Civil Excavations and Tunnelling

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 ($0.5 \text{ man-hours/m}^3$) compared with current conventional tunnelling today ($2\text{--}4 \text{ man-hours/m}^3$), 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 m³/h; draglines, which weigh 12 000 ton and have a bucket capacity of 170 m³; hydraulic excavators, which have a bucket capacity of 45 m³ 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.