft drilling

Rotary drilling has been used extensively for sinking gas and oil wells. The same technique has been applied to sink shafts in situations where conventional shaft sinking techniques (including the special methods) are economically impractical, particularly through the profile of aquifers or caving formations. Basically, this technique is applied in order to drill holes of large diameter (1.5–8 m) up to a depth of 2000 m or so. Usually, ventilation and emergency escape shafts can be sunk using this technique, but in exceptional circumstances main shafts have been sunk also.

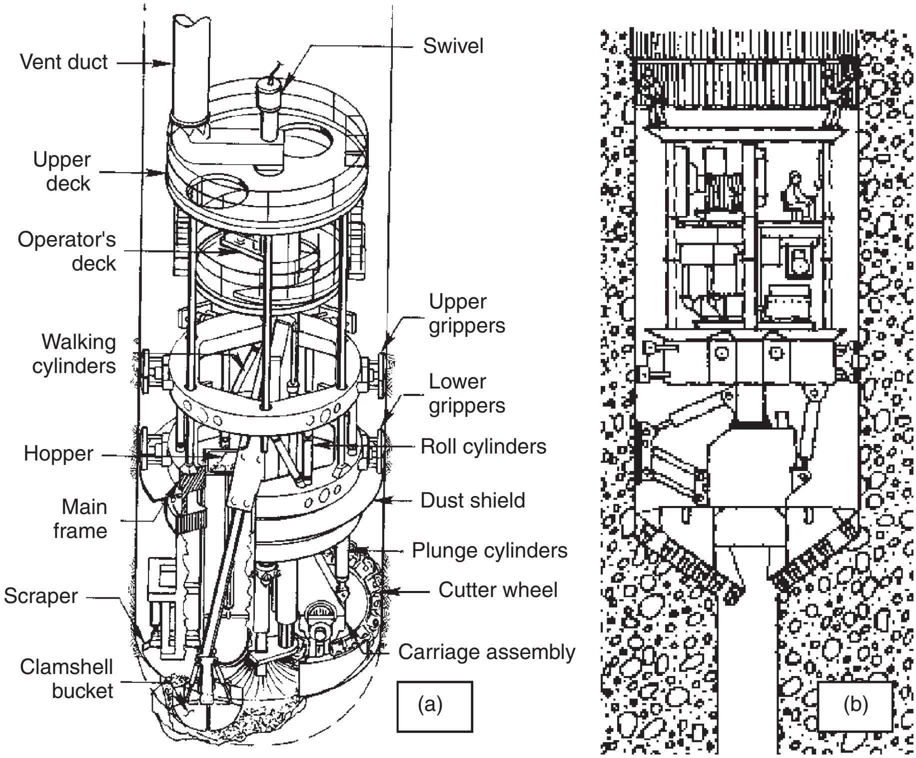
The method claims merits such as the possibility of carrying out all the operations from the surface, and effectively dealing with groundwater, and caving and soft formations. A smooth wall surface with fast penetration rates can be achieved while employing less labour. High capital cost and difficulties in drilling through the harder strata are some of its limitations.

9.3.2.2 Shaft boring

Although the concept of shaft boring using shaft-boring machines (SBM), which are like tunnel-boring machines (TBM) but drive horizontally, was introduced in the 1960s, it did not gain much popularity due to the fact that any difficult ground through which the shaft needs to be driven must first be treated or consolidated (Hendricks, 1985). In addition, there is the problem of removing the large volume of cuttings which, without a pilot hole leading to the lower access level, is a tedious task. The crew has to travel on board with the equipment.

The system (Figure 9.10(a)) consists of a cutter wheel mounted on a carriage and a clam-type mucking unit. The carriage is mounted on a slew structure that rotates about the vertical axis of the shaft. Grippers are used to fix this assembly into the shaft. The rock cuttings are mucked into a hopper, which discharges the muck into kibbles/buckets for disposal at the surface. Carboniferous rock is probably the most suitable formation for an SBM. Strata that contain large amounts of water must be sealed off with grout before the SBM begins boring (Hudson and Harrison, 1997).

Figure 9.10 Shaft boring using: (a) an SBM; (b) a 'V' mole



An SBM includes the shaft lining and equipping facilities, laser beam and mechanical direction control devices, support installation facilities, water handling and ventilation systems, and simplified access for cutter changes and maintenance.

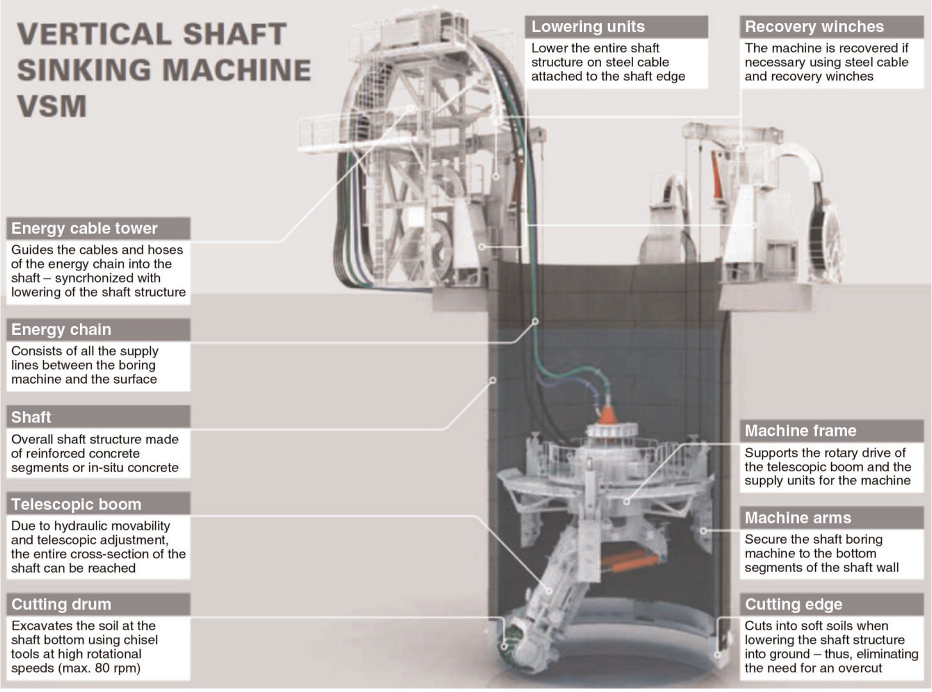
An innovation in this technique (Figure 9.10(b)) includes the drilling of a pilot hole of about 1.2 m at the centre of the intended shaft. This pilot hole provides information about the type of strata likely to be encountered and thus the ease of the subsequent reaming. In shaft-boring techniques, a drill string is not required and the precise verticality of the shaft can be maintained. Immediate lining is possible in unstable ground by making use of the walling platform immediately above the machine installation. The muck generated goes through the pilot hole. This system is known as a ‘V’ mole. The equipment shown in Figure 9.10(b) consists of cutter head, drive assembly, thrust and directional control cylinders, kelly, gripper assembly and working platform. This system was developed by a German company Wirth (Erkelenz, Germany) and has been used successfully used in some European mines.

9.3.2.3 Vertical shaft sinking machine

Shaft construction using the Herrenknecht AG (Schwanau, Germany) vertical shaft sinking machine (VSM) has a wide range of applications. With diameters ranging from 4.5 m to 16 m, they can be used as launch and reception shafts for tunnelling operations, access and ventilation shafts for traffic tunnels, or service and access points for all kinds of underground structures and buildings. Furthermore, special solutions such as inner-city, underground parking shafts (underground parking towers) or exploration and ventilation shafts for mining, extend the range of application of these flexible machines. Customised solutions for even larger diameters of up to 16 m are possible. Thus, VSM technology allows for safe, fast, and environmentally friendly production of vertical shafts of all kinds. Its advantages become particularly clear in difficult geologies beneath groundwater and where space at the site is constrained.

The Herrenknecht VSM consists of two main components: the SBM (shaft boring machine) and the lowering units (Figure 9.11). The SBM is lowered into the launch shaft structure and attached firmly to the shaft by its three machine arms. A rotating cutting drum equipped with chisel tools is attached to a telescopic boom. This roadheader excavates and breaks the soil at the base of the shaft. The roadheader is telescopic, and can swivel up and down or rotate. Hence, the entire cross-section of the shaft plus an overcut can be excavated gradually. The excavated material is removed hydraulically through a submersible pump and transported to the separation plant on the surface. The lower concrete ring of the shaft structure, also referred to as the shaft’s ‘cutting edge’, is bevelled, and therefore cuts into the surrounding soil underneath. In addition, the overcut of the roadheader-like telescopic boom and cutting drum below the shaft’s cutting edge, in combination with the bentonite lubrication in the annular gap, reduces the frictional forces between the shaft wall and the surrounding soil. On the surface, three or four lowering units with hydraulic cylinders are attached firmly to the ring-shaped concrete foundation around the shaft. They are attached to the lower concrete base ring of the shaft structure by steel cables. In this way, the entire shaft structure can be held and lowered in a controlled manner during excavation. Ring building takes place simultaneously on

Figure 9.11 A VSM with its components and their functions; the segmental lining is shown (courtesy of Herrenknecht AG)



Lowering units
Lower the entire shaft structure on steel cable attached to the shaft edge

Recovery winches
The machine is recovered if necessary using steel cable and recovery winches

Energy cable tower
Guides the cables and hoses of the energy chain into the shaft – syncrhonized with lowering of the shaft structure

Energy chain
Consists of all the supply lines between the boring machine and the surface

Shaft
Overall shaft structure made of reinforced concrete segments or in-situ concrete

Telescopic boom
Due to hydraulic movability and telescopic adjustment, the entire cross-section of the shaft can be reached

Cutting drum
Excavates the soil at the shaft bottom using chisel tools at high rotational speeds (max. 80 rpm)

Machine frame
Supports the rotary drive of the telescopic boom and the supply units for the machine

Machine arms
Secure the shaft boring machine to the bottom segments of the shaft wall

Cutting edge
Cuts into soft soils when lowering the shaft structure into ground – thus, eliminating the need for an overcut

the surface using prefabricated concrete segments. The simultaneous working processes (excavation, removal of excavated material, shaft construction and lowering of the shaft structure) make it possible for VSM technology to achieve high advance rates of up to 5 m per shift.

The entire shaft is flooded with slurry water at the start of excavation. The slurry water circuit required to transport the excavated material can be primed. This also means that lowering the groundwater table is not necessary. The separation plant removes the slurry water from the excavated material and recycles it back into the shaft pool. The shaft structure is lowered continuously while ring building takes place at the surface. When the desired depth has been reached, the machine is recovered (hoisted up). Subsequently, the shaft bottom is sealed by an underwater concrete plug and the annular gap is filled up with grout, creating a frictional support locking the shaft in place. Once the slurry water has been pumped off, the shaft is ready for further use. The main features of this technology are summarised in Table 9.2.

In this technique all operational processes are controlled and monitored from the surface. In addition to the separation plant, lowering units and recovery winches, the jobsite equipment includes a control container and power supply units. All information available about the excavation is collected and visualised on the control container.

Table 9.2 Operational details of VSMs (courtesy of Herrenknecht AG)

Geology, diameter, range and technical details	Significant features
Geology: soft ground, heterogeneous ground and rocks *Diameter range*: 4.5–16 m *Excavation*: a cutting drum equipped with excavation tools loosens the soil at the shaft bottom *Removal*: hydraulic removal of the excavated material to the surface using a submergible pump *Thrust*: controlled lowering of the shaft structure using the lowering units *Shaft construction*: shaft construction at the surface with precast reinforced concrete segments or in situ concrete casting	■ Can be used in soft and stable soils up to 80 MPa and below groundwater ■ High advance rates of up to 5 m per shift due to parallel work processes ■ Can be used under tight space constraints due to the flexibility of the equipment ■ More than 50 shafts have been sunk to depths of up to 160 m

There, the operator has a full overview of the situation at hand and can respond accordingly at all times. After completing the excavation or when changing excavation tools, the SBM is retrieved using the recovery winches. The advantages of the modular design of the overall system become particularly apparent in inner-city projects. The equipment can be arranged as needed. For example, the separation plant can be installed in a street next to the work site if there is not enough space for it next to the shaft. The operational details of VSM technology are summarised in Table 9.2.

9.3.2.4 Inclined shaft TBM

Herreknecht has developed an inclined shaft gripper TBM for driving inclined tunnels/shafts. This TBM has been used, for example, on a project in Switzerland for a tunnel gradient of 40° and a project in Russia for a tunnel gradient of 30° (downward). In order to safeguard against the backward movement of the TBM while the gripper shoes are repositioned, the boring machine is equipped with a dual fallback locking system. Two of the three clamping systems are always active in all operations (advancing/excavating, standstill, re-gripping/repositioning). The locking system operates mechanically on the principle of a self-locking toggle lever, and secures the machine even during a full power outage.

9.4. Subsurface excavations

9.4.1 Subsurface excavations – features and utilities

The use of underground space in urban areas is becoming increasingly important due to the scarcity of land in densely populated areas and environmental concerns (ASCE, 1989; Hudson and Harrison, 1997; Sterling and Godard, 2002). During the past 60 years, advances in methods for evaluating the ground conditions together with developments in ground consolidation and support techniques have enabled the creation of large underground excavations. Methods, techniques and equipment are available to excavate large volumes of rock beneath the surface efficiently. These large excavations, which are known as ‘caverns’, have been created for many purposes, such as civil works, storage facilities, defence installations, hydroelectric power plant, recreation facilities, etc. (see Figure 1.1). The design of these structures should take into account the following factors:

- Due to the long life span of these excavations, careful construction from the stability point of view is required, taking into consideration the likely forces during their operational life.
- Drilling and blasting can create very large caverns when the rock quality is good. Caverns created in hard rock may require little or no support. However, repair of such an opening, if not impossible, is a very difficult, time-consuming and costly affair, which is seldom preferred.
- The dimensions of caverns in soft rock or ground is limited by the support requirements; the permeability of the rock mass; by the presence of major discontinuities such as faults, folds, etc.; and by joints having a large aperture. In addition, the geometry and size of caverns may be restricted by major heterogeneity of the ground.
- The cavern shape may be restricted by the rock mass structure. The ideal shape is controlled by in situ stresses, which vary with depth. Large caverns need more support, and can destabilise a rock mass structure. The possible cavern size decreases with depth.
- Provisions for ventilation, emergency access, cross-passages and illumination are an integral part of the design of such excavations.
- Practically, there is very little scope for the collapse and even repair of the tunnel or cavern supports, and hence a support structure with an adequate safety factor is usually chosen. Infiltration of water, gases or any other liquid should not be possible.
- Smooth walls are almost mandatory, except for nuclear or hazardous waste repositories. In earthquake-prone areas, measures to minimise the effect of earthquakes should be given due importance during the design phase.

For large subsurface excavations the geophysical conditions should be favourable, which means that rocks should be competent and stable. For example, Scandinavian countries, in general, have favourable conditions for subsurface construction. Most of the bedrock consists of very competent rocks such as granite, gneiss and the like. Decomposed and weathered rocks were removed during the last big Ice Age, which means that it is easy to reach the bedrock without major excavation of the overburden. However, it should not be assumed that all rock in these countries is of good quality – bad rock conditions are encountered now and then. Special methods and equipment could be used in such cases, and projects can still be completed on a sound economic basis. The groundwater situation should also be favourable.

9.4.2 Important considerations

Subsurface structures require some investigation, studies, tests, design details and planning prior to their construction.

Subsurface excavation requires a combination of techniques to drive horizontal, vertical and inclined openings. The excavation starts from the surface to provide access to the intended subsurface excavation, which could be a powerhouse, an exhibition hall, a sports ground, a swimming pool, a repository, an oil storage cavern, a defence installation, etc. The access could be through adits, inclines, declines/ramps, shafts or their combination. These entries not only provide the initial access but also provide useful openings for the transfer of muck, material and work crews (see Figures 9.14–9.16). These openings are the service providers in terms of drainage, ventilation, the conveyance of power and communication cables.

Support. Due to varying geotechnical conditions, the type of support varies from site to site. In quite competent ground (see Figure 9.16) the support could be rock bolts, prestressed anchors, prestressed tendons, shotcreting, guniting or full-face reinforced concreting. In a fairly competent rock set-up, the bolt lengths in the roof could range from 0.15 to 0.30 times the cavern span, and in walls from 0.10 to 0.20 times the cavern height (Sterling and Godard, 2002).

Geomechanical aspects. Observations made in a study by Khot *et al*. (1988) provide some useful information:

- The ratio of horizontal to vertical stress (lateral stress coefficient) at the location of the cavity is the most significant factor affecting the stability of the cavity. The mid-roof and mid-floor portions of such cavities are under tensile stresses, and it is absolutely necessary to correctly estimate these stresses on site.
- When a multiple cavern proposal is to be executed (such as in the case of powerhouses), the minimum spacing between two adjacent openings should be half the width of the larger opening, to ensure that compressive stresses are within the compressive strength of the enclosed rocks.
- The two-dimensional, photo-elastic technique can be effectively used for rapid and precise determination of boundary stresses around the cavity, while the finite-element technique can be relied upon for determining the stresses inside the rock mass. The principal stress plot indicates this.

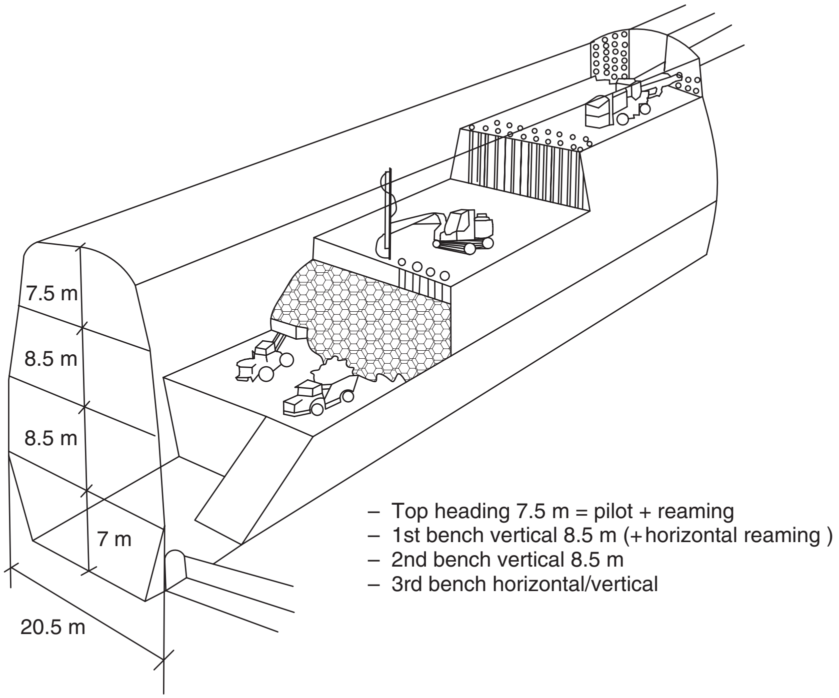
9.4.3 Construction procedure

As described in Section 4.8, special techniques and procedures are followed to drive large-sized tunnels and openings (Matti, 1999). In a similar way, large caverns are constructed using drill jumbos covering as large an area as is practicable of the cavern's total profile (dimensions). In order to cover the full size of the cavern, the excavation is carried out in a number of stages.

The excavation proceeds from top to bottom, by dividing the vertical span into a number of benches. This allows, first, supporting of the roof area, and then supporting of the sides as the excavation progresses downwards, as illustrated in Figures 9.12 and 9.15. The usual stages of such excavations are:

1 top section, by pilot heading and slashing the sides

Figure 9.12 Deployment of equipment, division into benches/horizons/levels and working sequence in a cavern



Pictoral view showing unit operations while creating large underground chamber/excavations

2 horizontal benching
3 vertical benching.

After reaching up to the intended excavation site using the access that has been created, the top section of a cavern can be driven using a multi-boom drilling jumbo, but in most cases it is unable to cover the entire width. Therefore, first, a pilot heading is drilled and blasted in the centre of the cavern; and then the sides and roof are slashed. This is also known as *side stoping*.

It is a common practice to take the next slice by horizontal benching so that use of the same drilling jumbo can be made. The height of this bench is governed by the capability of the drilling jumbo, which is usually within 5 m, and then the depth of the round to be drilled has to be decided; it is usually within 4 m.

The next slice can be taken as a vertical bench; its height is usually up to 12 m but it can be more. The same procedure is applied for the ensuing benches until the bottom of the cavern is reached.

In order to minimise overbreak and achieve a smooth configuration, smooth blasting of contour holes is almost mandatory in such excavations. For the top heading (uppermost section), the smooth blasting is as described in Sections 4.5.5 and 4.13, while for the benches, pre-splitting (see Section 2.5.3) or even lining drilling could be adopted.

The equipment used for various operations is almost the same as that used for driving tunnels, raises, shafts and ramps. The design parameters for the drill patterns are almost always the same, as is the use of supplies such as drilling accessories, explosives and other consumables. Usually, a trackless system of transportation and handling is used. Table 9.3 provides guidelines for executing these operations.

9.4.4 Powerhouse caverns

Some caverns are made to house various units (equipment and facilities) of a powerhouse, including the inlet valve (optional), the turbine and generator (machine hall), various mechanical and electrical subsystems, and transformers (optional) (ASCE, 1989; Matti, 1999; Willett, 1992). The dimensions of such excavations depend on the number of units and the power-generating capacity. An analysis made of some of the world's largest spanned underground power units for generating 40–475 MW power provided the following ranges of dimensions: width 24–35 m, height 19–57 m and length 70–296 m. Typically, a span in the range 18–24 m is usual (Sterling and Goddard, 2002). Allowance for the movement of service equipment and crew should be accounted for when determining the size of such caverns.

An example of a cavern excavated for a powerhouse is described in Case Study 9.1, and blasting related to hydropower projects is described in Case Studies 4.1 and 4.2 (see Chapter 4).

Case study 9.1

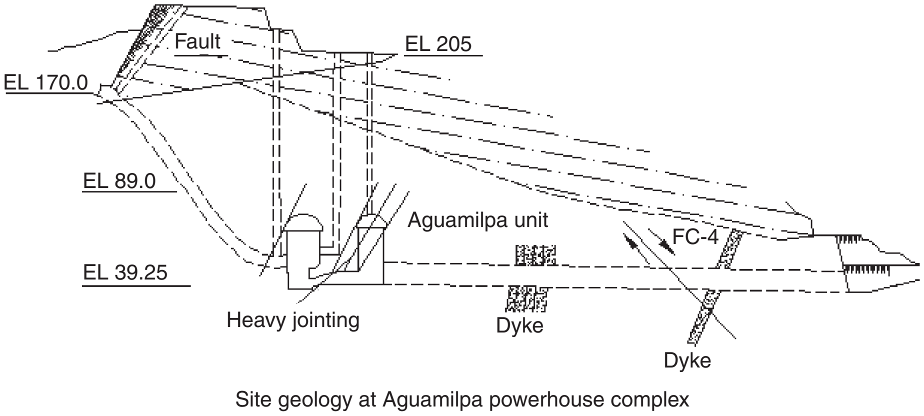
Aguamilpa powerhouse – a case study

The construction of the Aguamilpa powerhouse in Mexico is used here to illustrate how the different phases in the excavation for a hydroelectric power plant (or any large cavern below ground) can be completed (Fidencio, 1993; McKinstry, 1983). The project required the excavation of 109 577 m^3 of rock and 49 312 m of rock bolts, and took more than a year to complete.

The first step was to investigate the geology in detail, as shown in Figure 9.13. Figure 9.14 presents an isometric view of the underground works, which involved excavation of different openings, including tunnels, chambers, bins, etc. Figure 9.15 shows the excavation sequence within the large chambers such as the machine hall and surge chambers. Smooth blasting was mandatory to obtain the desired shape without any overbreak and to keep the disturbance to the ground stability to a minimum.

The primary system of permanent support specified for the excavation was rock bolting. Completion of the powerhouse excavation included the required rock bolting and grouting of bolts, drilling of drain holes and placing of shotcrete on the walls. Rock bolts sloping slightly upward were installed in the high vertical walls of the machine hall, as shown in Figure 9.16.

Figure 9.13 Site geology investigations. Identification of various structural geological features along the route and adjacent vicinities. EL, elevation



9.4.5 Oil storage caverns

Storing oil in unlined rock caverns works on the same principle that nature itself has arranged (Bjork, 1981; Goyal *et al*., 1988). It takes advantage of the fact that oil is lighter than water and that they do not mix together. A cavern is created so that its roof lies under the groundwater table in the rock. Through the fissures, which permeate every type of rock, groundwater percolates into the cavern, from where it is pumped out. In this way, a so-called 'cone of depression' is formed around the storage cavern. When oil is stored in the cavern, it floats on the water in the cone of depression and is prevented, thereby, from penetrating the surrounding rock. Oil storage in underground unlined rock caverns has some advantages compared to an installation above ground, as listed below:

- maintenance costs are one-third of those to be expected for steel tanks above ground
- the product temperature is more even and the breathing losses are less

Figure 9.14 The main components of the Aguamilpa hydropower plant

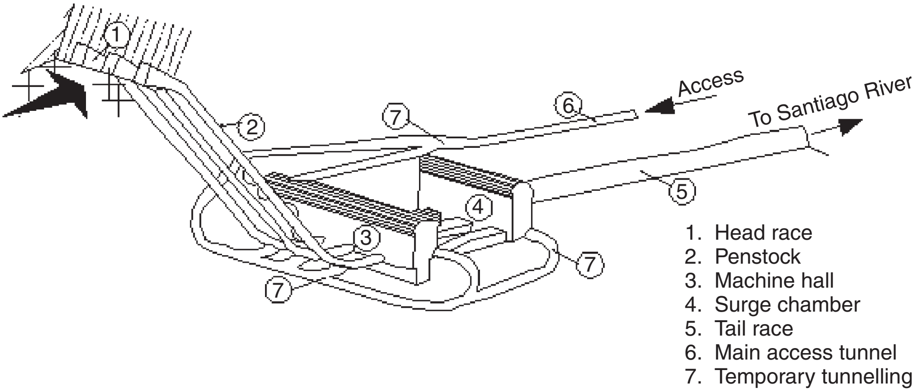


Figure 9.15 Design of the machine and surge chambers of the Aguamilpa powerhouse in Mexico (McKinstry, 1983). The numbers show the division of the excavation tasks and their sequencing

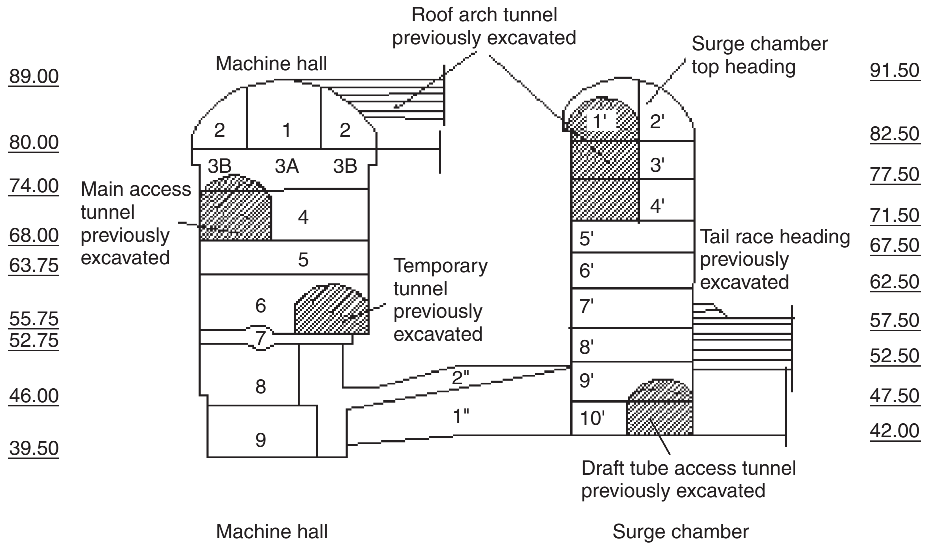


Figure 9.16 The main caverns in the Aguamilpa powerhouse are supported by rock bolts. Note the varying lengths of the rock bolts and the tensioning requirements

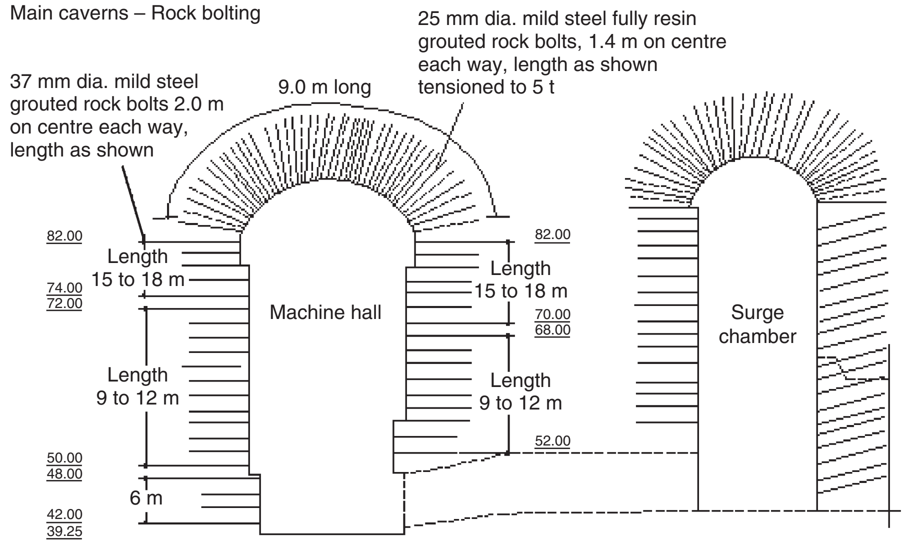
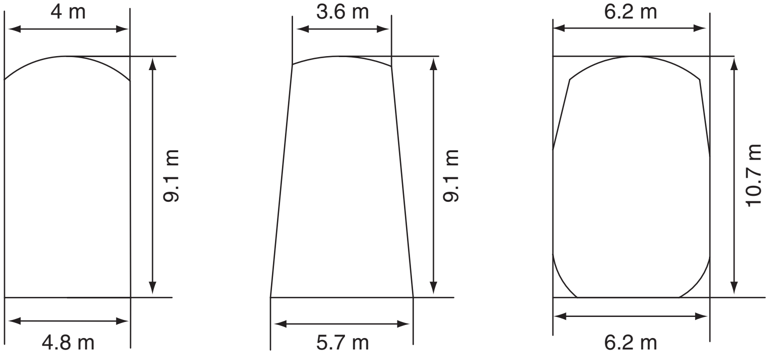


Figure 9.17 Geometrical shapes of oil storage caverns



- the risk of fire or other difficulties associated with leakage and accidental discharge of product decreases
- it provides much better protection against attack and observation
- tanks above ground may often fully occupy the site and there may be difficulty in acquiring further land.

Based on experience gained in Scandinavia, the cheapest and safest way of storing crude oil and refined products is in mined unlined caverns, provided the quantity of crude oil is adequate. Depending on the storage capacity, these caverns may range in span from 10 m to 21 m and be up to 30 m high. Figure 9.17 depicts different shapes of oil storage caverns (Sterling and Godard, 2002).

9.4.6 Storage caverns

Salt cavities are suitable for storing products that do not react chemically with the salt. These cavities can be used for the storage of crude natural gas, kerosene, chemical products and a few others. France has a number of such storage cavities. Formation of spherical, elliptical or cylindrical shaped cavities in salt can be achieved by water leaching. The two techniques available to achieve this are direct and reverse leaching.

Aquifers are widely used in the USA and Europe to store natural gas. The technique involves the injection of natural gas into the aquifer, displacing the water and creating an artificial reservoir for the natural gas.

The cost of storage depends on factors such as the characteristics of the product and its quality and quantity, and the geological and hydrological conditions of the site. The experience gained from operating such projects indicates that, wherever it is feasible, it has proved a cheaper means of storage.

9.4.7 Repositories

Various types of underground facilities are used for storage and disposal of radioactive wastes (Kumar and Singh, 1988; Mathur *et al.*, 1988). Designs depend on the quantity and quality of these wastes. Some of the storage facilities, such as tile holes, trenches and storage vaults, are shallow, up to a depth of 10 m, while others, such as geological repositories, are as deep as 500–900 m (Hudson and Harrison, 1997). Each of these installations has its own design and constructional and operational requirements to achieve isolation for a desired period of time.

These are complex designs that must take into consideration a number of factors, including those defined by the natural laws, regulatory authorities and the requirements established by political compromise (Matti, 1999). High-level radioactive waste is hazardous to man and the environment, as it emits alpha, beta and gamma radiation for an extended period of time, possibly thousands of years. Many writers have proposed conceptual designs for these complex structures. The life of a repository can be divided into four phases: constructional, operational, sealing/isolation and post-isolation.

During the construction phase, a network of excavation openings that includes shafts, ramps, tunnels, drifts, etc., is built. During the operational phase, the horizontal and vertical boreholes in the emplacement drifts and tunnels are drilled to place the specially designed nuclear waste canisters. These boreholes are then sealed and backfilled with a specially designed rock mixture. After this, underground facilities that were installed during the construction and installation phases, and including any artificial supports used, are decommissioned, and the encompassing drifts and tunnels are backfilled and sealed. Finally, all the access ways, including shafts, are backfilled and sealed as per the regulatory requirements of the country.

Geotechnical aspects of waste disposal. The desirable aspects of an ideal host medium for waste emplacement are (Kumar and Singh, 1988):

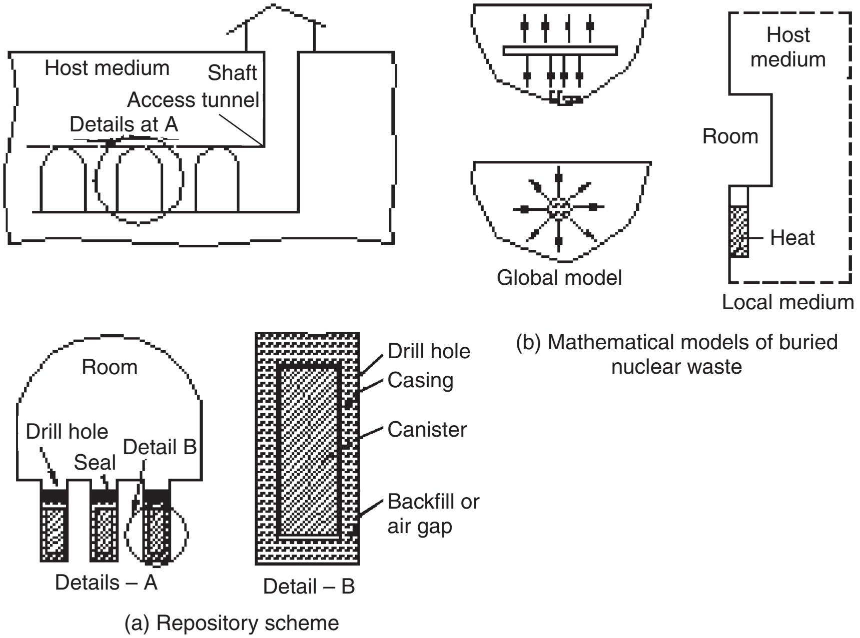
- good thermal conductivity
- high absorption capacity
- low permeability
- high plasticity and ease of mining
- negligible mineral value (barren rock mass).

The technical, geological and environmental factors to be considered are:

- formation depth – vertical and horizontal span
- permeability and porosity of rock and homogeneity of disposal horizon
- tectonic and seismic potential
- resource potential
- hydrological and thermal properties
- configuration on the surface
- climate and population density; source of potable water supply and chances of surface impact (environmental factors).

Figure 9.18(a) illustrates a typical repository; details of the drill holes, tunnel or room and a drill hole containing a canister are shown. The effect of this burial is estimated on a global as well as a local basis (Figure 9.18(b)). The global analysis takes into

Figure 9.18 Repository: (a) schematic representation of the concept and the network of subsurface structures that need to be built; (b) mathematical models for buried nuclear waste



account adverse effects on the entire repository and its environs, particularly the areas lying above, below and in the vicinity. Local models depict a limited area surrounding the place of nuclear waste burial. Thus, the difference between these models is the scale at which various details are drawn (Greenslade *et al.*, 1981).

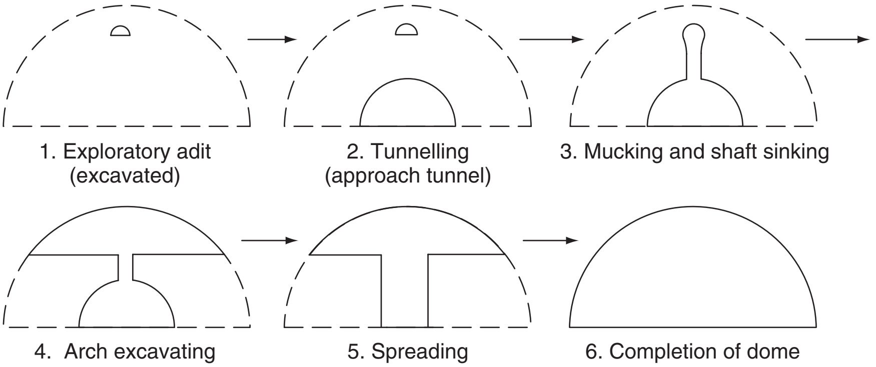
9.4.8 Underground exhibition halls

The importance of large halls such as exhibition halls and shopping malls has been mentioned in the preceding sections. It is important to investigate thoroughly and plan properly, and due consideration must be given to the geological, geomechanical, seismic and other constructional features (Sakurai *et al.*, 1998). A typical excavation sequence for an exhibition hall is shown in Figure 9.19.

9.4.9 CERN – a network of subsurface openings

CERN, the European Organization for Nuclear Research, which is the world's largest particle physics centre (founded in 1954), is one of the most important sites for underground works in Europe in recent years. It is a very good example of how to site important subsurface excavations. The expansion project was started in 1996 and was planned to be completed in 2004. The design and construction of the underground works involved companies from more than ten different countries, often working together in joint ventures. The construction consists of more than 5 km of tunnelling works, seven shafts, two large cavern complexes, and many smaller caverns and galleries (Watson, 2002).

Figure 9.19 Excavation sequence for a dome-shaped exhibition hall



9.5. Equipment and services selection

The guidelines given below could be used to select equipment for operations requiring driving or the creation of civil or mining excavations, as described in this book (Dangler, 1982; Singh, 1993).

Table 9.3 gives details of equipment, explosives, blasting accessories, service appliances and devices, etc. For a particular excavation, matching sets of equipment should be selected to carry out different operations. The matches given below are for guidance; the set of equipment that will give optimum results will depend on the local conditions, specific requirements and available resources in terms of men, machines, equipment, techniques, material and experience, and exposure of the working crews.

- *Conventional drifting or tunnelling operations using rocks drills*: this could be for development drives, cross-cuts, level drives, sublevel or small-sized civil tunnels.

  D1 + E1/E3 + B1 + M1/M3(a)/M3(b) + T1(a)/T2 + services as per Table 9.3(b).

- *Mechanised drifting or tunnelling operations using one or two boom rock drills (pneumatic or hydraulic)*: this could be for development drives, cross-cuts, level drives, sublevels of medium size, or medium-sized civil tunnels.

  D3(a)/D3(b) + E1 (as primers or in watery situations) + E2/E3 + E5(b)*

  + B2 + M3(b) + T1(a)/T2 + services as per Table 9.3(b).

  (*If smooth blasting is required.)

- *Large-sized tunnels, underground chambers and caverns using multi-boom hydraulic or pneumatic jumbos.*

  D3(a)/D3(b) + D2(c)* + E1 (as primers or in watery situations) + E2/E3/E4

  + E5(b)† + B2/B3‡ + M3(b)/M3(c) + T1(a)/T2 + services as per Table 9.3(b).

  (*Where benching is required. †If smooth blasting is required. ‡Practice in development stage.)

Table 9.3 Details of equipment, explosives and blasting accessories

Symbol – operation	Equipment, its suitability and its application locales	
(a) Main operations		
D – Drilling	1. Jackhammer with or without pusher leg (pneumatic powered) for hole lengths up to 3.5 m and diameters 32–38 mm	1. Medium hard rocks to hard rocks, small output, small size horizontal mine openings and civil tunnels and chambers. Pin holes for services
	2(a). Hand-held jackhammer, sinker for hole lengths up to 3.5 m and diameters 32–38 mm	2(a). Shaft sinking, winzing in all types of rock. Funnel and chamber excavations (downward)
	2(b). Shaft jumbo mounted with light-duty drifters for drilling downwards, hole lengths up to 5 m and diameters up to 50 mm (for large-diameter heavy-duty drifter)	2(b). Mechanised shaft sinking, winzing in all types of rock: holes are suitable for large-diameter explosives, including emulsions
	2(c). Rotary-percussive and down-the-hole drills; wagon mounted. Hole diameters 50–100 mm or more; lengths exceeding 5 m (All are pneumatic powered)	2(c). Bench blasting for large underground chambers, caverns, excavations and mine stopes. Allows bulk loading of explosives such as ANFO, slurries or emulsions
	3(a). Single- or multi-boom drifting jumbos fitted with light-duty pneumatic drifters capable of drilling inclined and horizontal holes up to 7 m long and 70 mm diameter	3(a). Drifting and tunnelling of almost all sizes in all types of rock; also suitable for large-sized chambers and caverns. Fast progress possible
	3(b). Single- or multi-boom drifting jumbos fitted with light-duty hydraulic drifters capable of drilling inclined and horizontal holes: lengths up to 7 m; diameters up to 70 mm. (*Note*: For large-diameter and longer holes use heavy-duty drifters; logic also applicable for 3(a)).	3(b). For fast drifting and tunnelling operations, and also suitable for large-sized chambers and caverns. Fast progress with better safety and quality possible
	3(c). Ring and fan drilling jumbos (pneumatic or hydraulic) in any direction: lengths 5–40 m; diameters 50–100 mm	3(c). For enlarging small-sized tunnels and chambers into big ones. Mainly meant for stoping operations in mines
	4. Stoper, or parallel raise feed; for hole lengths up to 3 m and diameters 32–38 mm	4. Raising (vertically up and inclined upward) operations. Over-hand drilling in stopes

Table 9.3 Continued

Symbol – operation	Equipment, its suitability and its application locales	
	5. Hand-held electric drill for hole lengths up to 2 m and diameters 32–38 mm	5. Soft/weak rocks, light duty and small output, small-size horizontal mine openings and civil tunnels. Pin holes for services
E – Explosives	1. Nitroglycerine-based explosives and dynamites in cartridge form. Diameters 25–50 mm, lengths 200 mm, or as supplied by the manufacturer	1. While driving tunnels, shafts, drifts, raises and winzes in watery conditions in medium hard to hard rocks. Strongest and costliest
	2. Dry blasting agent is ANFO for holes larger than 40 mm diameter; pneumatic charging in up holes and an antistatic detonation system is mandatory to avoid static hazards	2. Dry rock conditions, suitable for all types of rock, particularly with larger diameter and longer holes. For wet conditions use heavy ANFO. Non-cap-sensitive and needs booster charge for initiation. Cheapest
	3. Slurry explosives – wet blasting agents	3. Driving tunnels, shafts, drifts, raises, winzes in dry or watery conditions in medium hard to hard rocks. Cheaper than nitroglycerine-based explosives
	4. Emulsion explosives	4. Suitable for bulk loading in holes larger than 45 mm diameter during drifting, tunnelling, sinking and stoping (extracting ore/valuable mineral blocks)
	Special explosives	To be used for specific conditions
	5(a). Permitted explosives	5(a). In gassy coal mines and tunnels
	5(b). Smooth blasting	5(b). For charging perimeter holes of tunnels, shafts, caverns, chambers, etc. and to reduce overbreak in weak and unstable ground conditions
	5(c). Seismic types	5(c). Exploration
B – Blasting	1. Electric detonators with multi-shot exploder	1. With explosives other than E2 type
	2. Antistatic detonators such as Anodets, or systems such as Nonel and Hercudet	2. Where danger of electrostatic charge generation exists, as in case of E2 explosives
	3. Electronic detonators with computerised delay-setting system	3. In tunnels and mining operations but commercial viability is yet to be established
	4. Fuse blasting (use of detonating cord, connectors, etc.)	4. In metal mines while using ANFO explosives

Table 9.3 Continued

Symbol – operation	Equipment, its suitability and its application locales	
	5. Secondary breaking (pop or plaster shooting)	5. E1 or E3 type explosives. With detonating cord or electric detonators
C – Cutting	1. Cutting a kerf using coal-cutting machines while driving horizontal drives and tunnels in coal mines	1. In underground coal mines
	2. Cutting rocks using heading machines (partial-face boring)	2. Tunnels, chambers and horizontal mine openings of sufficient size and length
	3. Full-face tunnel boring machines (TBMs)	3. Tunnels and horizontal mine openings of sufficient size and length
M – Mucking	1(a). Overhead loaders (rocker shovels), tracked or trackless	1(a). Small-sized mine openings and tunnels. Crawler-mounted EIMCO-630 during shaft sinking and winzing
	1(b). Dipper shovels	1(b). Large-sized tunnels
	2(a). Arm loaders – suspension types such as cactus, grab, Cryderman, etc.	2(a). Shaft sinking and winzing
	2(b). Gathering arm loaders	2(b). Mucking from coal-mine openings (development and stoping)
	2(c). Digging arm loader (Hagg loader)	2(c). Mucking in tunnels and mine openings by discharging muck via a conveyor into Hagg haulers
	3(a). Auto-loader (Cavo)	3(a). Small-sized tunnels and mine openings such as sublevels
	3(b). Integrated unit (LHDs)	3(b). Mine openings and tunnels of 9 m^2 cross-section or more. Mucking from stopes (ore blocks)
	3(c). Front-end loaders (FELs)	3(c). Large-sized tunnels
	4. Integral with cutting unit	4. Mine openings and tunnels driven using roadheaders or TBMs
T – Transportation	1(a). Trackless low-profile dumper or trucks	1(a). Tunnels, large-sized mine openings and stopes. Transportation from ore/waste chutes
	1(b). Trackless – LHD	1(b). Direct transportation from stopes to ore pass or waste passes (leads up to 300 m)
	1(c). Hagg hauler	1(c). Mucking through a Hagg loader for tunnelling and mine openings
	1(d). Large-sized trucks	1(d). Large-sized tunnels

Table 9.3 Continued

Symbol – operation	Equipment, its suitability and its application locales	
	2. Locomotives (battery, diesel, trolley wire)	2. Tunnels and in mines for development and stoping operations
	3. Conveyors – belt	3. From long-wall mining faces at gate road and main (trunk) roadways in mines
	4. Rope haulage	4. Small to medium-sized mines
	5. Hydraulic transportation	5. For transportation of mine fill in stopes
R – Ripping	Hand-held rock breakers and rippers	In loose, soft and unstable ground during sinking and tunnelling operations
H – Hoisting	1. Drum winder/hoist	1. Sinking, regular mine production
	2. Koepe winder/hoist	2. Regular production from mines
(b) Auxiliary operations		
V – Ventilation	1. Main ventilation system using forcing or exhaust fans installed at the surface and coursing air current using mine entries such as shafts, inclines, declines etc.	1. Entire mine, including the network of mine entries
	2. Main ventilation system using forcing or exhaust fans at the surface, and coursing air current by rigid and flexible ducting	2. Entire tunnel, cavern network, sinking shafts
	3. Auxiliary ventilation using forcing, exhaust or contra-rotating fans and blowers with rigid and/or flexible ducting	3. For effective face ventilation by coursing the main air current by these means
	4. Spot coolers and air-conditioning system	4. Deep mines
S – Support	*Rock reinforcement*	To induce reinforcement forces within the rock mass: single set of discontinuities in hard rocks, or multiple discontinuities in soft rocks
	1(a). Grouting by bolts, anchors, dowels, cables	
	1(b). Anchoring rock bolts	
	1(c). Shotcreting, guniting	
	Rock support	To inhibit rock mass displacement
	2(a). Single member – props: wood or steel	2(a). Individual blocks in tunnels and mines
	2(b). Multi-member – sets and arches: wood, steel or concrete	2(b). Continuous rock mass in tunnels and mine openings
	2(c). Reinforced concrete cast in place	2(c). Continuous rock mass in tunnels and shafts

Table 9.3 Continued

Symbol – operation	Equipment, its suitability and its application locales			
	2(d).	Tubing of various designs	2(d).	Continuous rock mass in tunnels and shafts
P – Pumping	1.	Portable face pumps	1.	To deal with muddy water at the face during shaft sinking, tunnelling or driving an opening in mines
	2.	Pumps mounted on a trolley or hanging platform; to deal with muddy water at the face	2.	During shaft sinking and tunnelling
	3.	Main pumps installed at the sump to pump out water for its final disposal	3.	To deal with water from tunnels, shafts and mines
I – Illumination	1.	Portable face light (pneumatic)	1.	While sinking shafts, driving tunnels and at the working faces in mines
	2.	Fixed lighting arrangement	2.	Tunnels, underground stations, caverns where there is no chance of them being damaged by day-to-day workings

- *Drives and tunnels driven using roadheaders or full-face TBMs.*

  C2/C3 + M4 + T1(a)/T2 + services as per Table 9.3(b).

- *Raising – vertical development in upward direction.*

  D4 + E1/E3 + B1 + M* + T* + services as per Table 9.3(b).

  (*As and when required using existing mucking and transportation units that are used for drifting and tunnelling operations.)

- Winzing* and sinking operations (excavations in a downward direction), shafts, winzes, inclined shafts in a downward direction, inclines, ramps and declines.

  D1*/D2(a)/D2(b) + E1/E4 + B1 + M2(a)/M1(a) + H1 + services as per Table 9.3(b).

  (*Small-sized units are used for winzing. †If inclines or declines.)

9.6. Concluding remarks

- Creating any opening (shaft, tunnel, raise or cavern) is a very difficult and challenging task, as a new set of conditions is met at every step of advancement. As such, the safety of all those concerned must be ensured during both the construction and the operational phases (life).
- Recent advances in methods for evaluating ground conditions and developments in ground consolidation and support techniques have enabled the creation of large underground excavations. Methods, techniques and equipment are available to

efficiently excavate large volumes of rock beneath the surface. The long life span of these excavations requires careful construction, from the stability point of view, taking into consideration the likely forces during their operational life.

- Present technology allows the faster and safer creation of bigger and deeper networks of subsurface excavations.

9.7. Questions

1. What operation does the term ‘development’ refer to and why it is the most difficult and challenging task?
2. Underground excavations have some unique features, list them.
3. What benefits could subsurface excavations have in urban areas?
4. Define ‘raise’. How does it differ from a ‘winze’? When is a winze termed a ‘shaft’? Why is raising hazardous compared with winzing?
5. Why is shaft sinking a specialised operation? Why is sinking costly? In what situation is winzing or sinking indispensable?
6. What governs the shape and size of a shaft? Why are circular shafts preferred over other shapes? Where can rectangular or elliptical shafts be driven and what advantage do they offer?
7. Raises are one of the most important structures in many civil and construction projects. List their applications.
8. Draw a line diagram to show the classification of raise driving techniques.
9. What is the ‘open raising technique’? Where does it find application and what are its limitations? Where is raising by ‘long-hole drilling’ usually adopted? What are its limitations?
10. Describe briefly an Alimak raise climber. Mention its capabilities and salient features. What features have made it so popular since its introduction in 1957? Suggest the scope of use of each of the following units: (a) pneumatic-, (b) electric- and (c) diesel(hydraulic)-driven climbers.
11. How can an Alimak be used to drive a large cross-sectional area winze or shaft?
12. What is ‘drop raising’? How does it differ from long-hole raising? Which drilling equipment is utilised in this technique? What is the VCR concept and how it is used when driving raises by this technique?
13. Draw a schematic diagram to show working cycle of an Alimak raise climber.
14. How is the blast hole of a ‘drop raise’ plugged before charging it with explosive? Draw a diagram to illustrate the procedure.
15. Describe the raising technique by the use of ‘raise borers’. Where can it be applied? Is it suitable in relatively poor ground and, if so, up to what diameter? What size of pilot hole is drilled, and after drilling it what is the next step? List the advantages that a properly matched raise boring unit can provide. Draw a diagram to illustrate this operation.
16. The Robbins Company has achieved some milestones in raising. Give numerical values for the following: (a) shaft length; (b) diameter range; (c) box-hole (blind raises) length; (d) box-hole diameter?
17. List the purposes for which shafts are required. In conjunction with a tunnelling system or network, for what purposes are shafts necessary?
18. Draw a line diagram showing the classification of techniques used for shaft sinking.

19 List the three segments of a sinking operation. Describe each one of them.

20 List the 'unit operations' of a sinking cycle and describe each one of them. Describe how you would accomplish the following auxiliary operations: (a) dewatering; (b) ventilation; (c) illumination; (d) shaft centring.

21 Give the formulae for determining the number of holes, if drilling is with a shaft jumbo and the hole diameters are in the range 45–55 mm.

22 List the prominent mucking units used during shaft sinking.

23 During shaft sinking, when does it becomes necessary to adopt a special method or technique? List the special methods that can be used to deal with abnormal situations.

24 Where has extensive use been made of rotary drilling for sinking? Could the same technique be applied to sink shafts, particularly through the profile of aquifers or caving formations? What are the advantages of rotary drilling compared with the conventional methods (including the special shaft sinking methods)?

25 What diameter range and what depth of holes can be drilled using rotary drilling? Is this type of drilling suitable for sinking ventilation and emergency escape shafts rather than main shafts? List the merits and limitations of the method.

26 Why did the concept of shaft boring using SBMs not gain much popularity? Describe this system. Which rock formation is most suitable for the use of an SBM? Apart from boring, list the additional facilities and devices that form an integral part of this system.

27 What is a 'V mole'? Who developed it and what are its unique features?

28 What are the factors that have enabled the creation of large underground excavations?

29 For what purposes are large excavations (caverns) created?

30 List the factors that should be considered when designing caverns. Why is their repair, if not impossible, very difficult?

31 What are the parameters that govern the dimensions of caverns? Describe the procedure for creating caverns. How they are accessed?

32 Due to varying geotechnical conditions, the type of support varies from site to site. List the supports required for different ground conditions.

33 With regard to the working site/location:
(a) Why it is absolutely necessary to correctly estimate the lateral stress coefficient at the location of the cavity?
(b) When a multiple cavern proposal is to be executed, what should be the minimum spacing between two adjacent openings?
(c) How can the two-dimensional, photo-elastic technique be helpful, and what is the use of the finite-element technique when assessing the geomechanical parameters at the working site?

34 Describe the construction procedure used for large-sized caverns. Why is it necessary to carry out the excavation in a number of stages? Illustrate how the cavern is divided into a number of benches in order to achieve the full height. Why does the excavation proceed from top to bottom? List the usual stages of such excavations.

35 After reaching up to the intended excavation site using the access that has been created, how is the top section of a cavern driven? Why is it common practice to

take the next slice by horizontal benching? Why should the next and ensuing slices be taken as vertical benches until the bottom of the cavern is reached? Why is smooth blasting of contour holes almost mandatory in such excavations?

36 List sets of equipment to be used for various operations in such a project like the one described in Question 35.

37 Some of the world's largest-span underground power units generate power in the range 40–475 MW. Give the width, height and length of such caverns.

38 What principle is followed when storing oil in unlined rock caverns? Where is a cavern created and how is oil storage achieved?

39 List the advantages of storing oil in underground unlined rock caverns as compared with in an installation above ground. Is underground storage the cheapest and safest way?

40 What is the usual span and height range of oil storage caverns? Draw their usual shapes.

41 What are suitable for salt cavities? What could be stored in such cavities? In which country do you find storage cavities? What are the usual shapes and how can they be constructed? List the two techniques available to achieve this.

42 Aquifers are widely used in the USA and Europe to store natural gas. Describe the technique involved to achieve this. What are the governing factors for the cost of storage? What experience in terms of the storage cost has been gained from operating such projects?

43 List underground facilities that are used for the storage and disposal of radioactive waste. What parameters govern their design?

44 Describe a geological repository. At what depth are such repositories sited? What are the design considerations for such installations? Why is their design considered very complex?

45 Many writers have proposed conceptual designs for repositories, dividing their life span into four phases. Describe these, giving the salient features and with the aid of diagrams. [*Hint*: See Figure 9.18].

46 List the geotechnical aspects of hazardous waste disposal that it is essential to consider. Also list the technical, geological and environmental factors that must be considered.

47 Draw the excavation sequence for a large dome-shaped exhibition hall. What investigations are necessary when undertaking such a project?

48 CERN, the European Organization for Nuclear Research, is a very good example of how to site important subsurface excavations. Specify the amount of construction work involved in this project and the agencies that were involved in the project.

49 Using Table 9.3 and the nomenclature used therein, propose matching sets of equipment and services to accomplish the following types of excavations:
(a) conventional drifting or tunnelling
(b) mechanised drifting or tunnelling
(c) large-sized tunnels, underground chambers and caverns using multi-boom hydraulic or pneumatic jumbos
(d) drives and tunnels driven using roadheaders or full-face TBMs
(e) raising
(f) winzing and sinking operations.

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Chapter 10
Hazards, safety and the environment (HSE) and loss prevention

While creating excavations of any kind, whether surface or underground, damage to the environment (pollution) and accidents are unavoidable. They cannot be eliminated but efforts can be made to minimise them. Prevention is always better than cure.

10.1. Introduction

What is the meaning of ‘health, safety and the environment’ (HSE)? Consider the well-known proverb, ‘Health is wealth’. True, if you are healthy you can acquire wealth. But, how can this wealth be acquired? The main sources of wealth acquisition are our basic industries – civil, mining, electrical, mechanical, chemical and many more. Thus, it is industry that brings the wealth by which one can maintain one’s health by breathing fresh air, drinking safe water, eating nutritious food and buying comforts to satisfy one’s needs. Thus, HSE means ‘industrial safety and environment’. Any industry, however, besides providing wealth, also creates air and water pollution and land degradation, and it brings injuries due to accidents. All these are detrimental to health. Thus, it presents a dilemma: while we cannot stop encouraging our industries, at the same time we cannot allow our health to deteriorate. This calls for a balanced strategy that boosts productivity while maintaining safety and environmental standards at an acceptable level. It is the active industrialisation of more than a century, particularly in the developed and developing countries, that has brought us to a turning point with regard to health concerns. Today, due to this logic, every country is highly concerned about HSE. This chapter briefly describes potential hazards arising from excavation activities that could damage humans, machines, equipment, property and the environment.

10.2. Hazards

The meaning of *hazard* is ‘danger, risk’; and *hazardous* means ‘risky, dangerous’. A hazard is a condition with the potential to cause losses/harm to humans, machines, equipment, property assets or the environment, or a combination. Hazards can be natural or man-made (see Figure 10.9). Hazards can turn into disasters, causing massive injuries, including fatalities, and huge losses. Underground operations are full of hazards as they are a fight against nature. New situations and sets of conditions are met and encountered at every working moment. Workings (openings and structures) underground are usually of limited size, confined and narrow. Natural light and ventilation cease after attaining a depth of a few metres from the surface. In most cases, passing through the water-table and working below it are unavoidable. Excavation in a variety of ground types (see Table 1.7) and/or rock types (see Table 1.8) is mandatory. This disturbs the original settings of the rocks and ground through which an excavation is to be created. Thus, it disturbs the existing environment and could cause air pollution, water pollution and land degradation.

Use of machines, equipment and materials of different kinds by the working crews is necessary to create excavations. Failing of the working crews to comply with the set norms and practices during the operation and application of this equipment and materials could result in accidents. Accidents are unplanned, unintended events that can disturb routine and scheduled operations at any moment and bring about losses of all kinds, as mentioned above. An accident could be the result of

- unsafe conditions
- unsafe acts.

These phenomena are equally applicable to surface excavations which are created for the purpose of mining or civil or construction activities. Thus, while creating excavations of any kind at any locale, either surface or underground, damage to the environment (pollution) and accidents are unavoidable. They cannot be eliminated but efforts can be made to minimise them.

10.3. Potential hazards

- Adverse ground conditions – collapse, deformation, swelling, squeezing, subsidence, bumps and bursts, slow penetration and progress, water inrush and seepage, fluctuation in hydrostatic pressure, etc.
- Water inflows/inrush – flooding, improper sealing, inadequate consolidation or water-table lowering measures. Adverse effects of raw water.
- Ingress of gas.
- Mechanisation and automation.
- Heat and humidity.
- Fires and explosions.
- Health hazards – occupational diseases.

10.3.1 Adverse ground conditions

10.3.1.1 Ground collapse

The art of tunnelling in ground of different types has been developed over centuries (see Table 1.7). Different countries have developed the art of working in soft formations, and such methods have become known as the German method, the Belgian method, the Austrian method, the Russian method and a few others (see Section 4.9 and Figure 4.16). The idea is to divide a tunnel cross-section into small segments, and dig the ground following a particular sequence, preventing any collapse. These manual and conventional practices are still in vogue in some countries, particularly where manual labour is not costly or scarce. But the progress achieved is slow; methods are tedious and not very safe, economical or productive. For the past 60 years or so the creation of tunnels and ground excavations has no longer been an art but an engineering task.

The types of tunnelling machine available today take care of the ground that is likely to be encountered, and tunnel-boring machines (TBMs) are available that can deal with very soft ground (see Table 1.7) to tough rocks (see Table 1.8). Problems occur when the ground through which a tunnel has to pass has not been fully explored, or has been inadequately explored. Even a fully explored ground, which may not be the situation in most cases, could have some zones that can adversely affect tunnelling progress (Donovan Jacobs, 1975; Whittaker and Frith, 1990). The geological and geomechanical properties that influence the progress and costs of tunnelling are given in Table 1.8.

Adverse ground conditions could result in collapse during both the construction phase and the operational phase. Collapse is the result of deformations, swelling, squeezing, subsidence, bumps and bursts. It is a major tunnelling hazard today, as is evident from a survey of tunnel incidents, including collapses, by the Health and Safety Executive. The following types of incident were found:

- instability during construction, cave in, collapse
- large inflows and severe deformations
- serious surface settlements
- portal failure during construction
- TBM fire.

Analysis for the period 1992–1997, covering widely published tunnel incidents all over the world, indicates that more than 95% of incidents are accounted for by ground failures. Prominent among these are the collapses at Munich, Germany, and the Heathrow Airport tunnel, UK. In addition, in a catalogue of case histories of notable tunnel failures (CEDD, 2009) covering the period 1964–2008, of around 40 tunnelling sites, the incidences of ground failure continue to occur, including occurrences at the Channel Tunnel Rail Link, UK (February 2003), the Shanghai Metro, China (2003), the Singapore MRT (20 April 2004), the Lausanne M2 Metro, Switzerland (22 February 2005), the Sao Paulo Metro Station, Brazil (15 January 2007) and the Hangzhou Metro Tunnel, China (15 November 2008). Rawlings *et al.* (1998) are of the view that risks can be characterised as those that are present during the pre-construction, construction and operation phases. They consider that maximum risk is present during the pre-construction phase, due to the fact that major decisions are taken during this conceptual phase, and they insist that considering different options and alternatives should minimise this. A proper design will result in fewer failures during the remaining two phases.

10.3.1.2 Reasons for ground collapses

There are a number of possible reasons for ground collapse (Blyth and Freitas, 1988; Donovan Jacobs, 1975; Rawlings *et al.*, 1998).

Weathered ground. This is usually encountered at the portals. Support is essential before progressing with the works.

Presence of faults, folds and discontinuities. Faults influence underground excavations in the following manner. Rock in its crushed and comminuted state, caused by the grinding action of relative movement along the fault plane, is commonly referred to as *gouge*.

Gouge can contain clays. Any excavation that intercepts fault gouge under humid and watery conditions could initiate progressive ground collapse. Water could inrush through this gouge into the excavation. If an excavation is driven or located within these structures, they could be affected in the following ways (Anderson, 2000; Hudson and Harrison, 1997; Whittaker and Frith, 1990):

- Rocks become highly stressed locally.
- Rocks possess decreased competence due to the high state of fracturing.
- Folding and faulting are both associated with jointing, which divides the rock into blocks. Heavy support may be necessary to prevent an excavation from collapse in ground where jointing is severe.
- Many joints and faults also provide pathways for the movement of water to excavations. Consequently, it is quite common to encounter localised and significantly deep-seated weathering, particularly in near-surface situations.
- The width of a fault zone is difficult to predict and the width can vary along the length of the fault. Fault gouge is of low competence and has a poor stand-up time.
- Hudson and Harrison (1997) proposed the following relationship:

$$\text{stability} = \frac{1}{\text{number of discontinuities}} = \frac{1}{\text{engineering dimension}} \tag{10.1}$$

In some projects TBMs have become trapped when passing through the gouge of fault zones or squeezing ground (Whittaker and Frith, 1990). Sometimes tunnel cave-ins or collapses are associated with fault zones. Progress slows down during mechanised tunnelling.

Squeezing and swelling ground conditions (see Table 1.7). Squeezing ground commonly refers to weak, plastic materials, which are displaced into the tunnel excavation under the action of gravity and form a sort of stress gradient around the tunnel opening. Swelling ground displaces into the tunnel opening due to water adsorption and absorption. Rocks that are rich in clay minerals not only exhibit squeezing behaviour but are also likely to have swelling effects. Clay minerals such as mudstone, claystone, shale, fault gouge and highly altered rocks (pyroclastic and micaceous) usually possess strong swelling characteristics.

Support. When excavating ground following a particular sequence, support is essential, and special methods such as the new Austrian tunnelling method (NATM) could prove useful.

Seismic activity. In highly earthquake-prone areas a risk of damage and collapse of excavations could be expected.

Hard and abrasive rocks. Collapses in hydro tunnels (used for water conveyance) could occur due to wide fluctuations in hydrostatic pressure during normal operation of the tunnel (Donovan Jacobs, 1975; Whittaker and Frith, 1990). In such tunnels, if due precautions were not taken during the construction phase when approaching fault zones or highly jointed areas, and if these areas have not been properly sealed off and/or supported adequately, the hydrostatic pressure could cause tunnel failures.

Intense jointing, highly shattered ground or weak zones. Hard and abrasive rocks are usually blocky or slabby and so could easily become detached at the face, sides or roof of the tunnel, causing collapse. Such areas/situations are usually treated with rock bolts and light supports as immediate measures, followed by more permanent supports.

Mixed ground conditions – hard, soft and abrasive. Soft ground has its own problems and needs special care and due precautions against collapse. It requires least exposure and the immediate rocks pose a special problem. When approaching dykes (igneous rock intrusions), igneous and/or metamorphic rocks such as diabase, pegmatite, siliceous dolomites, quartzite, etc., could cause problems of high cutter consumption and the need for their frequent replacement. Such problems slow down penetration and contribute to low productivity and high costs.

The collapse of the station tunnel and partial damage of the access shaft at Sao Paulo Metro Station, Brazil, is described in Case Study 10.1, and ground failure at the Heathrow Express rail link, UK, is discussed in Case Study 7.1.

Case study 10.1

Tunnel collapse – Sao Paulo Metro Station, Brazil, 2007

On 15 January 2007, there was collapse of the station tunnel and partial damage occurred to the access shaft at Sao Paulo Metro Station, Brazil.

Background

- The NATM was used to excavate a 18.5 m diameter, 45 m long section of station tunnel.
- The tunnel failure occurred close to a junction with a 40 m diameter, 40 m deep access shaft.

The failure

- Collapse of the station tunnel and partial damage to the access shaft.
- The rate of settlement at the tunnel crown increased rapidly, reaching 15–20 mm 2–3 days before the failure

Possible causes of failure

- Failed to account for the geology of the site; fractured rock located over the excavation.
- A lack of sufficient support in the roof and side walls of the excavation.

Consequences

- Several vehicles dropped into the 30 m deep hole.
- Seven people were killed.

Remedial measures

- The tunnel section was stabilised with extensive reinforcement.
- A system of anchors extending 32 m into the soil was put in place, and excavation through the section was performed after pre-grouting.

10.3.2 Water in subsurface areas

Water enters underground workings for various reasons. As the geological and hydrological conditions of different ground formations vary, the inflow of water differs from one location to another. Underground water is variable in its chemical properties; it is often unsuitable for drinking and industrial use. Sometimes it contains free sulphuric acid, in which case it is called *acidic water*. This water is very harmful and needs to be managed with special care. Subsurface drainage includes the prevention of entry of surface water into mines/tunnels and their protection from a sudden inrush of water, and pumping of water to the surface.

The ability of rocks to contain water as a consequence of their porosity is called *moisture retention*. The *coefficient of permeability* (the rate (speed) of the flow of water through rock under a hydraulic gradient equal to 1) defines the degree of permeability of a rock. The presence of water in rocks can change their physical and mechanical properties considerably. Water in a rock can leach some of the rock ingredients, making the rock porous and permeable to water.

10.3.2.1 The main sources of water

- If openings such as tunnels, shafts, drives/drifts, etc., are driven through water-bearing formations or strata, water is bound to be encountered. Water is also bound to be encountered when working below the water-table (Vutukuri and Lama, 1986).
- A sudden inrush of water from water bodies such as lakes, rivers, sea, etc., when the workings are penetrated as a result of ground subsidence. During the rainy season, the direction of flow of the surface water should be checked, and the water should be diverted from large cracks, subsided areas, old workings, etc., through which it could pass underground.
- Water can come from underlying or overlying strata if it can get through via joints or fractures.
- Water that has been brought down into the mines and tunnels to carry out operations such drilling, dust suppression, etc.
- High water makes (seepage) and inflow (flooding). When approaching water-bearing zones, probing holes are often drilled 10–30 m ahead of the tunnelling face. Sometimes ground treatment ahead of the tunnel face becomes essential, in which case special techniques can be used (see Section 7.6). Without these measures, the ground could collapse due to excessive water seepage.
- Failure of linings (support work), which otherwise would seal off the fissures, could cause flooding during the operational phase. An inadequate barrier/separation between the subsurface excavation and water bodies, or waterlogged areas, and the puncturing of these barriers has been the cause of inundations in mines that have taken the lives of hundreds of miners.
- Sometimes it becomes essential to lower the water-table using the techniques described in Section 7.6 and Table 7.2.

10.3.2.2 Effects of water

Direct effects

- It adds to the pumping cost.
- If the make of water (seepage) is abnormal, special techniques (treating the ground by grouting, etc.) are applied to seal off the source. This means additional costs.
- A sudden inrush of water can cause loss of life, machines, equipment and production (progress).
- Working under watery conditions makes the mining and tunnelling operations slow, tedious and less productive.

Indirect effects

- There can be damage to the stability of openings in the presence of moisture, if the rocks forming them are sensitive to it. Floor heaving and roof falls are common problems if the openings are of shale or mudstone, as these rocks are very sensitive to moisture and the presence of even very small amounts of water.
- It increases the problem of humidity, particularly when mines and tunnels are deep seated. Extra ventilation is required to improve the working conditions.
- High maintenance costs of the equipment that are subjected to water.
- Watery holes during blasting require special types of explosives.
- Large-scale dewatering can cause subsidence.

The presence of water in sulphide formations adds problems. This water could be corrosive, resulting in damage to the service lines, such as tracks, pipes, equipment and support systems (corroding concrete and steel support work). It can also corrode the boots and clothes of the work crews.

10.3.3 Ingress of gas

Subsurface air differs from atmospheric air with respect to its humidity, temperature, pressure and density. The generation of foul gases, such as methane, carbon monoxide and hydrogen sulphide, could be the source of air contamination. These gases could be associated with the strata. The second source is the exhaust from diesel equipment, and gases/fumes that are generated due to the blasting operation (CO, CO_2 and NO); most of these gases are toxic and noxious. Radioactive minerals add an extra burden in the underground environment. An account of gases that can be found in subsurface horizons is shown in Table 10.1 (Lamont, 1998; Vutujuri and Lama, 1986).

Other sources of air pollution are the dusts that are generated during operations such as drilling, blasting, cutting, loading, mucking, haulage and crushing. Dust-laden air has adverse health effects. It affects many parts of the body. Combustible coal dust is a potential cause of fires and explosions.

10.3.4 Heat and humidity

Heat is produced due to

- operation of machines
- geothermal gradient

Table 10.1 Subsurface gases encountered in mines: sources, ill effects and safe limits

Gas	Composition	Source	Detection	Ill effects	Safe limits*
Oxygen (O)	SG = 1.1056	Normal air	Breathing, flame safety lamp, detector tube, electrochemical detector, paramagnetic method	Non-toxic Oxygen deficiency – can cause fatalities at 6% O_2	Minimum 19%
Nitrogen (N)	SG = 0.9673	Normal air, strata	Extinguishes flame safety lamp	Asphyxiation due to oxygen deficiency	Maximum 80%
Nitrous oxide fumes (NO_x)	Such as: NO, N_2O, NO_2 SG (NO) = 1.04 SG (NO_2) = 1.5895	Explosives, diesel exhaust, incomplete combustion		0.005% – detected by smell 0.01% – serious irritation and illness in 30 min 0.15% – great discomfort, bronchopneumonia as after-effect, death 0.25% – fatal after short exposure NO_x, in general, are toxic	NO_x not exceeding 0.0002%
White damp (CO + air)	Poisonous gas having no smell SG (CO) = 0.9672	Spontaneous heating, explosives, diesel engines, fire, explosion, etc.	Canaries, detector tube, catalytic combustion	Ill effects of CO: 0.02% – headache after 7 h or after 2 h if exerted 0.04% – severe headache in 5 h or in 0.5 h if exerted 0.1% – death in 3 h or in 1 h if exerted 0.2% – unconsciousness in 30 min 1% – unconsciousness and death in 3 min or in 1 min if exerted Death is painless and face becomes flushed	CO not exceeding 0.0006% TLV TWA = 0.005 TLV STEL = 0.04

Carbon dioxide (CO_2)	Heavier than air	Breathing, strata, groundwater, blasting, fires, diesel exhaust	Soluble in water, non-combustible	Asphyxiant (TLV = 0.5%) Toxic if exceeds 10%	STEL = 1.5%
Stink damp (H_2 + air)	H_2S smells of rotten eggs SG = 1.1912	Reaction of acid on sulphur, which is found in various forms	Odour, detector tube, electrochemical detector	Highly toxic 0.005% – no ill effect 0.01% – irritation of eyes and throat, headache 0.02% – intense irritation of eyes and throat 0.06% – pain in chest in a few minutes 0.1% – immediate death	H_2S not exceeding 0.00066% TLV TWA = 0.001 TLV-STEL = 0.0015
Sulphur dioxide (SO_2)	Burning and choking effect SG = 2.2636	Spontaneous heating, explosives, fire oxidation, etc.	Odour, detector tube	0.003% detectable smell 0.01% – uncomfortable 1.0% – bronchitis after exposure for 30 min	Sulphurous gases not exceeding 0.0007% TLV-C = 0.0005
Methane (CH_4)	Odourless, colourless, tasteless SG = 0.5545	Strata, blasting, diesel engines, organic decay	Flame safety lamp, detector tube Detectors: optical, thermal, infrared	Asphyxiating due to oxygen deficiency, explosive (inflammable)	Below 1.25% 5.3–14% – explosive
Radon (Rn)	Radioactive, heavier than air	Strata, groundwater	–	Radioactive	–

SG, specific gravity; TLV, threshold limit value; TLV-C, ceiling TLV; TWA, time-weighted average; STEL, short-term exposure limit.

* Differ as per the safety rules and regulations of a country.

- adiabatic compression
- blasting operations.

The presence of water adds to this problem significantly. It makes visibility poor and puts undue stress on the work crews.

As mentioned above, underground air differs from atmospheric air with respect to its humidity, temperature, pressure and density. The function of ventilation, apart from providing air for breathing, is to maintain normal temperature and humidity (Lamont, 1998; Vutujuri and Lama, 1986). In general, the quality of air that is warranted should have a composition as outlined below.

Quality of air:

- O_2 not less than 20%
- CO_2 not more than 0.5%
- temperature not more than 20°C.

Safe limits of mine gases:

- CO – 0.0006%;
- nitrous oxides (NO_x) – 0.0002%;
- sulphurous gases – 0.0007%;
- H_2S – 0.00066%.

The remedy lies in effective ventilation that can result in the following:

- Reduced dust exposure – by expulsion or dilution.
- Removal of gases – by expulsion and dilution, whether they are products of blasting and diesel engines or generated by the rock strata.
- Improved safety – improved safety records have accompanied improvements in the ventilation.
- Better efficiency – this is an intangible quality but absenteeism and labour turnover have reduced with the improvement in the ventilation.
- Control of fires – the problems of fire prevention, mine/tunnel evacuation and fume control are inseparable from the problem of mine ventilation. It is certain that many major mine and tunnel disasters due to fire underground could have been minor incidents if there had been positive ventilation control.
- Temperature control – heat is a problem in many mines and subsurface openings, including tunnels. The benefits of heat control by proper ventilation have been demonstrated in many instances.
- Minimisation of decay – good ventilation can be instrumental in reducing the growth of certain fungi, thus helping to prolong the life of timber and fabrics used underground.
- Reduction in the number of cases of silicosis – it has been demonstrated that the number of cases of silicosis is lower in properly ventilated mines.
- The mining of uranium in underground mines, or tunnels that need to pass through radioactive formations, would be seriously affected without the aid of

good ventilation. And it is equally certain that with good ventilation such mines can be worked with complete safety and without effects from radiation.

- Many mines and tunnelling projects have benefited from the introduction of diesel haulage units. This would not have been possible without the aid of adequate mechanical ventilation.

Guidance from the International Tunnelling Association on the safe use of temporary ventilation ducting in tunnels provides recommendations for the materials to be used in such ducts and their installation and maintenance (ITA WG 5, 2011a).

10.4. Mechanisation and automation

Increasing use is made of automation and mechanisation during tunnel construction, particularly the application of full-face and partial-face TBMs. The areas/locales/operations listed below are of great concern and require that proper safety measures are taken (Lamont, 1998, 2000, 2002; McFeat-Smith, 1987).

10.4.1 Tunnel support during machine tunnelling

One of the most hazardous areas of a machine is the segment build area within which the erector operator works. In large machines, the segments being handled are heavy and visibility over the build area for the erector operator is often limited, but miners are expected to place packing between segments as well as bolts to secure the lining in position. In this area, risks of injuries due to impacts and trapping are high.

10.4.2 Electrical power

High standards of electrical safety are necessary due to the fact that the power consumption of large TBMs is 5–10 MW and supply voltages could be up to 11 kV. In the presence of a flammable atmosphere, and possible oxygen enrichment and compressed air, the complexity of the use of electrical power has increased considerably. This has given rise to certain directives and legislative measures that have been formulated and are in force the world over.

Some of these agencies are the European Community (Directive 98/37/EC, 1998); CEN (Comité Européen de Normalisation, the European standards body) and CEN/TC 151/WG 4 (Working Group 4 of CEN Technical Committee 151, mandated to develop a number of harmonised standards for tunnel machinery safety). The UK, Germany, France and Switzerland, with some input early in the project from Denmark, have been the main participants in CEN/TC 151/WG 4. Some of the standards developed by this group include

- EN 815:1996. *Safety of unshielded tunnel boring machines and rodless shaft boring machines.*
- prEN 12336:2005. *Tunnelling machines – Road-headers, continuous miners and impact rippers – Safety requirements.*
- prEN 12110:2010. *Tunnelling machines – Air locks – Safety requirements.*
- prEN 12111:2002. *Tunnelling machines – Shield machines, auger boring machines, lining erection equipment – Safety requirements.*

Any manufacturer supplying machinery into the European Community must show that these machines conform to the essential safety requirements of the (machinery) directive. Usually the manufacturers assure conformity with the relevant standard(s).

EN 815:1996, prEN 12111:2002 and prEN 12336:2005 address a wide range of machinery-related hazards specifically within the context of tunnelling, including

- access to the cutter head
- handling of heavy components
- rotation/stability
- walkways and access openings
- visibility
- control points and systems
- hydraulic and electrical systems
- fire protection
- operator protection
- occurrence of potentially explosive gas.

These standards apply to all sizes of machines. It is apparent that manufacturers supplying into the European Community have incorporated the safety requirements in their machinery designs, which has resulted in improvements in TBM safety over the past decade.

prEN 12110:2010 addresses hazards specific to airlocks, including

- design, manufacture and testing for safe working pressure
- controls and instrumentation
- minimum dimensions
- fire protection
- oxygen breathing.

Tunnelling machinery for use in potentially explosive atmospheres must conform to the essential safety requirements of the so-called ATEX Directive (1994), which has been revised as ATEX Directive 2014/34/EU (European Community, 2014). Compliance with this directive has been mandatory since 20 April 2016. It covers both mechanical and electrical equipment (Lamont, 2000).

10.4.3 Transport

Transportation and handling of workers, machines, equipment, construction material and spoil (which could be ground or rocks) is one of the major tunnelling operations. Any negligence could cause accidents. In the confined space of a tunnel, which is often poorly lit and where visibility is poor, the risk of collision between workers and machines in close proximity is high. Such collisions could damage equipment and injure personnel. Proper clearance between vehicle and pedestrian routes could avoid such collisions. Better illumination is always desirable. Other methods of removing excavated material from the tunnel include slurry systems and conveyors. Both give major safety benefits as they significantly reduce the number of transport movements required in the tunnel.

10.5. Fire, rescue and escape

Natural sources of flammable gases such as methane are the strata themselves. Combustible coal dust that can be generated due to mining and tunnelling operations, together with its presence as a source of ignition, has been the reason for fires and explosions. Self-oxidation of sulphide ores is also a potential source of a rise in temperature and fires (usually confined to metalliferous mines). A rise in temperature due to increasing depth (this may not be true for civil tunnels), together with the presence of combustible materials such as timbers, rubbers, textiles, grease, oils and lubricants, could be the cause of fire. Exhaust from diesel equipment also generates hot and toxic gases. TBMs and partial-heading machines also generate excessive heat which, if not dissipated through adequate ventilation, could lead to fires. Electric short-circuiting and sparks are common reasons for fires. Fire and its smoke are one of the most significant tunnelling hazards for work crews. It is dangerous to humans, machines, equipment and property. It leads to health hazards to the extent of serious and fatal injuries. The tunnel itself could be damaged very badly. Listed below are some of the issues that should be addressed (Fire Protection Association, 2000):

- Due to the high mechanisation and automation of tunnelling operations, the use of a large quantity of hydraulic fluid, grease and diesel fuel (in some cases) is unavoidable. These highly combustible and inflammable materials are very sensitive to fires. The best approach is to minimise the use of these substances and/or, wherever practical, substitutes that are less dangerous should be used. The quantity of such substances should be kept to a minimum, within practical limits. Proper maintenance and good engineering practices can achieve this.
- In addition, all mechanical and electrical plant and equipment being used underground should be fitted with fixed on-board fire-suppression systems. Hand-held extinguishers are likely to prove useless against oil-jet fires. Furthermore, their use requires someone to remain in a position of danger to fight the fire.
- Good housekeeping is very important to ensure that the build-up of flammable rubbish, including timber, plastic bottles, paper, discarded hoses and cables, is kept to a minimum.
- Comprehensive fire detection and alarm systems as well as communication systems should be installed underground. They should be linked into the main tunnel control systems.
- All personnel should wear oxygen self-rescuers underground. Filter self-rescuers do not give any protection against oxygen deficiency or contaminants other than carbon monoxide (Lamont, 2001).
- Preferably, all crews should be rescue-trained; otherwise there must be easy access to call rescue-trained personnel in an emergency.
- Keeping an unobstructed access walkway throughout the length of the TBM and from the rear to a safer place is mandatory.

10.5.1 National Fire Protection Associations

The Fire Protection Association, established in 1946, is the UK's national fire safety organisation. Its guidelines were updated in 2015. It works to identify and draw attention to the dangers of fire and the means by which the potential for the occurrence of fire and loss can be kept to a minimum (FPA, 2017). The equivalent organisation in the USA is the National Fire Protection Association (NFPA, 2017). Most countries have such associations that can provide useful assistance in addressing these issues.

10.5.2 EN 16191:2014

EN 1619:2014 (*Tunnelling Machinery – Safety Requirements*) is the European standard applicable to the tunnelling machinery used for the construction of tunnels, shafts and other underground excavations. It covers monitoring for hazardous atmospheres within the confines of the tunnelling machinery, but it is not applicable to roadheaders, continuous miners or impact rippers. It covers tunnelling equipment, boring machines, construction equipment, equipment safety, safety measures, electrical safety, hazards, maintenance, tunnels, wall linings and fire safety.

10.6. Occupational hazards (health and physique)

Tunnelling and mining operations are considered to be rough, tough and extremely hazardous. In the long term, the regular inhalation of dusts of various kinds for long periods by the work crews may result in silicosis, asbestosis, manganese poisoning or some other lung disease. Dusts and toxic gases affect many parts of the body, and adverse working conditions put undue strain on the body. The idea is that duties on site should not lead to any strain or disease. To ensure the health and fitness of personnel, the following occupational health checks are necessary (Gibb *et al.*, 1999):

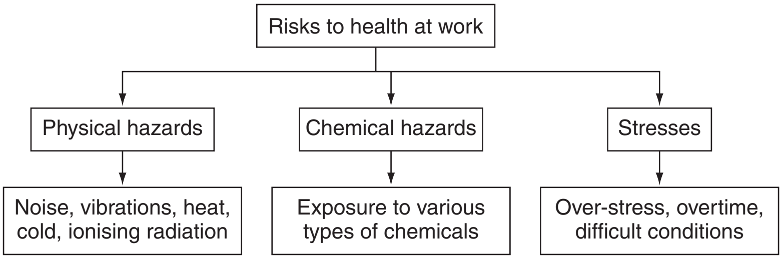
- Periodic check-ups for occupational fitness – in terms of vision, hearing, etc.
- Monitoring the danger to personnel suffering from any disease that could be posed while working in construction and tunnelling industries. For example:
  - Dermatitis – due to regular and prolonged contact with and exposure to cementitious material.
  - Skin and respiratory problems – due to exposure to epoxy materials.
  - Impaired hearing – exposure to noise is a common health problem. Noise should be reduced at source to the extent that use of personal protective wear is at a minimum.
  - Heat strain/heat stroke – due to working in an improperly and inadequately ventilated working area.
  - Vibration syndrome – due to continuous working with hand-held pneumatic or hydraulic tools. Low-vibration tools and proper maintenance of the tools could minimise the syndrome.
  - Musculoskeletal injury – due to the repeated handling heavy loads.
  - Lung disease – due to breathing in silica dust.

Figure 10.1 summarises the risks to health of an industrial worker.

10.7. Legislation, guidance and norms

It is discipline, either self-imposed or enforced, that minimises problems and reduces hazards significantly. Without sufficient education, vocational training and refresher courses, it is difficult to achieve industrial discipline. Here, the meaning of ‘industrial discipline’ is to abide by the norms, procedures, codes of practice, rules, regulations,

Figure 10.1 Classification of risks to health due to working in an industrial setup



laws, standing orders, etc., that are laid out for an industrial setup (BSI, 2001; DOE, 1996; European Community, 1989, 1992, 1994, 1998, 2014; Health and Safety Executive, 2015a,b; Jardine and McCallum, 1992). Violations and non-observance of these guidelines lead to failures, cost overruns, accidents, disasters, and unproductive and unhealthy industrial atmospheres, any of which can become the cause of a dispute.

Rules, regulations, laws, standing orders and statutory requirements for tunnelling and construction industries differ from one country to another. But the basic ideas remain the same. Some of them are listed below.

- *The EC Framework Directive* (European Community, 1989). This standardises the general requirements for health and safety within Europe. Many of the risks to be found in construction, including tunnelling, were already subject to statutory control through the implementation of the directive on temporary or mobile construction sites and its Annex IV (European Community, 1992) in member states.
- *Relevant regulations in the UK*. The Construction (Design and Management) Regulations 2015 (CDM 2015) from the Health and Safety Executive Great Britain came into force on 6 April 2015, replacing the CDM 2007 (Health and Safety Executive, 2015a). The regulations describe:
  - the law that applies to the whole construction process on all construction projects, from concept to completion
  - what each duty holder must or should do to comply with the law to ensure projects are carried out in a way that secures health and safety.
- *Compressed Air Regulations 1996*. These are accompanied by an extensive guidance document (DOE, 1996).
- Working Group 5 of International Tunnelling Association – *Safe Working in Tunnelling 2011* (ITA WG 5, 2011b).
- *BS 6164:2011 – Code of practice for health and safety in tunnelling in the construction industry*. This gives guidance on health and safety practices in shaft sinking and tunnel construction. It takes into account the advances in technology and equipment that are available to the tunnelling industry. It also takes account of new techniques and the effect of changes in legislation and guidance relating to health and safety and environmental matters.

- BS 6164:2011 is written for all those involved in tunnelling projects, and addresses the safety of both those engaged in the tunnelling process and those who could be affected by it.

10.8. Safety and accidents

Safety can be defined as the conditions that keep the mind, body or property free from injury, damage or destruction. Safety strategies can be classified into four categories:

- inherent
- passive
- active
- procedural.

Inherent strategies do not need any human intervention – just incorporate them and forget about them. For example, a lift will not start if its door is not closed (interlocking), and this is how the hazard of falling from a lift when it is in motion is controlled. Passive strategies need some human intervention – the hazard remains but it is under control. Active strategies need periodic testing and maintenance, but the hazard could materialise if maintenance is not done properly. Procedural strategies depend on training the people concerned and hoping that they will do as they were trained to do.

In most countries, speeding of cars is a major cause of road accidents. The possible solutions are

- inherent – design automobiles so that they cannot run above a certain prescribed speed (within practical limits)
- passive – install and maintain speed breakers/bumps (strategic locations, good design, warning signals and regular painting)
- active – synchronous road signals, police patrols and radar speed guns, heavy fines for offenders
- procedural – proper education of drivers.

Looking at the above scenario, one would agree that inherent safety is the, best but the other strategies are equally important and should be enforced as much as possible. Inherent safe design works out to be the costliest. The extent to which this cost is shared will depend on the judgement of those concerned.

10.8.1 Safety elements

10.8.1.1 Safe practices (unsafe acts)

To guard against unsafe acts, it is important to deploy competent and trained crews. It is the man behind the machine that matters rather than machine itself, and hence the quality of personnel employed for the job should not be compromised. Training and education are ongoing processes that are essential for everyone, right from the lowest category of worker to the highest executive of an organisation. Arranging vocational training, workshops, seminars and refresher courses can help achieve this. Other aspects that should be looked into are:

- accident reporting and analysis
- organising safety week celebrations, competitions, debates and lectures
- information through posters, films, live drills and demonstrations
- regular practices for rescue, recovery and first-aid operations
- rewarding safe and efficient workers
- safety audits
- it is important that working crews, contractors, management and all those concerned with the job in hand comply with the design specifications (supports and lining, ground treatment and advance probing, etc.)
- deploying competent persons suitable for the job, and retraining and refreshing them from time to time.

10.8.1.2 Safe working conditions and welfare

It is important to make sure that safe working conditions that are not detrimental to health prevail at the working site. This means that the following should be ensured at the working site:

- Perfect layout (design). Working spots should be safe and free of any danger of ground collapse. They should be properly scaled (loose dressed).
- Proper ventilation.
- Preferably illuminated, maybe using portable pneumatic or other sources of illumination.
- Maintenance and sufficient numbers of equipment, tools and appliances. Safety fittings of working equipment should be checked as recommended by the manufacturers.
- Provision of gas detectors, warning and information mechanisms.
- Proper drainage and sanitation.
- Periodic check-ups of safety appliances and fittings.
- Use of materials of the correct quality.
- Perfect working conditions also include the provision of basic amenities (at strategic locations) at the work sites, including
  - space for basic toilet and washing facilities, and provision for their regular cleaning
  - provision of potable water
  - first-aid, refreshment and changing rooms
  - means of communication
  - emergency escapes and shelters.

In addition, the work crews should be provided with safety wear and appliances, and should be thoroughly familiar with their proper use. Good standards of health and safety require the commitment of resources in terms of time and money but a productive workforce can only be sustained if working conditions are healthy and safe. Respect for people must be our goal in the 21st century (Lamont, 2002).

10.8.1.3 Preventive measures and accident analysis

- Ensure the use of proper safety wear.
- Undertake routine and scheduled equipment maintenance.
- Implement accident reporting, analysis and prevention measures.
- Formulate and implement an HSE plan.
- Prepare standing orders for dealing with emergencies.

10.8.2 Accidents

An accident is an abnormal event or occurrence, whether or not it causes injury or damage. When it does not cause any harm, or it is a 'near miss', it is known as an 'incident'. An accident is a three-step process:

1. Initiation – the event or cause that starts the accident.
2. Propagation – the events or causes that maintain or expand accidents.
3. Termination – the events that stop the accident or diminish it in size.

Inherently safer strategies can impact on or influence the accident process at any of the three stages. The most effective strategy will prevent initiation of the accident. Inherently safe design can also reduce the potential for propagation of an accident, or provide an early termination of the accident sequence before there are major impacts on property, people or the environment.

Accidents are calculated as

- Accident rate: number of injuries per 200 000 man-hours worked.
- Severity rate: number of lost days per 200 000 man-hours worked.
  (The Occupational Safety and Hazards Administration (OSHA) calculates the incidence rate similarly but based on lost days: incidence rate = number of lost days per 200 000 man-hours worked.)

Definitions and calculations differ from one organisation to another. The degrees of injury are:

- fatal – causing death
- serious – causing forceful absence from work
- minor – injury without loss of work-days.

10.8.2.1 Accident causes

The causes of accidents will differ from one project to another. Listed below are some common areas of accidents:

- Haulage – speeding, improper turns and gradient, inadequate safety fittings or their failure.
- Machines and equipment (hardware) – failures due to improper maintenance and operation.

- Ground failures – inadequate support measures, design defects, encountering and not properly sealing discontinuities.
- Slip or fall of workers – slippery roads, inadequate width of workings and roads.
- Material handling – explosives, tools and appliances.
- Fall or sliding of material – absence of fencing.
- Improper supervision – incompetent, negligent, overstressed, miscommunication and lack of coordination.
- Miscellaneous – any not covered above.

10.8.2.2 Accident costs

- Injury, loss of body parts – disability.
- Absence from duty, delays, loss of time.
- Loss of morale, loss of efficiency of crew/workers.
- Loss of material, property, equipment.
- Cost of treatment, cost of production loss, overtime payment.
- Cost of replacement, clean-up, repair, standby, etc.
- Fines or penalties made by the government or safety authorities.
- Cost of legal assistance.
- Cost of compensation.
- High insurance premiums.

10.8.3 Interrelation of important parameters

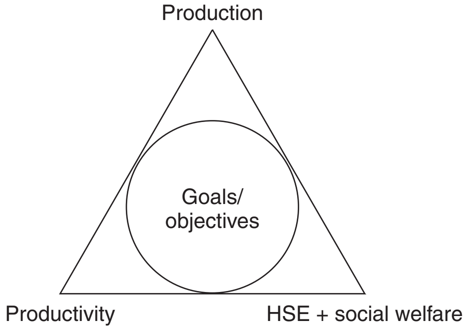
The above-mentioned salient features of an accident reveal that each accident adversely affects the production, costs and productivity of any industrial setup. Accidents spoil reputations and demoralise workers. Many times they result in courts of inquiry and disputes. They may damage the environment. They are a public concern. Ultimately, accidents result in a deviation from the laid out objectives and goals of a company. The logical approach is a thorough balance between production, productivity and occupational HSE and the welfare of society, giving equal weight to each of these components, like three sides of an equilateral triangle (Figure 10.2). This results in the fulfilment of objectives. Any deviation or imbalance could jeopardise the objectives of an industrial setup.

10.8.3.1 Remedial measures

Measures that can be taken to prevent accidents include

- Conceptual planning, detailed design and evaluation.
- Compliance with design specifications – supports and lining, ground treatment and advance probing.
- Safe working conditions – lighting, ventilation, sanitation.
- Safe equipment – fittings.
- Safety wear, detectors and warning mechanisms.
- Precautions and measures against fires and explosions.
- Training, education and refresher courses.
- Emergency measures (CSA, 1995).
- Welfare amenities and medical check-ups.

Figure 10.2 Interrelation of important parameters



- Legislation – rules, regulations, codes of practice.
- Accident analysis and preventive measures.
- Risk analysis.

Some of the items listed above have already been discussed in the preceding paragraphs and sections; the remainder are discussed below.

10.8.3.2 Teamwork

The terms in Figure 10.3 have the following meanings:

- reactive – action in response (which is the natural human tendency)
- dependent – one who is dependent on others (there is an element of fear that if the dependent does not obey instructions there is the possibility of disciplinary action against them)
- independent – one who is not dependent on others (empowering an individual with responsibilities provides the opportunity for self-development and for the individual to show his or her worth)
- interdependent – mutually dependent.

Figure 10.3 illustrates the fact that it is teamwork which can bring the desired results from the various options available.

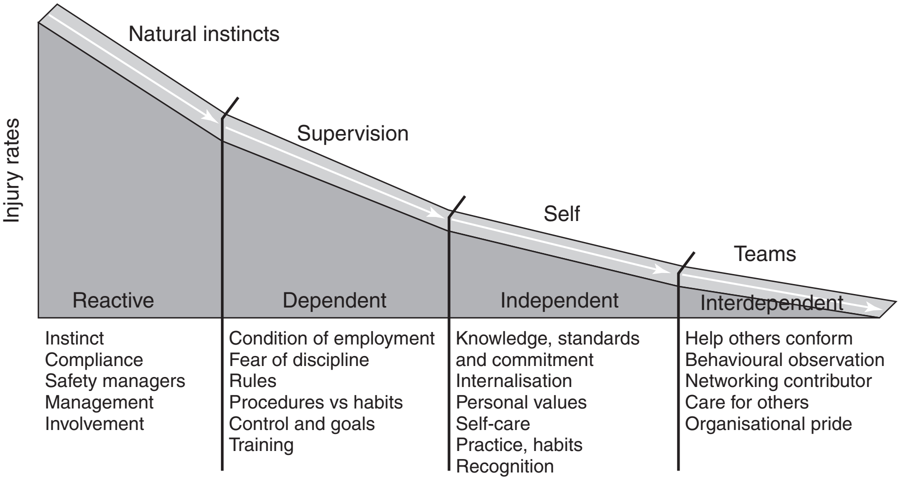
10.9. Conceptual planning, detailed design and evaluation

Current trends divide any major tunnelling or subsurface excavation into four phases (Gupta, 2000; Pegg, 2000; Standish and Reardon, 2002):

1. planning and design
2. construction
3. operation
4. post-operational period.

The planning and design phase is considered to be the most risky, as major decisions are taken during this phase. At this time, a conceptual model is first prepared and then

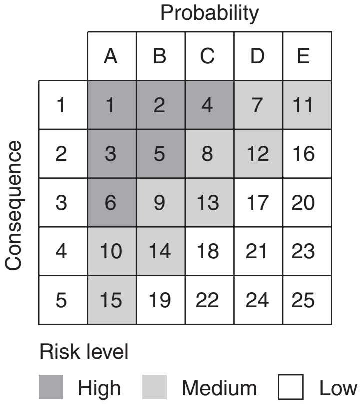
Figure 10.3 Teamwork can minimise injuries and losses (after Latus, 2006)



evaluated using different alternatives and schemes, of which the best one is selected for engineering details. This phase also includes making detailed drawings, drawing up equipment specifications, and forecasting the resources and budget required. Any deficiency at this stage could result in problems and delays during the construction phase, and could even be a cause of failures during the operational life. It is important to plan and take into account the cost of sealing off or closing the tunnel as per the relevant legislation of the country. This is known as the 'life-cycle approach'. During the design phase modern techniques concerning the safety of subsurface excavations, such as those outlined below, could be considered.

- failure scenarios

Figure 10.4 Risk ranking (matrix) – combined consequence and probability consequence ranking



	A	B	C	D	E
1	1	2	4	7	11
2	3	5	8	12	16
3	6	9	13	17	20
4	10	14	18	21	23
5	15	19	22	24	25

Risk level

▨ High ▒ Medium ☐ Low

- HAZOP (systematic identification of hazards and operability problems) and HAZAN (systematic analysis of hazards and their potential consequences) – the application of these techniques is almost mandatory in chemical industries
- fault-tree analysis
- event-tree analysis.

It is important that there is close liaison and a collaborative effort between designers, manufacturers, engineers and all others who are concerned with the project. This could minimise tunnelling risks. There is considerable scope for improvement in standards of health and safety in excavation technology worldwide. Some countries have more developed regimes than others. All can improve further. We should all share knowledge, guidance and good practice in these matters.

10.10. Risk analysis

Subsurface excavations that include large tunnelling projects, underground mines and large caverns involve huge investment and input of resources – workers, machines and equipment – for long durations. One traditional approach of risk management is to control a hazard by providing layers of protection between it and the people, property and surrounding environment to be protected. These layers of protection may include

- operational supervision, control systems, alarms, interlocks, etc.
- physical protection devices (relief devices, dykes, pillars, barriers)
- emergency response systems (plant/project emergency response, community emergency response).

In such projects, modern techniques such as a risk matrix (Tables 10.2 and 10.3 and Figure 10.4) can be applied to identify potential hazards (Standish and Reardon, 2002).

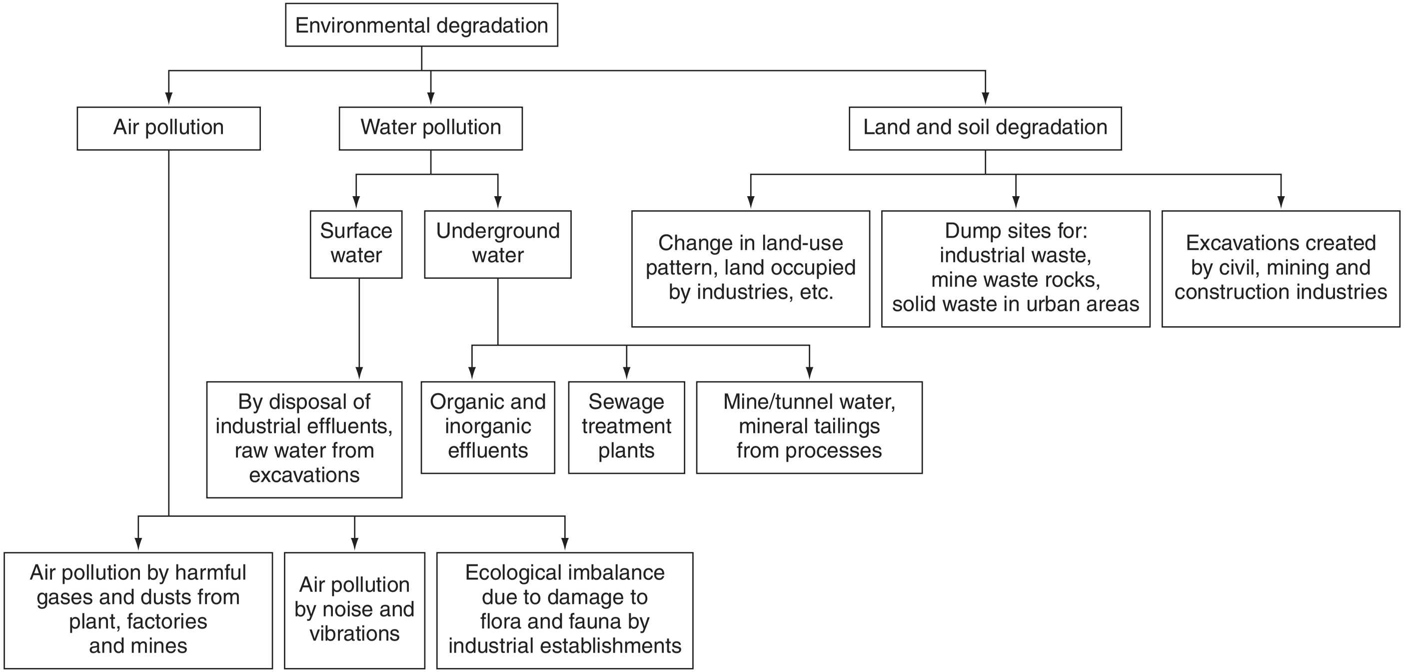
Table 10.2 Probability ranking

Category	Definition
A	Common or frequent occurrence (1 year)
B	Is known to occur or it has happened (1 : 10 years)
C	Could occur or hear of happening (1 : 100 years)
D	Not likely to occur (1 : 1000 years)
E	Practically impossible (1 : 10 000 years)

Table 10.3 Consequence ranking

People	Equipment	Production loss	Environment
Fatality	\$10 million	2 weeks	Major
Disabled	\$1–10 million	1 day–2 weeks	Serious
Major LTI (weeks)	\$100 million	1 shift	Moderate
LTI (lost time injury)	\$10 000	2 hours	Minor
Minor	\$1000	<1 hour	Insignificant

Figure 10.5 Main sources of pollution in air, water and land environments



Guidelines for tunnelling risk management published by the ITA Working Group 2 can also be referred to (Eskesen *et al.*, 2004).

10.11. Environment

10.11.1 Why pollution?

As described in the preceding sections, tunnelling, excavations and mining operations are bound to pollute air and water, and degrade land. To understand the basics of how these industries affect the environment, let us take the example of gold mining. Gold is mined if its grade (concentration) is 5 g/ton. This means that of 1000 kg (1 ton) of gold ore mined, only 5 g (on an average) would be useful and the remaining 999.995 kg of rock would be waste. To recover this 5 g of gold; the processes followed includes mining (breaking the rock into small fragments in its in situ location); concentration (crushing, grinding into powder and separation from the rest of the rock mass using chemicals); smelting; and, finally, refining and casting into bars or any other shape. One can imagine how much energy this task requires, the materials of different kinds consumed, the foul gases produced and the land required for disposal of the wastes generated. This is the reason why mining is blamed as a polluting activity. However, after sun, air and water, minerals are among our basic needs, and even food cannot be produced without them, and hence we cannot live without them.

Similarly, the importance of civil excavation should not be underrated. Such excavation activities were first undertaken by ancient civilisation, and are now done in both surface and subsurface locales for various purposes (see Figure 1.1) and will continue to increase (see Section 1.10) for as long as mankind exists. These excavations include benching, trenching, channelling, pitting, demolishing, mucking, scarping, digging, casting, pushing, shifting, ripping, dozing, levelling and dragging the earth material at surface locales, and drifting, tunnelling, raising, sinking and creating large excavation (caverns) at subsurface locales. The uses of civil excavations are multiple, as they meet the requirements of many industries and public utilities. Excavation machinery is working round the clock worldwide to cater for the needs of a growing population, which with a current annual rate of growth of 1.8% doubles every 39 years.

This is the reason why many multinational companies (manufacturers) are in the arenas of the production of explosives and their accessories, and earth-moving, rock drilling and cutting, and tunnelling machines of a wide range of capacities and from mini to giant in size. Equipment such as bucket-wheel and hydraulic excavators, draglines, off-highway trucks (320 ton capacity) and TBMs are among the largest man-made equipment on Earth.

These vital excavation activities are creating billions of cubic metres of ‘space’ from the Earth’s crust and generating about 30–40% more than this volume of earth-material daily (due to the increase in volume compared with the volume of the in situ rocks and ground).

Imagine the magnitude of the energy consumed and the dust, heat, noise, vibrations and foul gases produced during rock and ground fragmentation and the subsequent disposal (mucking, loading, transportation and stacking). The environmental degradation (pollution) due to these operations is quite obvious.

One should not forget that more than 75% of the power used in civil excavations and mining is generated using fossil fuels (coal, oil and gases), the burning of which contributes to the greenhouse effect. In the UK, for example, the carbon dioxide (CO_2) emissions produced by the construction industry account for almost 47% of the total CO_2 emissions. In addition, industrial pollutants are the cause of acid rain (e.g. a survey has found that acid rain in China is affecting one-third of the land area). The exhaust from automobiles is responsible for bad ozone.

All the above helps us to understand what has happened in the past – rivers have become stagnant (do not flow), the sky has become shrouded in smoke (smog) and waste sites have become odoriferous and unsightly. This went on for many years and was ignored. However, populations began to experience negative effects on their health and wellbeing, as well as negative impacts on aesthetic and cultural pleasures and economic opportunities.

This has called for an awakening, which is known as *sustainable development*. The United Nations World Commission on Environment and Development defined the term 'sustainable development' in 1987 for Ecological Sustainable Development as 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs' (Lamont, 2002).

Figure 10.5 describes the types of pollution caused by an industrial setup. It also includes operations, activities and materials that are responsible for causing industrial pollution that damages air, water and land regimes. Figure 10.6 details various air pollutants.

It is necessary to consider what approach to follow – whether or not to continue production and, if so, to what extent.

10.11.2 Mass balance system/equation

The fundamental mass balance relationships are

$$\text{accumulation} = \text{input} - \text{output}$$

$$\text{accumulation rate} = \text{input rate} - \text{output rate} \pm \text{transformation rate}$$

10.12. Environmental management

Environmental management is a mechanism that involves the following three steps:

1. determining the baseline (i.e. the existing or pre-excavation scenario)
2. making an environmental impact assessment (EIA)
3. making an environmental management plan (EMP).

Table 10.4 briefly summarises the steps that need to be taken during the three phases listed above.

Figure 10.6 Classification of air pollutants

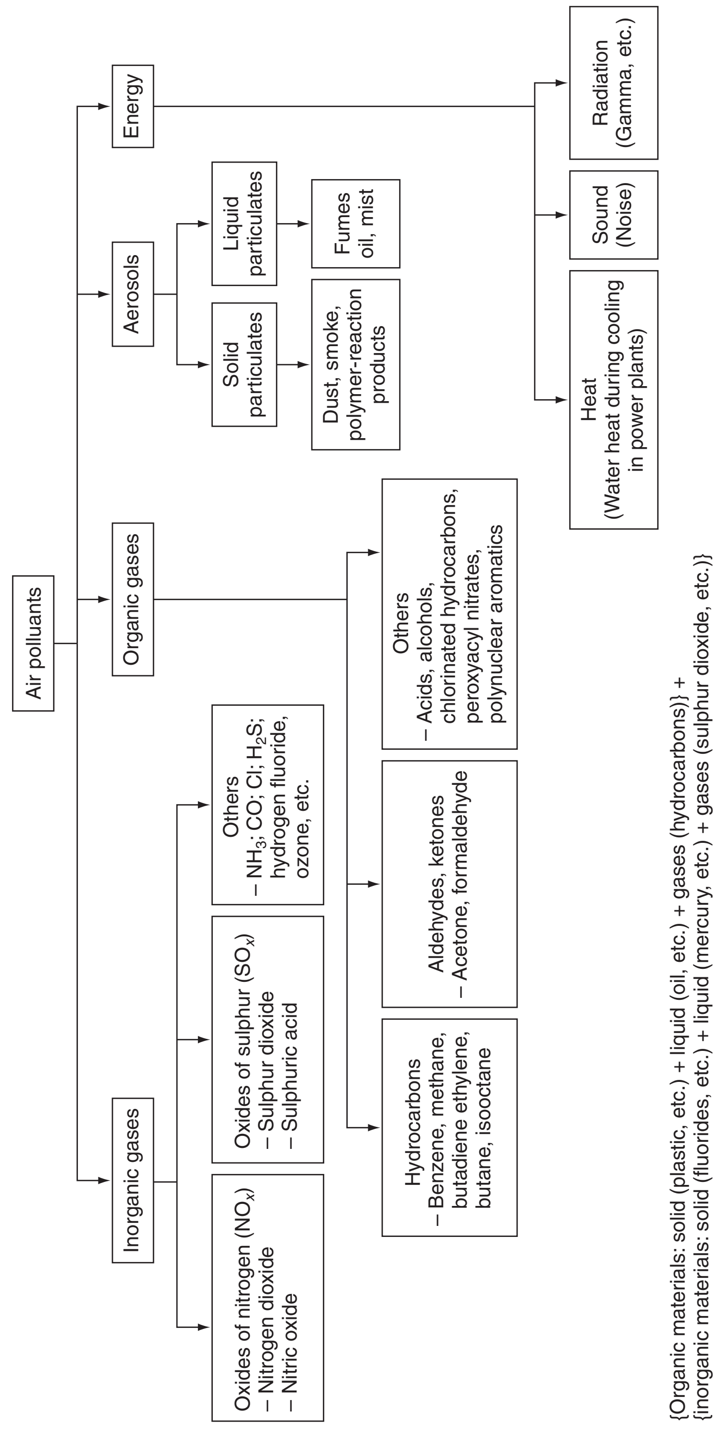


Table 10.4 Summary of aspects to be considered when preparing an environment management plan

Baseline information	Environmental impact assessment (EIA)	Environmental management plan (EMP)
1. Ground/land environment	1. Likely impacts	– Diversion plans of existing land-use pattern (if any) together with its mechanism, schedule and cost implications – Excavation/mining sequence ensuring minimum land disturbance at any time – Dumping scheme for waste rocks, with location and procedure, ensuring minimum horizontal spread. Provision for bunds around dump yards to prevent silt flow to the surrounding areas – Stacking different mineral wastes separately and keeping a record for future reference – Land reclamation and beautification schemes; reuse schemes for useful soils
1.1 Surface topography	1.1 Surface topography – magnitude, location	
1.2 Plain land Hilly terrain Soil – Type (quality) – Thickness	1.2 Soil – quantity, extent	
1.3 Land-use pattern – Industrial – Residential – Grazing and forest – Occupied by infrastructure – Barren land – Other – not covered by the above	1.3 Land-use pattern; magnitude and location of disturbance; land occupied by waste rock dumps; effluents from process plants	
1.4 Aesthetic – existing natural beauty	1.4 Impacts on the existing natural beauty	
2. Water environment	2. Impacts on the water environment	– Diversion of water flow if required, with costs, schedule and mechanisms – Provision for effluent discharge – Provision for raw water treatment (including acid water, if any) before its discharge – Assessment of pumping requirements, including standby arrangements to avoid any flooding or inundation – Water surveys, quality monitoring and plans for meeting potable water requirements
2.1 Existing water bodies and their proximity to the project	2.1 Diversion of water bodies, if any	
2.2 Position of water-table; potable water availability (quality and quantity)	2.2 Water pollution – quality, quantity (resultant water-table lowering)	
2.3 Sewerage water disposal	2.3 Sewerage water – quantity	
2.4 Industrial water disposal	2.4 Effluents – types and quantity	
2.5 Rain – Average rain – Rainy months – Natural drainage system	2.5 Impacts of rain water on the workings; chances of flooding; water pumping requirements; impacts on existing drainage system; chances of acid water and acid rain, if any	

Table 10.4 Continued

Baseline information	Environmental impact assessment (EIA)	Environmental management plan (EMP)
3. Air	3. Air pollution assessment	– Provision for effective ventilation – fan types, location; meeting water-gauge and air quantity requirements – Periodic air surveys – Noise-containment measures – Dust sampling, analysis and suppression measures – Measures to maintain temperature and humidity of the surroundings within allowable limits
3.1 Existing climate	3.1 Assessing any rise in temperature, humidity, if any	
3.2 Air quality (existing industrial and general pollution)	3.2 Pollutants – types and quantity	
3.3 Noise – magnitude and sources	3.3 Noise sources and quantitative assessment	
3.4 Dust – airborne dust (quantity and quality)	3.4 Likely dust generation – sources, quality and quantity	
4. Seismic – Existing (natural) – Induced by industrial activities	4. Assessing vibrations due to pneumatic machines, and as a result of blasting operations	– Measures to design blasts enabling peak particle velocity to be within allowable limits, so that damage to surrounding structures is at a minimum. Scheduling blasts by considering minimum disturbance to the workers and local inhabitants
5. Bio-environment	5. Impacts on existing flora and fauna	– Revegetation, planting schemes: location, schedule, manner and costs – Possibility of relocating existing fauna, if any
5.1 Flora – vegetation type, tree density, crop types	5.1 Assessing magnitude of vegetation removal, deforestation	
5.2 Fauna – birds, insects, animals (types and population)	5.2 Fauna likely to be affected by the project activities	
6. Social environment	6. Assessing likely impacts on people and facilities within a radius of 5 km or so (as required by the relevant regulations)	– Planning relocation of local inhabitants and facilities, if any, with schedules, costs and mechanisms. Assessment of compensation, if any – Diversion plans for existing infrastructure and facilities, with details and costs – Provisions to settle public disputes and grievances
6.1 Local inhabitants – population, trade and vocation	6.1 Relocation of existing inhabitants	
6.2 Places of worship and historical importance	6.2 Disturbance/demolition, shifting of places of public interest	

Table 10.4 Continued

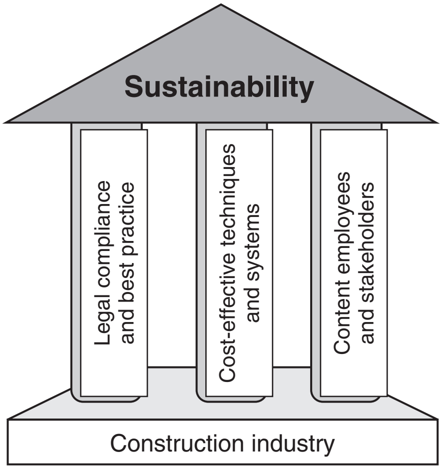
Baseline information	Environmental impact assessment (EIA)	Environmental management plan (EMP)
6.3 Existing facilities – education, medical, housing, power, roads, recreation, playgrounds, transport, communication	6.3 Diversion of or damage to existing facilities	
7. Existing legislation and labour	7. Implications of enforcing existing laws – impacts on production, productivity and costs	– Provision for employing competent persons to comply with the regulations, and carry out activities with safety and least harm to the environment
7.1 Rules, regulations, laws regarding environment, health and safety	7.1 Necessity of formulating code of conduct, or procedures, in absence of local laws	– Provision for periodic tests, check-ups and inspections
7.2 Trade unions – types of labour	7.2 Assessing likely problems from local labour and trade unions, if any	– Provision for safety wear, training, and basic health and welfare facilities

10.13. Sustainable development

As described in the preceding section, ‘sustainability’ in operations is the best way to execute any venture, including those related to civil and construction engineering. A few guidelines that should be adhered to are given below.

- Mechanised tunnelling operations consume huge amounts of fossil fuels, which contributes to the generation of greenhouse gases. Improving the energy efficiency of tunnelling and mining operations is warranted. In particular, increasing the substitution of virgin aggregate with concrete products is required.
- New materials that will drive sustainability should be tried.
- Design engineers need to include sustainability as a purchasing and design criterion.
- The industry needs to participate in the development of new technologies and products. The collaborative efforts of designers, manufacturers, engineers, government and university research agencies could achieve this. Initiatives in this direction have already begun, as is evident from published literature on this issue (a few examples are given in Sections 10.13.1 and 10.13.2).
- Consideration of environmental impacts must be made during the design phase itself. Matching sustainable products and materials with construction requirements is an emerging area requiring the industry to develop expertise and/or provide additional training to those concerned.

Figure 10.7 The three pillars for sustainability in the civil and construction industries



- As shown in Figure 10.7, there are three pillars of equal strength that support sustainability in the civil and construction industries:
  - legal compliance ensures safety and least pollution, and best practice enhances productivity and brings precision to the operations
  - cost-effective technologies and systems ensure least cost
  - content employees could do miracles for the company and the people around it (the society).
- Section 10.15.4 describes losses of various kinds in the civil and construction activities and suggests ways and means to minimise them, which could result a cost reduction per unit of excavation together with least pollution to the surroundings, and hence, a sustainable development, which is beneficial to the present as well as future generations.
- *Environmental and Sustainable Development Reasons to go Underground*, a report the ITA Working Group 15, could also be referred for the guidelines on this issue (ITA WG 15, 2010).

Any imbalance could jeopardise the situation/scenario. The sections below give a few examples but each country has its own regulations that should be complied with.

Details of the Crossrail project in London, UK, are presented in Case Study 6.3. During the execution of this project special care was taken for the operations to be sustainable. Some of the best practices adopted are described in Case Study 10.2.

Case Study 10.2

Sustainability – Crossrail, London, UK

Crossrail is Europe's largest infrastructure construction project.

Reuse of chalk

- The tunnelling process created chalk slurry that was dried in a treatment plant to form a chalk 'cake' to allow its reuse. The 187 179 tonnes of chalk was transported to Pitsea in Essex where it was used to restore a landfill site to a grassland habitat. This type of habitat had been identified as threatened in the UK's Biodiversity Action Plan.
- The remainder of the chalk was transported to the previous power-station site at Kingsnorth in Kent, where it was reused to fill a void created by remediation of the site so that it is suitable for future land development.

General site installation

- Photovoltaic LED site lighting.
- Hybrid working platforms.
- Recycled hoarding.
- Hydrogen fuel cell in place of generators.
- Dust suppression using chemical membrane.
- Biometric site access controls.
- Diesel-particle filters (DPFs) on all construction equipment.

Exhaust emission management: advanced systems

- Engines – Euro 4 rated.
- JCB Telehandler on the C310 Plumstead site.
- Efficient engines – no DPF needed, hybrid technology.

10.13.1 British Tunnelling Organization's sustainability guidelines

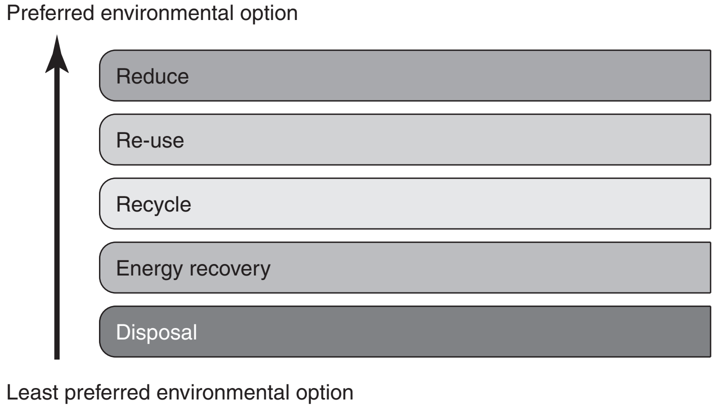
Best practice measures for sustainability listed by the British Tunnelling Organization include the following:

General

- 90% of construction waste materials will be reused and recycled.
- Soil-washing facilities.
- Usage of clamshell excavators.
- Bored piles with polymer support instead of bentonite (polymer is biodegradable).
- Crushed concrete as general fill material for working platforms/haul roads, etc.
- Re-use of hydraulic props in place of steel props.
- Ultra low carbon concrete.
- Jet-grout spoil used to fill temporary construction shafts in place of special disposal.
- Non-destructive pile removal.

Waste management. The hierarchy of the means of dealing with waste is shown in Figure 10.8. Disposal is the final, least preferred, option. The reduction, reuse and recycling of waste, and using it to produce energy are the logical, sensible disposal options that should be tried.

Figure 10.8 Waste hierarchy: British Tunnelling Organization's waste management strategy



10.13.2 HMJV's carbon reduction measures

To ensure their carbon-reduction targets are met HMJV use:

- hybrid mobile elevating work platforms and lighting towers, which emit 94% less carbon than regular plant
- eco-cabins with motion-sensor lighting and double glazing
- LED site lighting.

10.14. Emergency measures/preparedness

Table 10.5 shows the checklist that should be prepared for the project in hand to assess the likely hazards or events that could cause problems, and the remedial measures that will have to be taken. Figure 10.9 outlines and briefly reviews the types of hazard, both natural and man-made. An emergency management system is an integral part of industrial safety. Standing orders (emergency development plan, Figure 10.10) (CSA, 1995) should be prepared and workers should be trained to act as per these orders in the event of an emergency. This requires coordination, liaison and cooperation between different agencies. It requires enforcing scheduled training, refresher courses and demonstration and practice for all concerned – crews, rescue and recovery trained staff, and others.

10.15. Best practice

10.15.1 The 5S concept

5S is a Japanese concept that helps in achieving a workplace that is neat, clean, safe and minimises wastage. The five phases of the concept are

- *Phase 1 – Seiri (Sorting)*. Going through all the tools, appliances, materials, items, etc., at the work place, which could be a construction site, plant or work area, and keeping only essential items. Everything else is stored or discarded.
- *Phase 2 – Seiton (Straighten or Set in order)*. Arranging the tools, equipment and parts in a manner that promotes work flow. The focus is on efficiency.

Table 10.5 What-if checklist – a risk analysis

WHAT-IF CHECKLIST
REVIEWER ________________________ OPERATION TYPE __________________
LOCATION ________________________

What if? (1)	Cause	Consequences	Risk control measures	Monitoring measures	Likelihood	Severity	Risk	ERP* recommendations
Any event or situation that may arise	What could have potentially caused the event/situation in column (1)?	What could have potentially occurred as a result of the event/situation (1) (escalation)?	What measures are in place to prevent, mitigate and recover an incident/accident?	What active/reactive monitoring measures are in place? Are these measures adequate and reliable?	The probability frequency that the event/situation in column (1) will occur based on hazard matrix definitions	The severity of the consequence based on the hazard matrix definitions	Taken from the hazard matrix: risk = consequence × likelihood	Any additional information or investigation required? Are there practicable changes that could reduce risk or eliminate hazards?

* Emergency response plan.

Figure 10.9 Classification of hazards

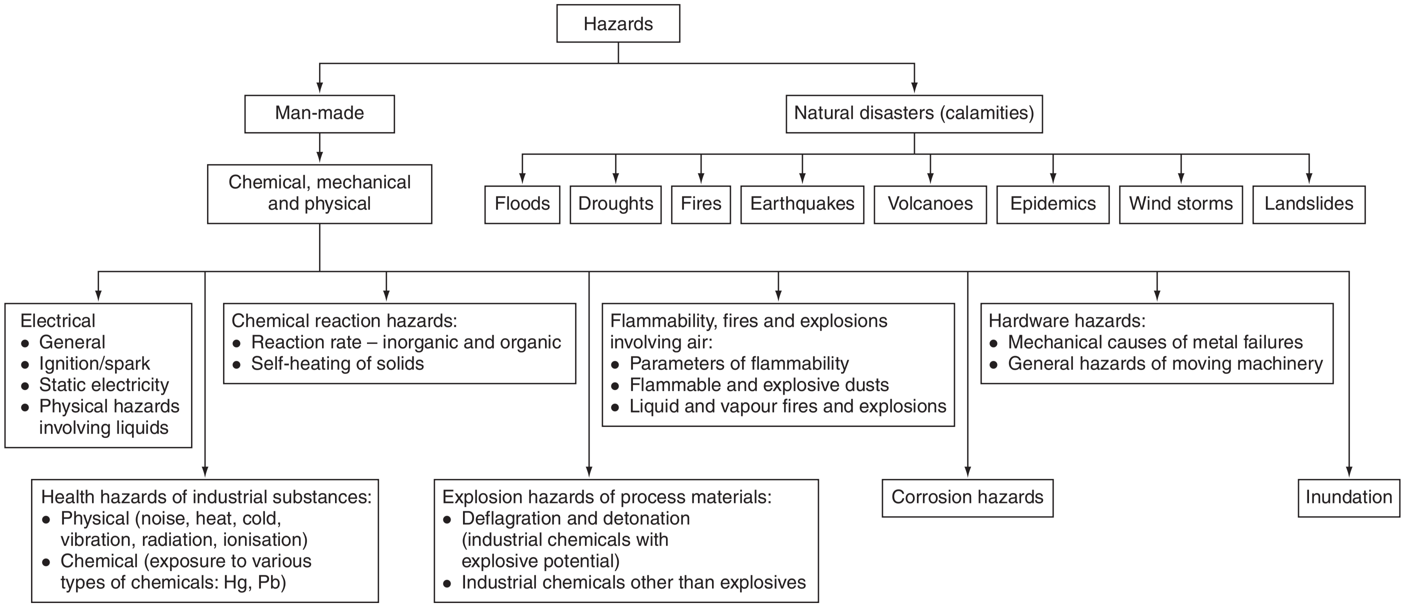
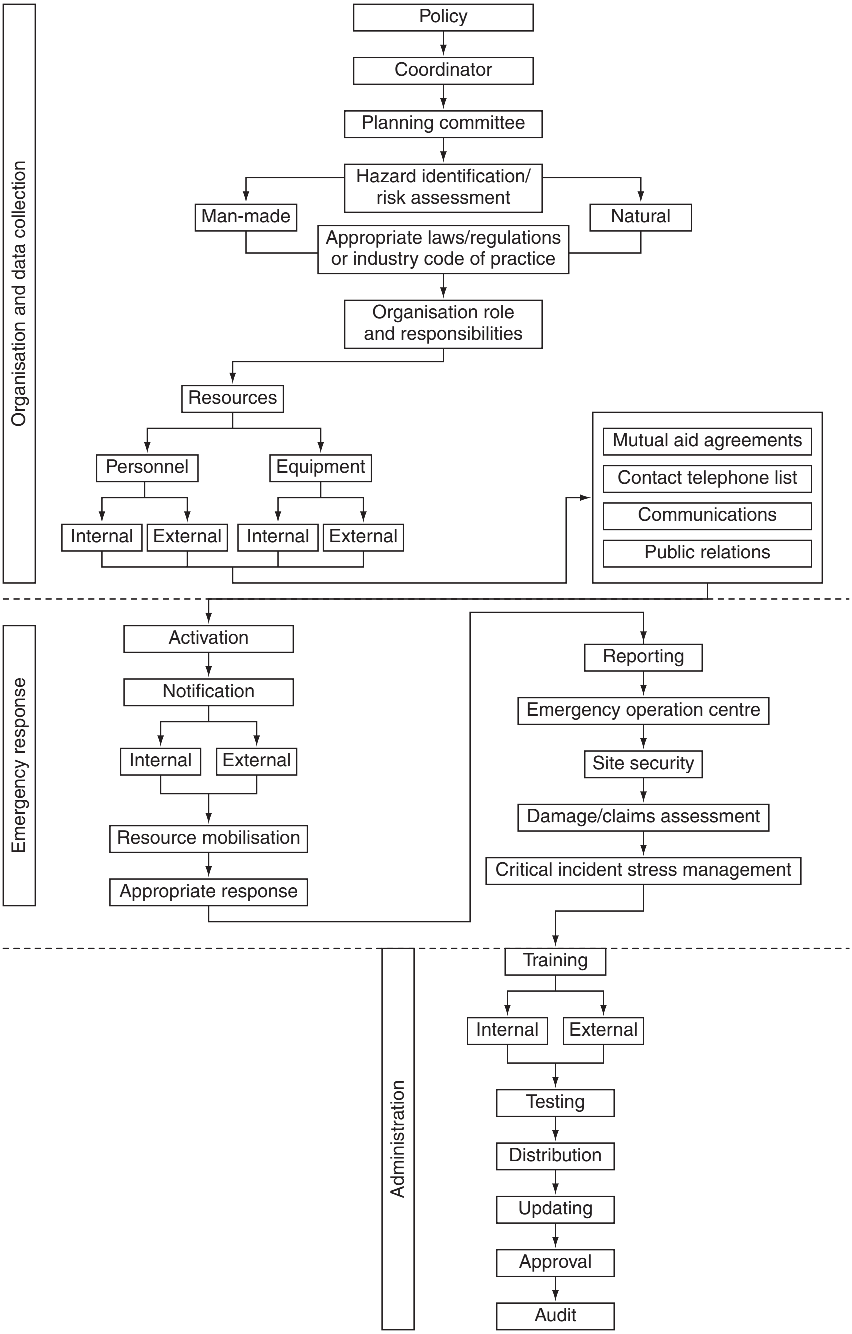


Figure 10.10 Emergency development plan



- *Phase 3 – Seisō (Sweeping, Shining or Cleanliness)*. Systematic cleaning, or the need to keep the workplace clean as well as neat. At the end of each shift, the work area is cleaned up and everything is restored to its place. The key point is that maintaining cleanliness should be part of the daily work, not an occasional activity initiated when things get too messy and dirty.
- *Phase 4 – Seiketsu (Standardising)*. Standardised work practices or operating in a consistent and standardised fashion. Everyone knows exactly what his or her responsibilities are to keep to the above three Ss.
- *Phase 5 – Shitsuke (Sustaining the discipline)*. Once the previous four Ss have been established, they become the new way to operate. However, when an issue arises, such as a suggested improvement, a new way of working, a new tool or a new output requirement, then a review of the first four Ss is appropriate.

The key objective of 5S is improved workplace morale, safety and efficiency. Try it at your own worksite, including your office and home, to understand this philosophy and its underlying advantages.

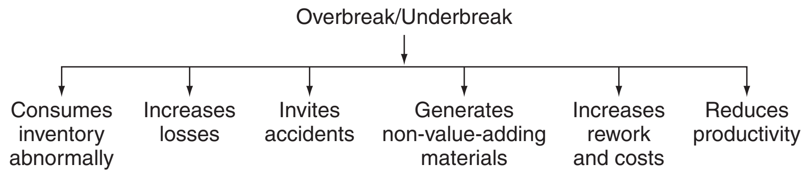
10.15.2 Ergonomics

It is important to understand that machines, equipment, procedures and systems are made to assist the users, and as such they should be ‘user-friendly’. This is the simplest way to understand ‘ergonomics’. Anything that is not user-friendly is un-ergonomic. Ergonomics aims to make things human compatible. At the workplace the focus should be on making the tools, appliances, equipment, methods/procedures/techniques, layouts and the working environment user-friendly. The switch by humans from stone-age tools to modern tools and appliances is an example of good ergonomics.

Poor ergonomic conditions have adverse impacts on health, and can cause muscle strains and sprains; pain in the joints, back, wrists, shoulder, forearms, knees, etc.; numbness in the hands and feet; swelling; a burning sensation; fingers or toes turning white; and many more ill effects on various parts of the body. Good ergonomics:

- results in improved labour relations
- safeguards skilled and experienced human resources
- offsets the limitations of the age of employees
- reduces maintenance downtime.

Figure 10.11 Adverse impacts of overbreak and underbreak



10.15.3 Training

In any organisation the most valuable resource is the workers themselves. It is important to recruit the best person for a job, whether they are a novice, semi-skilled, skilled or even highly skilled, or an executive of a company. Over time, methods, techniques, equipment, procedures, laws, regulations, policies and job-related parameters change, and therefore everyone needs some degree of training and education if they are to contribute maximally to the organisation. This is an ongoing process, which starts on day one of joining the company/project and ends on the last day.

Training needs should be evaluated using the well-established concept of: Why, Who, When, Where, What and How and How many times (frequency) (the 5W-2H concept). Germain and Arnold (2001) mentioned the following benefits of effective HSE training and education:

- reduced accidents, personal harm, property damage and related losses
- increased awareness of the value of tools, appliances, material, supplies and facilities
- decreased downtime and delays
- improved morale and motivation
- reduced mistakes and wastage
- optimum performance, productivity and profitability.

If you think education and training are expensive, try ignorance and inefficiency. There are excellent guidelines available from the regulatory bodies in your own country. For example, the guidelines of the Occupational Safety and Health Administration (OSHA in the USA) comprise seven steps:

1. Determine if training is needed, as many performance problems can be solved by
    - hiring the right person to the right job
    - improved design, layout and maintenance of the workplace
    - use of ergonomically improved/designed tools, appliances and facilities
    - job aids such as task procedures, flowcharts, decision tables, trouble-shooting guideline, hotline, etc.
    - effective communication and administration.
2. Identify training needs – as described at point 1.
3. Identify goals and objectives.
4. Develop learning activities.
5. Conduct the training.
6. Evaluate the effectiveness of the programme.
7. Follow up.

10.15.4 Losses and measures to minimise them

The civil engineering and construction industries need resources, which could be natural or man-made. Air, water, sun (heat and light), flora, fauna, rocks and minerals are natural resources, and energy, materials, machines and equipment, infrastructure and people (themselves) are human-made resources. Success lies in using resources optimally

Table 10.6 Losses: types, causes and remedial measures to minimise them

Loss type	Reasons for loss and measures to minimise it
Inadequate and improper site investigations Site investigation is the foundation on which a future structure is built. A shaky foundation is always dangerous.	Trouble starts in floating tenders, negotiating bids, awarding tenders and, ultimately, during the execution of a project. It often becomes the cause of dispute between a contractor and the owner. Cost overrun, delays and abnormal incidences could be the results of improper and inadequate site investigation. ■ The rock mass classification as detailed in Tables 1.10 and 4.6 could provide a better understanding of geological and other parameters. ■ The set of seven construction-oriented geological parameters (Table 1.8) can be correlated with major construction consequences. ■ Table 1.9 displays the ranking of geological and geotechnical factors influencing key issues. Factors having critical or major influence should be given due importance during the planning, design and construction phases. This would lead to better engineering judgement and communication regarding the matter, and ultimately to cost savings and better execution of the project.
Performance losses **Advance (progress) rate related issues** The increase in the cost per unit of excavation is the result of the factors given in column 2.	To achieve targeted progress (production), deviation from the practices outlined below could result in losses or reduced profits. ■ Quick handling/removal of the muck generated from a working face is essential for safety and productivity, and therefore methods allowing this feature should be preferred. ■ Concentrating the activities within a 'compact layout' and deploying resources accordingly can yield better productivity (i.e. output per man per shift) due to effective supervision and better coordination and minimum movement. ■ Proper matching of equipment, methods, techniques and layouts brings optimum results. ■ Progress (production) rates: higher advance (progress) rates can reduce expenses on services, overheads and fixed costs. As such, during tunnelling with the aid of explosives, larger rounds up to 8 m could be chosen with the application of 'smooth blasting'.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
	■ Minimise the cost of production by keeping minimum inventory. Selecting safe, eco-friendly, technologically sound and economically viable equipment always pays. ■ Minimise the pre-production or gestation period. ■ Less advance/progress than targeted is usually due to: – shutdowns or frequent stoppages – frequent interruptions due to failure of equipment (keep standby ready; following maintenance schedules and practices strictly could minimise this problem) – mismatch of the 'unit operations'.
Lack of effective utilisation of time Faster speed enhances productivity.	Improper allocation, ambiguity in job profile and responsibility assigned, sequencing operations improperly, mismatch of equipment, layout and working conditions, and absence of clear instructions are some of the reasons for time lost and delays. In addition, the following guidelines are useful: ■ Punctuality always pays. ■ Every moment is precious and should be utilised to add value. ■ Time is directly related to speed; accomplishing any task at a faster speed means adding to the productivity. ■ Waiting time should be minimised. ■ Undue delays and interruptions add costs and overall dissatisfaction among those involved.
Lack of effective management, training and education Mismanaged companies ultimately experience losses, closures and industrial disputes and unrest.	This relates to the effectiveness of 'systems', which includes personal efficiency and the performance of equipment or plant. To achieve an efficient system the following guidelines are useful: ■ Maximise mechanisation, wherever feasible. ■ Maximise automation. ■ Computer-aided design (CAD) has been found to be effective, so use it wherever appropriate. ■ Adverse working conditions add to inefficiencies. ■ A content employee is an asset to the company. *Training* ■ Everyone needs some degree of training and education to contribute maximally. Training is an ongoing process, which starts on day one of joining the company and ends on the day of leaving. ■ If you think education and training are expensive, try ignorance and inefficiency. See also Section 10.15.3.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
Improper breakage (configuration/profile/contour) Causing the least disturbance to the in situ ground setting pays. Improper configuration of excavations increases costs and endangers safety.	The faster the advance rate the better. The following guidelines could be useful: ■ Tunnel borers are costly equipment not suitable for tunnelling lengths shorter than 3 km. For shorter lengths other methods, as described in Chapters 4 and 7, should be adopted. ■ The lowest excavation cost is achieved using explosive, if used judiciously. If not judiciously used, the use of explosive results in excessive noise, vibrations and throw, improper breakage and damage to the surrounding ground/rock mass. ■ Explosive energy not used for fragmentation and displacement is sometimes more than 85% of the energy developed in a blast. This reduces the structural strength of the rock mass outside the theoretical radius of excavation. New fractures and planes of weakness are created, and joints and bedding planes are opened that initially were not critical, affecting the rock-mass cohesion. This is manifested (evident) as overbreak, leaving the fractured rock mass in a potential state of collapse. This aspect is illustrated by the case studies in Chapter 4. ■ Overbreak or underbreak of excavations due to poor drilling and blasting results in adverse impacts, as detailed in Figure 10.11. ■ Adapting controlled blasting (see Sections 2.5.3 and 4.13, Tables 4.8 and 4.9), automated drilling and use of electronic detonators results in a precise shape and size of tunnels (see Sections 2.6.1 and 4.13) and large-sized excavations. It should be preferred. Rounds larger than 5 m should be the established practice (see Section 4.13).
Imbalance between production, productivity and HSE HSE and the welfare of society (see Figure 10.2) should be considered a 'critical' business activity on a par with production and productivity.	Productivity is a function of the effective utilisation of available resources to accomplish a job. Productivity is expressed as the output per man per shift. Thus, it is a measure of the amount of work done per unit time by a worker, and also by a machine or equipment. The following guidelines are useful for enhancing productivity: ■ Carry out scientific studies to reduce the cycle time for various 'unit operations', as detailed in Chapters 3 and 4.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
	■ Maximise natural support by causing the least disturbance to the original ground setting. Tunnelling and shaft sinking methods that do not involve the use of explosives are available, and these should be preferred and selected from those detailed in Chapters 5–9. ■ Maximise the use of gravity, wind direction; surface terrain and topography wherever feasible to boost productivity (see Section 2.9).
	Equally important is the safety of people (both those directly involved and third parties), equipment and processes (see Section 10.8).
	■ Inadequate safety directly affects production targets, productivity and, ultimately, costs. ■ Inadequate safety results in accidents, which have indirect costs. They degrade the morale of the people involved and give the company a bad reputation. ■ Pollution has an adverse impact on workers' health and reduces their efficiency. Precision in operations could minimise pollution (see Section 10.12).
Performance of equipment and plant An autonomous maintenance system (AMS) should be adopted.	Equipment plays a very important role in the prevention of losses and the reduction of costs. The availability and effective utilisation of equipment is key to success**.** World Class Management (2017) recommends the use of an AMS.
	A team is developed to take care of the plant and equipment. The team is trained to diagnoses abnormalities, problems and deficiencies in the equipment, and in ways to remediate them and bring the equipment to its ideal condition. The equipment is then running it to its full efficiency, regularly without interruptions.
Use of substandard materials, auxiliary machines and spares This leads to losses rather than savings. It must be avoided.	The input material and its quality play an important role in preventing losses. Substandard material has following demerits: ■ It can damage the process, equipment and plant. ■ It can endanger the safety not only of those directly involved but also of third parties. ■ Operational failures can be increased. ■ Timely procurement of material of the correct quality and its proper storage, handling and issue is equally essential to avoid such losses.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
Improper working conditions (services), auxiliary machines, tools and appliances	■ Proper ventilation, drainage, illumination, power supply, communication, logistics, muck disposal, ground support, hygiene, IT and computing, welfare, etc., are the essential services, and any shortcomings in or interruptions to these results in losses. (See Section 4.14 and Table 4.12.) ■ Equally important are auxiliary machines, equipment, tools and appliances, which play vital role in the running of any project smoothly. The following guidelines are useful: – Proper selection and matching with the system must be ensured. – Regular maintenance and timely replacement must be ensured. – Substandard quality of material used for their construction often leads to failures and proves to be problematic, and could cause losses of different types, as detailed above. – Used and worn-out items should not be used as replacements. – Outdated and mismatched items are often not reliable, and should not be used.
Frequent interruptions, inconsistencies and shutdowns These must be avoided.	Unplanned and unscheduled layoffs, lockouts and shutdowns are evils that must be prevented. ■ They bring non-value additions and unrest among those involved – workers, management and stakeholders. ■ They could be due to mismanagement (lack of proper planning and foresight) and can result in huge losses. During a planned or scheduled shutdown: ■ Ensure the delivery of supplies, effective communications and the supplier's presence to avoid delays. ■ Proper planning, including use of the *critical path method* which is helpful for monitoring progress. Planning should include resources (workers, tools, appliances and material handling mechanism), which should be readily available. ■ Use experienced crews during shutdowns to do the job right within the time allocated.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
Defective design and layouts, and lack of planning Proper coordination between experts, manufacturers, contractors and consultants pays.	It is always sensible to prepare different designs, alternatives and options during the conceptual and planning phases, and to select the best. ■ Spending a dollar during these phases could prevent losses of many dollars if the design is defective and the equipment has been procured and the project has been started. ■ Input from experienced experts and professionals during the conceptual phase pays. ■ Eco-friendly design should be incorporated wherever practical. Such designs pay in the long run, and are sustainable. ■ Inadequate internal as well as external infrastructure also adds to poor layouts.
Energy losses and excessive material consumption Technologies consuming excessive material, energy and consumables should be avoided.	■ Methods that involve a higher consumption of materials and consumables are often costlier and should be avoided. ■ The energy per unit of output, which is required to carry out different 'unit operations' and services such as ventilation, pumping, illumination, etc., is a consumable item. ■ Minimise power distribution and transmission losses. ■ Minimise wastage of water. Besides the judicious use of a precious resource this will add to savings. ■ Pollution means more energy has already been spent than was required. The lowest possible pollution and a clean environment are keys to success. This can be achieved through the precision of driving tunnels and ground excavation tasks/projects. ■ It also includes the selection of an appropriate energy source (electric, diesel, compressed air, hydraulic or non-conventional (if available)), which could bring an overall benefit to the company.
Lack of tools, techniques and renovations 'Kaizen' and renovations should be part and parcel of the working culture.	■ Lack of tools, techniques (up-to-date technology) and renovations is like a soldier at the front without adequate and up-to-the-mark arms, ammunition, weapons and know-how. And imagine if the enemy is fully equipped with all these! ■ *Kaizen* is applied to remove or minimise bottlenecks in the process or technique and the use of equipment and machines by making use of existing resources. It should be encouraged.

Table 10.6 Continued

Loss type	Reasons for loss and measures to minimise it
	■ *Renovation* is a change in technology, method or equipment, which can bring improvement to the system and result in increased in profits as well as a safe and clean environment. For company growth and to compete in the market renovations are essential. Periodic renovations are almost mandatory in any industry, including the civil engineering and construction industries, to improve both quality and output rates (see Chapters 4–9).
Lack of attention to abnormalities Identifying abnormalities using our five senses.	■ Any abnormality in plant and equipment, rock and ground stability, rock fragmentation and reinforcement, waste generation, make-up of water, air quality (presence of foul gases, heat and humidity), use of resources (air, water, spare parts, materials, consumables, energy, etc.) should be given due attention and must be removed and rectified immediately, as they are a hindrance to smooth running and cause delays. In identifying them there is no substitute for the five senses – sight, sound, smell, feel and touch – and we must use them fully. ■ Equally important is preparedness to face emergencies and the unforeseen (see Section 10.14). Unplanned events or chains of events could cause injury, illness and/or damage and losses to assets, the environment or third parties.

to achieve the desired rate of production, with maximum productivity and least cost. There is no simple and straightforward way to achieve this, but by minimising the losses of various kinds, as detailed in Table 10.6, we could certainly achieve it.

10.16. Concluding remarks

- The six letters of the word ‘SAFETY’ describe a well-balanced strategy to accomplish it (Box 10.1).

Box 10.1 Some selected applications of combined mode machines

Systemise your operations & be ***‘self-disciplined’***
Avoid any negligence including ***‘unsafe acts & unsafe conditions’***
Follow ***‘best practices’*** & ***timely accomplishments***
Ensure ***legal compliances & teamwork***
Train everybody (topmost executive to shop-floor worker) &
Yield ***‘goodwill’*** to your company by following above guidelines

- Rules, regulations, directives and any legal framework are formulated after much debate and discussion. As such, ensuring their compliance with these will take care of HSE and social welfare. However, we should do more than just comply to become a 'bench marker'.
- 95% of incidents occur on account of 'ground failures'. As such, due care should be taken during the pre-construction (planning) phase, when major decisions are taken to minimise the occurrence of this phenomenon.
- Production (the successful completion of a project) is our bread and butter, and productivity brings excellence to our operations (as it results in cost reduction). Neither can be achieved if accidents are frequent, workers' health is not looked after and the welfare of society is neglected. Considering HSE together with social welfare as a critical business activity on a par with production and productivity will result in a sustainable development – a development that is beneficial socially, ecologically and economically to the present as well as future generations.
- 'What if' analysis, hazards identification, risk analysis and emergency preparedness are some of the best practices that should be adhered to.
- The growth and development of the civil engineering and construction industries lie in completing projects safely, at least cost, with least disturbance to the surroundings (flora and fauna) and while taking care of the people in and around a project. This is a sustainable model which is beneficial to the present as well as future generations.

10.17. Questions

1. Do you agree that when creating an excavation of any kind pollution and accidents are unavoidable and, although they cannot be eliminated, efforts can be made to minimise them? If 'yes', suggest ways and means to minimise them.
2. Define the term 'hazard'. Classify hazards. Why are underground operations full of hazards? List them.
3. Define the term 'accident'. Do you agree that 90% of accidents are due to unsafe acts and the other 10% are due to unsafe conditions? List unsafe acts and conditions; suggest remedial measures to minimise them when undertaking excavation activities at any locale, either surface or underground.
4. Justify the statement: 'For the past 60 years or so the creation of tunnels and ground excavations has no longer been an art but an engineering task.'
5. List adverse ground conditions. What could be their result? When can collapses occur? List the reasons for the occurrence of ground collapse. Is this a major tunnelling hazard today? List some collapses that have occurred in the past.
6. An analysis for the period 1992–1997 indicated that more than 95% of incidents are accounted for by ground failures. What strategy should be followed to minimise such occurrences when executing forthcoming projects?
7. The presence of faults, folds and discontinuities has been one of main reasons for ground collapses. How could we safeguard against this phenomenon in the future?
8. Apart from the geological discontinuities listed in Question 7, the reasons for ground collapses include weathered ground; squeezing and swelling ground conditions; inadequate support; seismic activity; hard and abrasive rocks; intense jointing; highly shattered ground; weak zones; and mixed ground conditions

(hard, soft and abrasive). What strategy should be followed to counter each of these so that collapses can be minimised?

9 Give the relationship proposed by Hudson and Harrison for the stability of an opening/excavation.

10 List the main sources of water in subsurface workings. Why does subsurface water often need treatment?

11 What does subsurface drainage include? What adverse impacts can result from the presence of water in rocks?

12 If openings such as tunnels, shafts, etc., are driven through water-bearing formations or strata, then water is bound to be encountered. List its direct and indirect effects.

13 In what manner does subsurface air differ from atmospheric air? Tabulate the foul gases that could be a source of air contamination. What are the sources of these foul gases?

14 List sources of air pollution other than foul gases.

15 List sources that add heat to air. Why does the presence of water significantly add to this problem and what is the result?

16 Apart from providing fresh air to breathe in, what is the function of ventilation? Specify, in general, what the composition of air should be. Effective ventilation can result in number of benefits. List them.

17 There is increasing use of automation and mechanisation in tunnel construction. List the areas, locales and operations that pose great concern and require proper safety.

18 High standards of electrical safety are necessary due to the fact that the power consumption of large TBMs is 5–10 MW and supply voltages can be up to 11 kV. This has given rise to certain directives and legislative measures that are enforced the world over. Some of the standards specified are EN 815:1996; prEN 12336:2005; prEN 12110:2010 and prEN 12111:2002. What does each of these cover?

19 Tunnelling machinery for use in potentially explosive atmospheres must conform to the essential safety requirements. What are these called?

20 Describe how you would manage the transportation hazards that arise during tunnelling operations. How do slurry systems and conveyors give major safety benefits?

21 What could cause a fire and explosion in subsurface workings? List the issues that should be addressed to safeguard against these hazards.

22 Why are the issues listed below important when working in subsurface locales and how would you address them?
   (a) Safeguarding against large quantities of hydraulic fluid, grease and diesel fuel which are combustible.
   (b) Good housekeeping.
   (c) Fire detection and communication systems.
   (d) Use of oxygen self-rescuers underground and rescue-trained crews.
   (e) Keeping access walkways unobstructed.

23 Why are tunnelling and mining operations considered to be rough, tough and extremely hazardous? What are the adverse impacts of inhaling dust regularly?

24 Give a classification of the risks to health due to working in an industrial setup, including the one you belong to.

25 In order to ensure employee health fitness, two tasks are necessary in addition with occupational health measures. List them.

26 Give the factors in the construction and tunnelling industries that cause the following diseases:
(a) dermatitis
(b) skin and respiratory problems due to epoxy materials
(c) impaired hearing
(d) heat strain/heat stroke
(e) vibration syndrome
(f) musculoskeletal injuries
(g) lung diseases.

27 What does ‘industrial discipline’ mean? How can it be achieved?

28 The statutory requirements for the tunnelling and construction industries differ from one country to another. Some are listed below. Describe each one.
(a) The European Community Framework Directive 1989
(b) relevant regulations in the UK
(c) Compressed Air Regulations 1996
(d) the ITA’s *Safe Working in Tunnelling 2011*
(e) BS 6164:2011 *Code of practice for health and safety in tunnelling in the construction industry.*

29 Define the term ‘safety’. Safety strategies can be classified into four groups. List them. In most countries, speeding of automobiles is a major cause of road accidents. Suggest possible solutions.

30 Do you agree that inherent safety is the best strategy but that other strategies are equally important and should be enforced as much as possible?

31 What is the British Tunnelling Organization’s waste management strategy?

32 Training and education are ongoing processes that are essential. How could they be achieved effectively?

33 With respect to safety, how would you address the following:
(a) accident reporting and analysis
(b) organising ‘safety week’ celebrations
(c) safety promotional initiatives.

34 It is important to make sure that safe working conditions prevail at the work site. List the provisions that should be ensured to accomplish this.

35 Perfect working conditions also include the provision of basic amenities (at strategic locations). List these amenities.

36 Differentiate between an accident and an incident. An accident is a three-step process. List the steps. What strategy can impact this process?

37 Define and give formulae to calculate the ‘accident rate’ and the ‘severity rate’.

38 The causes of accidents differ from one project to another but there are some common causes. List these and the degree and type of injuries sustained.

39 List the costs associated with an accident. What remedial measures can be taken to prevent accidents?

40 Ultimately, accidents result in a deviation from the laid-out objectives and goals of a company. As such, what is the logical approach to avoiding this deviation?

41 List the four phases of a tunnelling or subsurface excavation project and describe each one. What is the 'life-cycle' approach?

42 Why is the planning and design phase considered to be the most risky? List techniques concerning safety that could be considered during this phase.

43 What strategy would you suggest to improve the standards of health and safety associated with excavation technology (a) specific to your work site, (b) in general and (c) worldwide?

44 The traditional approach to risk management is to control a hazard by providing layers of protection between the work site (the project in hand) and the people, property and surrounding environment to be protected. List these layers.

45 What is a risk ranking matrix for identifying potential hazards? Explain it by way of a table and a figure.

46 What inherent features of the mining industry make it the most polluting? Could we do away with mining?

47 Why have we started to experience negative impacts on health, aesthetic and cultural pleasures and economic opportunities?

48 Give the fundamental mass balance relationships (equations).

49 What is 'sustainable development'? List its three pillars as applicable to the civil engineering and construction industries.

50 Draw a line diagram to show the types of pollution caused by an industrial setup, including your own project.

51 Draw a line diagram to show the air pollutants that occur in civil excavations and tunnelling projects. What are the main sources of pollution of air, water and land environments?

52 Environmental management is a mechanism that involves three steps. List the steps and describe each one.

53 Why is it important to prepare a 'What if' checklist for the project in hand? Prepare one for your own project.

54 Illustrate by way of a line diagram the types of hazard, both natural and man-made, present in an industrial setup.

55 Why is an emergency management system an integral part of industrial safety? Why is it necessary to prepare standing orders (an emergency development plan)? Prepare the same for your own project. List the agencies with which coordination is essential for its effective implementation.

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