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Handbook on Tunnels and Underground Works

Volume 1: Concept – Basic Principles of Design

Edited by Emilio Bilotta, Renato Casale,
Claudio Giulio di Prisco,
Salvatore Miliziano,
Daniele Peila, Andrea Pigorini
and Enrico Maria Pizzarotti



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Handbook on Tunnels and Underground Works



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Volume I: Concept – Basic Principles of Design

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Preface

The Italian Tunnelling Society is pleased and proud to introduce to the international tunnelling community this three-volume *Handbook on Tunnels and Underground Works*:

Volume 1: Concept – Basic Principles of Design

Volume 2: Construction – Methods, Equipment, Tools and Materials

Volume 3: Case Histories and Best Practices

The three sequential and integrated volumes have the purpose of offering a comprehensive and up-to-date scientific and technical content regarding the design and the construction of tunnels and underground works, useful for both universities and post-university studies and in the professional field.

As a handbook, it also aims to be a tool, in everyday tunnelling works, to rely on when facing specific dilemmas, such as:

- the assessment of a specific geotechnical risk or a computational analysis problem (Volume 1),
- the estimation of tunnel excavation rates or of the increased ground parameters achievable by a consolidation work (Volume 2),
- a search for suggestions or help in consulting data from previous important design and construction experiences (Volume 3).

The first volume ‘Concept – Basic Principles of Design’ describes the different stages of a project, related to the management of the uncertainties (risk management) in the design of underground works, starting from the analysis of initial data and models: functional data, geological and geotechnical model, and environmental framework.

The necessary theoretical elements are then provided for the development of computational calculations, with reference to the stability of the face and of the cavity, the analysis of the interaction with pre-existing structures and with the overall context and the design of temporary and permanent supports, both in static and dynamic conditions.

Specific detailed analysis is provided for monitoring activity during construction and for the design of refurbishment and maintenance of existing tunnels, always with reference to the definition of the theoretical basis and the main design elements.

Finally, we wouldn't neglect the stakeholder engagement process, which is essential for the acceptance of wide and complex infrastructures, such as those underground, to which an entire chapter is dedicated.

The second volume, 'Construction – Methods, Equipment, Tools and Materials', describes the main construction methods, the equipment, the machinery and the materials used for excavation, soil and rock enhancement, and construction of provisional and final supports, providing results according to geotechnical contexts and boundary conditions.

A specific detailed analysis is provided on monitoring tools and site plants and logistics.

The third volume, 'Case Histories and Best Practices', describes a number of tunnelling experiences, focusing mainly on how the risks identified in Volume 1 have been addressed in the design and construction phases, and refers to specific cases, in Italy and abroad, in order also to present the Italian underground works' know-how.

To sum up: design theory (Volume 1), construction and technology (Volume 2), and case histories and best practices (Volume 3).

We have entrusted the writing of these books to a scientific committee, whose members are:

- Professor Daniele Peila (Turin Polytechnic),
- Professor Claudio di Prisco (Milan Polytechnic),
- Professor Salvatore Miliziano (Sapienza Rome University),
- Professor Emilio Bilotta (Federico II Naples University),

either directors of postgraduate master's courses or holders of postgraduate courses in tunnelling (Turin and Milan Polytechnics) and in geotechnics applied to infrastructures (Rome and Naples Universities), held in Italian universities.

They have coordinated a group of about 50 experts from universities, engineering firms, construction companies and tunnelling industry and have been supported by a scientific secretariat. All of them invested knowledge, energies, passion and valuable time in this work: for that we are very grateful.

Furthermore, we would like to give a special thanks to Tatiana Todaro and Matteo Zerbi, two young engineers who hold the scientific secretariat.

The use of underground space is progressively growing, due to global urbanization and public demand for efficient transportation, together with energy saving, production and distribution. The increasing need for surface space, along with its ever-rising value and the challenges of meeting the goal of sustainable development, demands a greater and better underground space exploitation.

This will ensure a great support for sustainable and resilient transport infrastructure and more liveable cities and meeting the necessity to increase tunnelling knowledge, to rely on proper and valuable projects and on well-defined construction budgeting and scheduling.

We believe that the handbook will be a valuable reference text for university and master's degree students, tunnelling specialists, engineers, geologists and architects involved in underground planning, design and construction worldwide, to enhance the tunnelling culture.

The Editorial Board

Andrea Pigorini	SIG President
Renato Casale	Editorial Board Coordinator
Daniele Peila	SIG Vice-President & Scientific Committee Coordinator
Enrico Maria Pizzarotti	SIG General Secretary



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Foreword I

The field of tunnelling is one of the most fascinating ones for an engineer, for we must work with the crust of the Earth itself. This material is only apparently docile, but instead ever changing and unexpected. Indeed, it is the true construction material with which underground works are made.

In the past decades, tunnelling has made giant steps as regards both conventional and mechanical digging, and thanks to new design approaches and new technologies, tunnelling has reached that goal which the specialists have always pursued: meeting the deadlines and costs of construction, in other words the industrialization of underground work sites.

However, the construction of tunnels remains an activity subject to uncertainties of various kinds that make it a particularly complex and difficult subject of civil engineering to address. Unlike the works built on the surface, the tunnels, in fact, have completely unique characteristics:

- They are built by subtracting, rather than adding material.
- The properties of the construction material (ground) aren't as well defined or known.
- The thrusts on their structures aren't previously known, nor is the response of the work in terms of resistance or deformability.

These are uncertainties that, if not addressed with adequate design and construction approaches, easily translate into higher costs and intolerable delays in construction times than those foreseen in the design stage.

In order to give a solution to the problem and to learn to approach the construction of large, long and deep tunnels with industrial criteria as required by the new means of transport and the growing demand for mobility, important progress has been made since the end of the 19th century, which in just over a hundred years has revolutionized the way of designing and building underground works. Considerable are the results achieved.

The first major revolution was undoubtedly the introduction by Sommeiller of the first drilling machine driven by compressed air for the excavation of the Frejus railway tunnel, which was followed between 1920 and 1960 by a second important revolution thanks to the studies of Terzaghi (the 'rock load' due to the weight of broken ground resulting from the excavation of the tunnel), Kastner and Fenner (the development of a

‘plastic zone’ in the rock mass surrounding the tunnel), Rabcewicz (NATM) and Lombardi (characteristic lines). The latter was the first to highlight how the static problem of the tunnels was a three-dimensional problem and not simply a two-dimensional one as previously considered. In 1950 Robbins, on the other hand, successfully experimented with the first modern full-face TBM in a rock mass, giving way to the birth of different types of TBMs, suitable for excavating not only stone materials, but also soft materials, above or below water table (hydroshield and EPB TBMs).

It was in this context that in the 1980s the second great revolution in the design and construction of tunnels took place, when with the introduction in Italy of the approach according to the ADECO-RS, having exploited the three-dimensionality of the stress field present deep in the rock mass, the importance of the ‘core-face’ was clarified, suggesting that the analysis and the control of the behaviour of the ground ‘core’ upstream of the excavation face are the secret to successfully build tunnels, economically and safely, in all stress–strain conditions, even the most difficult ones, guaranteeing certainty of construction times and costs. Consequently, the false dichotomy between conventional excavation and mechanized excavation has also been overcome, highlighting how the common key to success lies in the pre-confinement action of the cavity which, always advancing full face, is permanently ensured by acting on the core-face, an action that allows to constantly maintain the triaxial coaction σ_3 , originally present in the rock mass, on different and greater than 0 values, up to the implementation of the radial confinement of the cavity, generally operated through the timely installation of a load-bearing lining closed by the invert put in place close to the face.

The book that I have the honour to present here is the first volume of a very complete treatise. All the issues that preside over the realization of these difficult engineering works are examined, starting from the criteria for managing the uncertainties that are always present in these works, deriving from the initial data and models: functional data, geological model, geotechnical model and environmental aspects. The necessary theoretical elements are provided for the development of three-dimensional computational calculations (with reference to the stability of the core-face and of the cavity, to the analysis of interaction with pre-existing structures and to the environmental context) and for the design of temporary and final linings in static and dynamic conditions. Specific insights are provided for monitoring during construction and for the design of adaptation and maintenance interventions of existing tunnels, always with reference to the definition of the theoretical bases and the main design elements. Finally, even the stakeholder engagement process is dutifully considered, essential for the acceptance and sharing of complex works such as the infrastructural works in tunnel, to which an entire chapter is dedicated.

In short, an indispensable volume for all of us who dedicate ourselves to the noble and exciting task of designing and building tunnels!

The Italian Tunnelling Society (SIG) is to be congratulated for this excellent three-volume *Handbook on Tunnels and Underground Works*, which contains a wealth of information for researchers, students and professionals in the tunnel construction business. It comes at a time when the underground construction industry is experiencing a global boom, with growth rates significantly and consistently higher than the rates of the general construction industry. SIG is a highly qualified group to produce this book in view of the knowledge accumulated in Italy, a country actively involved in the

construction of many heritage tunnels and in remarkable achievements in tunnelling during the 19th century, most importantly because Italy is the home of many developments of the modern tunnelling industry. One example is the design approach based on the analysis of controlled deformation of the ground mass. The book covers this innovation in sections dealing with both design and construction. The development of new materials and equipment because of that approach is also included.

Volume 1 establishes rational bases for tunnelling to be classified as a predictable engineering activity, rather than the almost heroic endeavour plagued with myriad geological uncertainties, which was the reality facing the industry in the past. Due to the recent progress in this topic, de-risking of projects has allowed contractors and private investors to feel more comfortable with the level of uncertainty to be faced in tunnelling operations. In addition, the topic of risk assessment is also contemplated in chapters devoted to modern computational methods for the analysis of the hydro-thermo-chemo-mechanical coupled processes which take place during construction and operation of tunnels. Quantitative and consistent probabilistic methods of analyses and the design of risk mitigating measures are also indicated.

The book is organized in such a way that the need for consultation of external references is minimized. For example, the chapters on input data related to geotechnics, geology and hydrogeology appropriately cover concepts of soil and rock mechanics.

In addition to the well-consolidated concepts of design that focus on structurally and geotechnically sound construction, the book covers the holistic approach to design, with chapters related to the minimization of both permanent and temporary negative environmental impacts as well as considerations regarding health and safety. Not only do these chapters provide guidelines for projects to be sustainable and useful for the society in a broader sense, but they also contribute to their acceptance by the society, a topic covered in Chapter 13. The chapter on occupational health and safety shows how a tailored design may promote those concepts. Information is given about how the number of casualties has decreased in underground construction as the industry aims at safer and predictable practices.

Volume 2 gives a broad overview of the latest construction techniques and the most modern systems and installations able to support the construction phase. The most modern technologies are described, which, at the present time, make use of highly automated apparatuses and processes and which allow companies to operate often without the direct involvement of workers in high-risk activities and with processes more and more similar to those of the manufacturing industry.

Finally, Volume 3 contains a rich series of case histories, which represent the application of the design and construction methodologies described and the most effective synthesis of the level reached by Italian engineering in the field of underground constructions. The described examples have been identified in such a way as to constitute a broad reference for each design and construction approach in the widest possible number of morphological, geomechanical, anthropic and environmental contexts.

This three-volume book will be a valuable tool in the search for better, safer and sustainable practices of underground construction.

Pietro Lunardi
SIG Honorary President

Tarcisio B. Celestino
Professor, University of Sao Paulo



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Foreword 2

This three-volume series edited by SIG, which is the result of the World Tunnel Congress, held in Naples in 2019, not only collects, organizes and reports on the testimonies, the suggestions, the technical culture and the experiences of that fascinating ‘other world’ of underground work – that is the universe of tunnels, but also records, in the period after this international scientific event, the radical and unexpected historic change that has taken place in the international context. Therefore, we can say that the Congress itself took place in ‘another world’.

The world before the pandemic – that saw a global outbreak which changed the behaviours and social life of millions of people, subverting their consolidated values and perception of the future, as well as the economic policy priorities (among others) of countries – and the world before the European Green Deal – with the new mottos of ecological transition, as an unavoidable feature of the new development, and of widespread digitalization, as a new mass technological literacy – constitute, in their inseparable interpenetration, the innovative binary paradigm for an accelerated transformation of the economy, manufacturing, services, education, the life of people and, above all, the new generations. It seems that, as in a sort of karst phenomenon, a lot of long gestating underground processes have suddenly emerged into the sunlight with an unpredictable potential for innovation that we are only now discovering in their disruptive scope, as they are coming out from our beloved WTC tunnels.

Faced with changes of this extent, the unavoidable topic is the new perspective of sustainable development based on a new meaning of growth, which calls for a closer dialogue between technical and humanistic disciplines. In this ecological transition context, a special role – for goods and passengers – is given to modal balance between road and rail and to sustainable mobility. In this context, train – of all types – represents the cornerstone in urban areas with underground railways, and also, on a large scale, with the TEN-T network, which will be an extraordinary continental metro, with cities as the stops and corridors as the interconnected lines.

This fundamental transport choice requires radical technological and infrastructural adjustments for thousands of kilometres of network, to be carried out in a tight time frame (within the 2030s) and in a coordinated manner to allow the ‘system effect’. This effect cannot fully emerge without overcoming the main geomorphological constraints such as mountain chains, which risk becoming geopolitical constraints as well. Trains are efficient and profitable when they travel at plain surface. When there is a mountain, the only way to overcome it is to drill the mountain at the level of the plain

and to build ‘base tunnels’ such as those – the longest in the world – of Mont Cenis and Brenner, currently under the responsibility of the authors.

A great innovation, compared to the past, is that today requirement is not only to work to ensure a strategic role in the long term, but also to be the creators of a solid immediate anti-recession action. The aim is to enhance all the economic and employment-related effects of the public expenditure envisaged for the system of European companies and the different countries, as well as, first of all, for the territories in which the work will take place.

The intervention area is potentially wide and covers not only construction activities themselves, but also the widespread added value that can be created in terms of services for people and companies such as accommodation, food services and, at a more sophisticated level, collaborating with schools and, in particular, with universities for training. The aim is to launch leading-edge disciplinary specializations as well as the interdisciplinary culture, to reach at the end the widespread innovation to be implemented using the extraordinary opportunity offered by our construction sites as laboratories for *in corpore vili* experimentation to solve today’s problems while training a generation of technicians for tomorrow’s increasingly global labour market.

In this context, the completion of the major Alpine tunnels currently under construction under our Alps represents, according to the concrete data available, a very important symbolic step.

It confirms the awareness of reaching environmental sustainability both in the construction phase, with the adoption of construction sites based on the criteria of circular economy, compatibility and integration with the territory, of environmental impact minimization and continuous implementation of safety, and in the operating phase, with the aim of complete transition towards diversification of transport modes and progressive decarbonization of this sector. These represent strategic projects for the entire European Green New Deal, which envisages a 90% reduction in CO₂ emissions from transport by 2050.

In addition, we would like to emphasize that these major projects represent the tangible realization of a technical-scientific and socio-economic dialogue between generations and peoples and constitute a laboratory of knowledge, experience and technological innovation for young engineers, young underground workers and young European citizens.

The work carried out in our construction sites, collected in this book from different perspectives, tells a story of miners, sometimes of their sons and grandsons, who dig the tunnels of our country, with courage and disdain for fatigue, inside the mountains, one volley after the other. And they do this colonizing a new universe of the underground each time and passing on a profession that, without excessive rhetoric, has the characteristics of an ancient art, even when the most modern technologies are used.

This work also tells the story of young technicians who, driven by their resolution, had the opportunity to complete their studies in our offices and construction sites, enriching the designs of these works with their enthusiasm, curiosity and knowledge, borrowing extraordinary experiences. These are young people cultivating ideal, in this case pursued with the language of knowledge combined with the language of work, new stories, probably among the most significant for our country.

Finally, it may be seen as a sign of the times that the legacy of the WTC of 2019 is being illustrated in books in 2021, the ‘European Year of Rail’. The year has been declared by the EU Commission on the occasion of the 150th anniversary of the inauguration of the historic Mont Cenis tunnel, strongly advocated by Cavour, with the support of the great innovative engineers of that time (Sommeiller, Grattoni and Grandis).

Mario Virano

Tunnel Euralpin Lyon Turin – TELT

Board of Directors – CEO

Gilberto Cardola

Brenner Base Tunnel – BBT SE

Board of Directors – Italian CEO



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About the editors

Emilio Bilotta graduated cum laude as Civil Engineer at the University of Napoli Federico II, and he got his PhD degree in Geotechnical Engineering from the University of Roma La Sapienza. He is currently Associate Professor at the Department of Civil, Architectural and Environmental Engineering of the University of Napoli Federico II, where he holds courses of fundamentals of geotechnical engineering for undergraduates and of tunnels and underground structures and underground constructions for postgraduates. His main research interests concern tunnelling in urban areas, tunnels under seismic actions and ground improvement for seismic mitigation.

He is Italian delegate of the Technical Committees TC 104 (Physical Modelling) and TC 219 (System Performance of Geotechnical Structures) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE); a member of the Italian Geotechnical Association (AGI) and of the Italian Tunnelling Society (SIG); a member of the editorial board of the journal *Rivista Italiana di Geotecnica* and of the scientific committee of the journal *Gallerie e grandi opere sotterranee*; and an associate editor of *Frontiers in Built Environment*. He is also co-founder of the academic spin-off and start-up Smart-G – innovative solutions in ground improvement and geotechnical engineering.

Renato Casale is currently CEO at EnginSoft SpA, based in Trento (Italy), and President of the Editorial Board at SIG (Italian Tunnelling Association) of *Handbook on Design and Construction of Tunnels*. Prior to this, he was Senior Advisor at SWS Group, based in Trento (Italy), President of the Organizing Committee of WTC 2019 at SIG (Italian Tunnelling Association) and Senior Engineer at Rocksoil (worldwide-known design company in the underground infrastructures). Prior to this, he was Vice-President and Chief of Rail Research Department at Ducati Energia S.p.A., based in Bologna (Italy), from June 2014 to June 2017 and, from May 2016 to May 2017, CEO at Telefin S.p.A., a railway telecommunication company, owned by Ducati Energia Group. Prior to this, Mr. Casale worked as an Executive with Ferrovie dello Stato Italiane Group from 1979 until April 2014. Mr. Casale was Director of special projects at Ferrovie Dello Stato Italiane SpA from October 2013 until April 2014. Prior to this, Mr. Casale was CEO of Italferr SpA, company of Ferrovie Dello Stato Italiane Group, from May 2007 until September 2013. Italferr, the engineering Company of Italian State Railways Group (Gruppo Ferrovie dello Stato Italiane), is a market leader in the field of multidisciplinary services

and comprehensive designs in the railways. Prior to this, Mr. Casale was Chief Investment Officer of Rete Ferroviaria Italiana (RFI) from April 2000 until April 2007, which is the company of the Ferrovie dello Stato Group with the public role of Infrastructure Manager. Previously, he was Designer, Site Engineer and Project Manager at Ferrovie Dello Stato Italiane, from October 1989 until March 2000.

Claudio Giulio di Prisco graduated at Politecnico di Milano. He developed his doctoral thesis under the supervision of Prof. Roberto Nova at Politecnico di Torino. He collaborated with Prof. Ioannis Vardoulakis and prof. Elias Aifantis. He is Full Professor of Geotechnics and Slope Stability at Politecnico di Milano since 2005, and from 2015, at the same university, Director of the Master on Tunnel Engineering. He was Director of the International Association Alert Geomaterials. He is the author of more than 70 scientific papers in international journals and of many book chapters, mainly concerning the constitutive modelling of the mechanical behaviour of granular materials, instabilities in geomaterials (localization and liquefaction) and the design of shallow foundations, reinforcement of tunnel faces, piled embankments, geo-reinforced sand columns, etc.

Salvatore Miliziano, PhD, is Professor in Advanced Soil Mechanics, Director of Second Level Master in Geotechnical Design and Member of Teaching College of PhD Course in Structural and Geotechnical Engineering of Sapienza, University of Rome. His research activities span from theoretical studies to practical applications. He is the author of more than 100 scientific papers published in national and international journals and conference proceedings. Salvatore is scientific head of several research projects at Sapienza University involving, among others, several tunnelling projects worldwide. He is founder and shareholder of the engineering company Geotechnical Design Group. He is also founder and president of Geotechnical and Environmental Engineering Group (GEEG), an innovative start-up of Sapienza. GEEG was set up with the aim of sharing the results of years of applied research in mechanized tunnelling field with all stakeholders. Salvatore developed advanced multidisciplinary knowledge in his 30-year career as civil and geotechnical engineer in the design and construction of engineering project in Italy and worldwide. Referring to tunnelling, he is an expert in the design of tunnels (both mechanized and conventional). He is a member of the Scientific Board of the Italian Tunnelling Society and Editor of *Tunnels and Large Underground Works Journal*.

Daniele Peila graduated cum laude as Mining Engineer in 1987, at Politecnico di Torino where, after a period as a field engineer in construction firms, he become research assistant first and then professor. He presently is Full Professor at Politecnico di Torino teaching ‘tunnelling’ and ‘reinforcements of soil and rock’. He is Director of the Postgraduate Master Course on ‘Tunnelling and Tunnel Boring Machines’ and chair of the laboratory ‘Tunnelling and Underground Space’.

He has been vice-president of International Tunnelling and Underground Space Association and, presently, acts as vice-president of Italian Tunnelling Association and a member of many editorial of international journals.

His fields of specialization are tunnelling (conventional and mechanized), mining and rockfall protection. In these fields, he acted as person in charge of many research projects and is the author of more than 250 papers published on both

international journals and congress proceedings. Furthermore, he is often called upon to give worldwide lectures and seminars for events organized by international universities as well as by cultural associations and to act as keynote speaker.

Andrea Pigorini is an experienced mining engineer who has been working for more than 30 years in design and construction of important infrastructural projects in Italy and abroad, with a specific deep experience in tunnelling and underground works.

He formerly worked in construction companies, and he completed his professional background, working for a leading geotechnical engineering company, where he was in charge as designer and project manager of several road, railway and metro tunnelling projects.

He has been working at Italferr since 2002, and he has been responsible for the Tunnelling Design Department from 2002 to 2015, and since 2015, he has been responsible for the Civil Infrastructural Engineering Department. From 2011 to 2017 he was also involved in the construction of the Brenner Base Tunnel, as project manager in charge of the supervision of the works of two construction lots.

Since 2013, he has been the President of the Italian Tunnelling Society, a scientific association sharing technical and scientific knowledge in engineering, design and construction of tunnels and underground works.

He has carried out several training sessions on tunnelling, and he has been the author of several papers on tunnel design and construction aspects, published in technical journals and international/national congress proceedings.

Enrico Maria Pizzarotti graduated at Politecnico di Milano in 1983. He has over 35 years of experience in planning and consultancy of large underground and geotechnical works, including both conventional and mechanized tunnels, underground caverns and stations, also in urban area, among which is the Brenner Base Tunnel (Italian side). He is Chairman of the BoD, Legal Representative and Technical Director of the engineering company Pro Iter S.r.l. based in Milan and a member of the ExCom and SG of SIG, of which he is the animator of the Working Group 2 – Research. He has been speaker in numerous seminars and conferences and is the author of numerous articles and technical publications and a co-author of the book *Engineering Geology for Underground Works* (Springer 2014).



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Introduction

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I.1 HISTORICAL OVERVIEW

Tunnels were ‘invented’ by man in the Stone Age to mine orebodies and have then been improved over the centuries to meet a large variety of economic, military and social needs. For example, the hydraulic tunnel of Eupalinos, on the Greek island of Samos, excavated more than 2,600 years ago and 1,250 m long, was bored to provide water to the fortified city. As is well known, there are numerous Roman tunnels to install services, such as for aqueducts, to remove waste waters, to drain wet areas and to allow a way through mountains, as shown in Figure 1.1. The genius Leonardo da Vinci clearly guessed the potential of tunnels for solving transportation problems in urban areas and improving urban livability. By designing his ideal city after the plague that caused an enormous number of fatalities in Milan, he promoted the use of the underground space for the transport of goods and for the supply of clean water and removal of waste water:

Per le strade alte non de’ andare carri [...] anzi, sia solamente per li gentili uomini; per le basse devono andare carri ed altre some ad uso e comodità del popolo. [...] Per le vie sotterranee si de’ votare destri, stalle e simili cose fetide (along upper roads trucks should not travel [...], these should be reserved for noble men, in the lower roads trucks and other things needed by the people should go [...]. Underground, toilets, stables and similar dirty things should be realized).

(Manuscript B – Institut de France, Paris, written between 1487 and 1490)

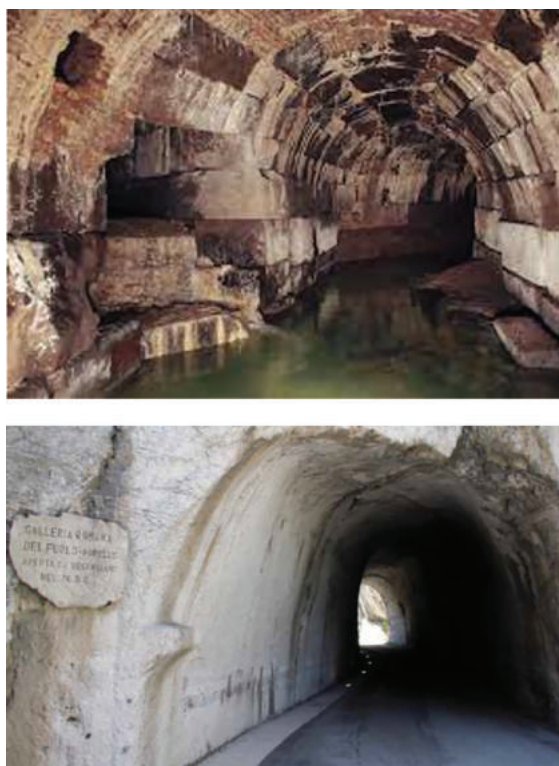


Figure 1.1 Cloaca Maxima (Rome) (above), a 600-metre-long tunnel constructed in Rome between 400 B.C. and 578 B.C. with the purpose of draining the wet areas north of the Palatine Hill, and the Furlo Tunnel, still in use, opened by Emperor Vespasiano in A.D. 76 (below).

Today, the use of underground space and tunnels, in both urban and extra-urban areas, is systematic: to cross natural obstacles, to improve the transport networks (rails, railways, metro and pedestrian) and for an incredibly wide number of applications. The modern success of the use of tunnels is also due to both their resiliency and durability, since, compared to other surface infrastructures, they are intrinsically protected against natural hazards such as floods, rockfalls, earthquakes and atmospheric action.

Generally speaking, tunnelling is the engineering process, very often implemented for transportation purposes, that, by means of the removal of large volumes of soil/rock from their original underground position, allows the creation of an underground void characterized by one prevalent dimension and a predefined cross section. The final product of the process consists in obtaining a tunnel that is capable of fulfilling, over a prescribed period of time, the provision of the necessary maintenance works, and the specific use for which it was planned and designed. This goal is achieved by considering a set of predefined ‘constraints’, strictly related to the specific site, and by minimizing both the time and costs of construction.

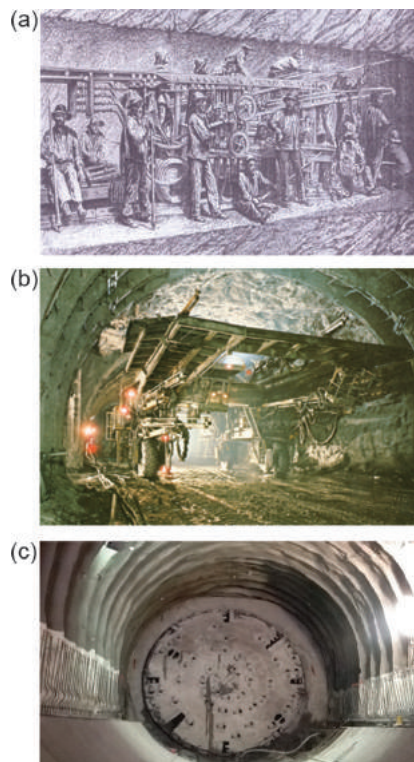


Figure 1.2 One hundred and fifty years of evolution of excavation techniques. The pictures show three Alpine tunnels close to each other: (a) Sommeiller's drilling device used in the excavation of the first Frejus Railway Tunnel (1857–1871), (b) the drilling device used for the excavation of the first Frejus Road Tunnel (1975–1979) and (c) the full-face TBM for the excavation of the second Frejus Road Tunnel (2011–2014).

With time, engineers have introduced solutions: to make the excavation safer for workers, the number of which, owing to more and more efficient mechanization, has also been progressively reduced; to safely excavate in more and more variable and 'poor' or potentially dangerous geological environments; to reduce costs and construction time; to improve the durability of the works; and, finally, to improve construction sustainability. Figure 1.2 makes clear the progressive improvements in mechanization in the excavation process that have taken place in the past decades: the three pictures refer to tunnels excavated nearby in three different epochs.

Generally speaking, tunnel engineering requires:

- an optimal merging of the design phase processes,
- the management of the construction/technological phases,
- a good knowledge of how the various techniques have been implemented in similar case histories.

In this editorial project starting with this volume, all these three different points of view are tackled. In fact, the second volume is mainly focused on the technological construction aspects and the third one provides a comprehensive overview of construction case histories.

For a long time, tunnelling has been seen as an art: both designers and builders had to be capable of accepting and dealing with the unpredictability of both geological and geotechnical conditions. They had to tailor their tunnel design to the current needs, these being discovered during construction and often evolving with each advancing step. Any inadequacy of their knowledge implied that the tunnel design would develop only during the tunnel construction. Today many things have changed, however, and no client is willing to accept the amount of time and the costs that would be needed to build tunnels without the help of a modern design approach, as well as modern excavation and supporting techniques. Moreover, no one can now accept the safety level that was associated in the past with tunnel construction. At the same time, although today's tunnels are larger, longer and deeper (or, in urban areas, shallower under surface structures), designers and construction engineers must manage the complexity of tunnelling within defined costs and time.

Numerous challenges are faced by designers. These are mainly related to:

- the stability of both face and cavity,
- settlements induced by the excavation,
- safety during construction and operations,
- the quality of the final product,
- the feasibility of the construction process so markedly influenced by the hydro-thermo-chemo-mechanical behaviour of the natural soils and rock mass formations to be excavated.

Nowadays, a modern tunnel design protocol has to be based on suitably detailed geological and geotechnical studies (Chapters 3 and 4). This is necessary, as today numerical codes and sophisticated constitutive relationships allow, in most geological and geotechnical environments, reliable three-dimensional stress–strain analyses of the excavated soil/rock mass to be performed (Chapter 9): only a reliable preliminary investigation phase can provide the necessary and correct information for a rational and effective design. For this reason, the risk is still greater in all geological environments where investigations and previsions are more difficult, as in the case of long and deep tunnels (Chapter 7). As observed by Lunardi (2008),

there are no tunnels easy or difficult because of the overburden or the ground to be tunneled, but only stress-strain situations in the ground in which it is, or is not possible to control the stability of the excavation, which will depend on our knowledge of the pre-existing natural equilibrium, on the approach to the design and on the availability of adequate means for excavation and stabilization.

Moreover, the design of an underground work should be developed according to the 'philosophy of doubt' (Pelizza, 1998; Barla & Pelizza, 2000), that is to say to find, on

the one hand, the structural solution that minimizes the risk and, on the other, the construction technologies capable of dealing with them under safe conditions: it is necessary to assess and critically verify all the possible hazard scenarios. Therefore, tunnel design is basically a multi-stage decision (Chapter 2), where each decision deals with the uncertainties associated with a certain degree of residual risk.

1.2 DESIGN APPROACHES

During the past decades, different approaches have been used for design and construction, strictly linked to the upgrading and development of design tools, and excavations and means of support in conventional excavation. Starting from the traditional excavation by drilling and blasting in rock masses, the evolution of design and excavation techniques in more complex and poor ground has been great.

From the late 1800s, the Sequential Excavation Method was used: this multiple-drift tunnel construction technique was based on the design concept that a smaller excavation volume was easier to support by employing the poor supporting means available at that time (mainly wood). In the 1950s, the New Austrian Tunnelling Method was introduced (still used nowadays in several circumstances): this uses partialized face excavation and suggests multiple methods of excavation and means of support, to be tailored to the rock mass classification. This took good advantage of the use of shotcrete and bolts as readily available supports for excavation. In Italy, since the 1980s, the systematic use of pre-confinement and pre-support interventions (also named pre-reinforcement interventions) ahead of the tunnel face has become standard and has evolved in a design approach (named Analysis of Controlled Deformation in Rocks and Soils, or ADECO-RS). According to this approach, the unsupported, always full-face, tunnel core-face mechanical response (forecast of extrusions, pre-convergences and convergences) has to be three-dimensionally studied, the excavation operations and supports (Chapters 8–10 and Volume 2) have to be designed by performing three-dimensional analyses considering and using the core-face, improved if necessary by means of an adequate pre-confinement and/or reinforcement actions/interventions, as a stabilization tool, the monitoring, to be carried out during and after construction, has to be designed, and during construction, the design has to be updated (according to the project), by considering monitoring data in terms of deformation phenomena of core-face, cavity and ground level. This approach has widely been used for the construction in Italy and all around the world of more than a thousand kilometres of underground infrastructures. This also ensures reliable design predictions in terms of construction times and costs and improves the safety of workers. The wide use of this approach has pushed forward the development of new technologies and equipment, to install reinforcing elements in the core-face also for large lengths, and boosted the excavation of tunnels with a full section.

The greater the need for tunnel construction to deal with difficult stress–strain situations, the more important it is to operate with nearly circular full-face excavation rather than in a partialized face: this allows the invert lining to be built close to the excavation face and therefore a full round structural section to be achieved close to the

tunnel face, better controlling the rock mass deformation. The extrusive phenomenon of the core-face is directly responsible for the evolution of the subsequent cavity convergence phenomena, and therefore of the tunnel's stability. The convergence is thus the last stage of the deformation response due to excavation, which begins upstream of the excavation face, due to the extrusive behaviour of the core, and then evolves into pre-convergence, which can increase and amplify the convergence downstream of the tunnel face itself (Lunardi, 2008, 2015).

At the same time, since the 1970s, there has been great development of the use of full-face TBMs (Tunnel Boring Machine). These started from gripper TBMs, able to excavate stable rock masses, and evolved to shielded TBMs, which are also able to apply a pressure at the face to counterbalance the water pressure and the soil pressure by means of different types of fluids. The excavation by means of shielded TBMs allows control of the deformation around the tunnel both at the face (with the applied pressure in the bulk chamber) and at the cavity, with the immediate support action of the shield and of the continuous installation of the full round segment lining, put in place inside the shield tail, close to the tunnel face.

1.3 GEOMETRY OF TUNNELS, LAYOUT AND ALIGNMENT

As previously mentioned, tunnels are built, as far as the alignment is concerned, with the final objective of being as short as possible and overcoming natural/anthropic obstacles. Tunnels have a prevalent longitudinal dimension and a transversal section, the size of which is strictly related to the use of the tunnel (inner section) and to the tunnel's structural design (excavation section) (Table 1.1). The longitudinal profile is strictly related to the access point elevation, but is also influenced by construction requirements. For instance, in the case of long conventionally excavated tunnels, to minimize the tunnel construction time, lateral adits are needed every 3–5 km. The longitudinal profile has also to take the tunnel use into account: railway tunnels are usually characterized by gentle slopes, varying from less than 1%–2%, while road tunnels may reach 5%–10%. Water management should also be considered so as to provide a natural water flux and avoid the need for pumping stations. In some cases, for long tunnels driven from both portals, humpback tunnels could be a solution to manage large amounts of water during construction. Higher slopes can be reached in rack tunnels (up to 20%–30%) and in hydraulic or service tunnels, these latter characterized in some cases by a vertical inclination (shaft). A transversal section may require a horseshoe excavation shape to reduce the tunnel excavated volume and guarantee available operational space in the tunnel crown (needed for electric traction and ventilation equipment for railway and road tunnels). On the other hand, a circular shape excavation section, despite the increment in the tunnel excavated volume, guarantees optimal management of high geotechnical and hydrostatic loads. Horseshoe shape tunnels may or may not have an invert depending on the ground properties: for example, recent Italian railway standards and codes indicate the invert as mandatory, to guarantee tunnel stability under any geotechnical condition and to avoid potential settlements in the railway embankment. Modern full-face machines are able also to excavate circular tunnels with very large diameters, and different layouts can be used to optimize the use of the section to host several utilities and transportation means in the same section (Table 1.2).

Table 1.1 Different tunnel functions, excavation methodologies and transversal sections (# refers to the number in Figure 1.3)

#	Project name	Tunnel function	Tunnel excavation methodology	Inner section data	Structural section data
1	Italian State Railway Standard Codes	Railway tunnel Single track $V \leq 200$ km/h	TBM	Radius 4.0 m	Excavation area 65 m ² Excavation radius 4.55 m Segment thickness 40 cm
2	Italian State Railway Standard Codes	Railway tunnel Double tracks $V \leq 200$ km/h	Conventional	Radius (crown and sidewalls) 5.4 m	Excavation area 112 m ² Preliminary support 20 cm Final lining (crown and sidewalls) 60 cm Final lining (invert) 70 cm
3	Virgolo Tunnel Bolzano – Italy	Railway tunnel Three tracks	Conventional	Radius 8.3 m (crown), 5.4 m (sidewalls)	Excavation area 185 m ² Preliminary support 20 cm Final lining (crown and sidewalls) 80 cm Final lining (invert) 80 cm
4	S. Lucia Tunnel Florence – Italy	Highway tunnel	TBM	Radius 7.15 m	Excavation area 201 m ² Excavation radius 8.0 m Segment thickness 55 cm
5	Santa Caterina Tunnel Sicily – Italy	Road tunnel	Conventional	Radius 6.45 m (crown and sidewalls)	Excavation area 154 m ² Preliminary support 30 cm Final lining (crown and sidewalls) 90 cm Final lining (invert) 100 cm
6	Eurasia Tunnel Istanbul – Turkey	Double-deck road tunnel	TBM	Radius 6.0 m	Excavation area 147 m ² Excavation radius 6.85 m Segment thickness 60 cm
7	Green Line Doha – Qatar	Metro tunnel	TBM	Radius 3.1 m	Excavation area 39 m ² Excavation radius 3.5 m Segment thickness 30 cm
8	Gibe III Hydroelectric Project Ethiopia	Hydraulic power tunnel	Conventional	Radius 5.5 m	Excavation area 140 m ² Preliminary support 10 cm Final lining (crown and sidewalls) 70 cm Final lining (invert) 80 cm
9	Stad Ship Tunnel Norway	Boat tunnel	Conventional	Height 49 m Width 36 m	Not available

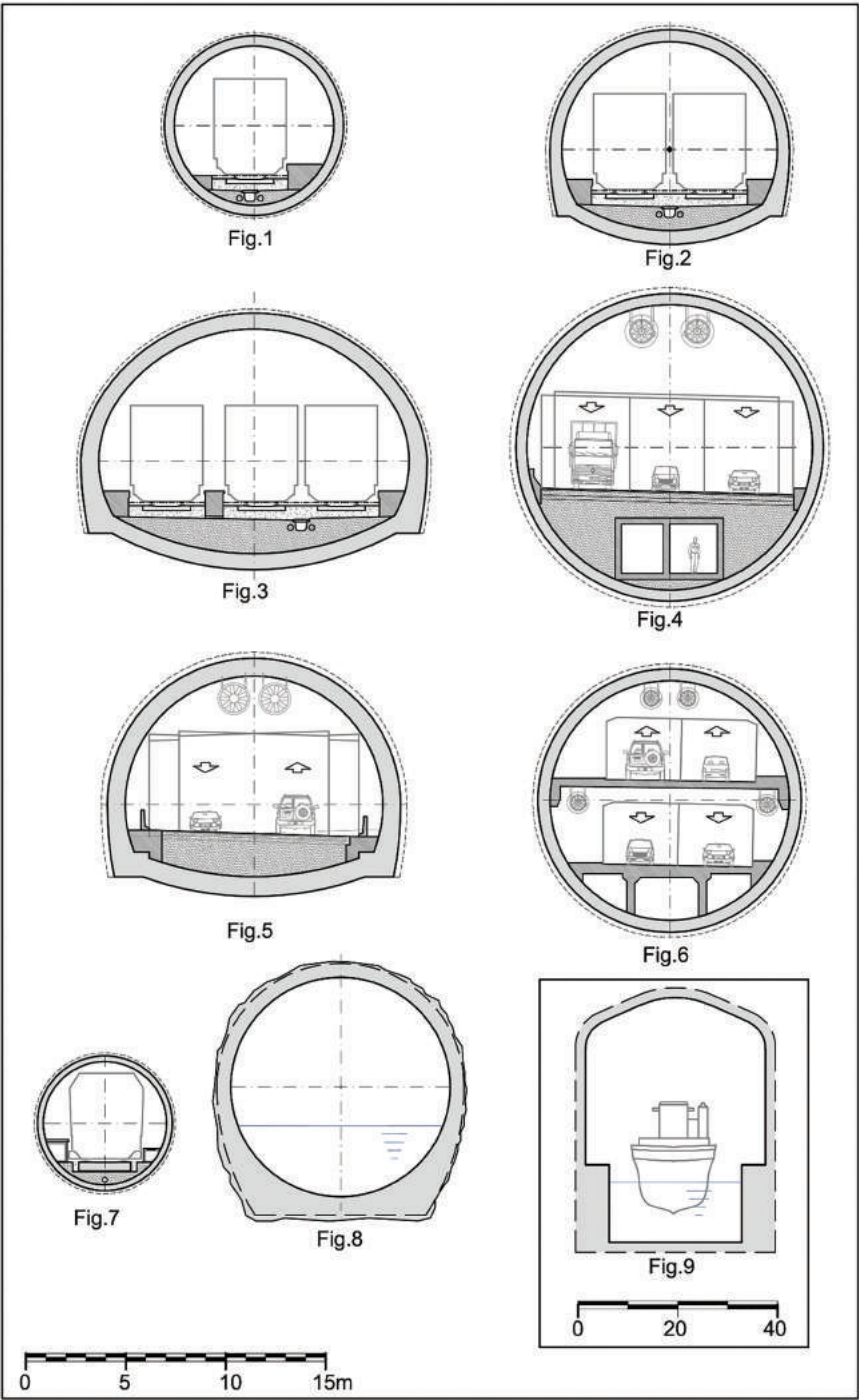
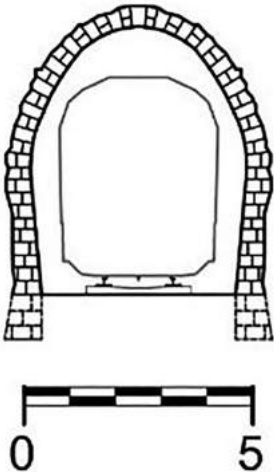
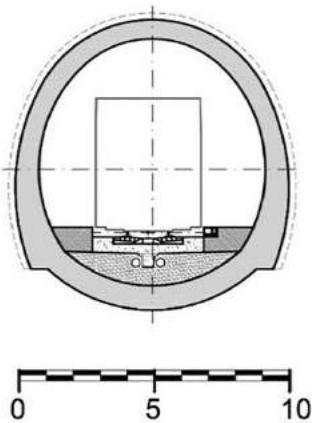
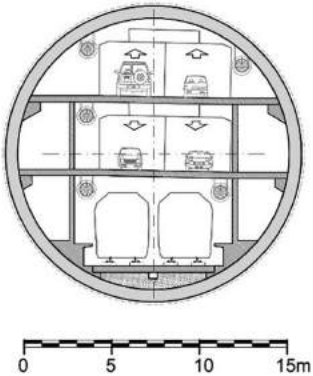


Figure 1.3 Section sketches according to Table 1.1.

Table 1.2 Different tunnel transversal sections – horseshoe without invert, polycentric with invert and circular shape (measurements expressed in m)

Project name	Tunnel function	Section peculiarity	Section sketch
Porrettana Railway Line (1864) Bologna–Florence Italy	Railway tunnel	Horseshoe shape tunnel without invert	
High-Speed Railway Tunnel Milan–Genoa Italy	Railway tunnel	Polycentric shape tunnel with invert	
Kat 3 Tunnel Istanbul Turkey	Mixed traffic Metro and road tunnel	Circular shape tunnel	

1.4 MANAGEMENT OF THE DESIGN PROCESS

The management of the design process of an underground work, passing through the different design phases and ending with the construction phase, plays a key role in the successful construction of an underground infrastructure. Costs and construction time are the pillars to be monitored and compared during the design process. From the very initial design stages, different alignments and different infrastructural solutions (requiring natural/artificial tunnels or open work stretches) have to be compared, by means of a multi-criteria analysis, so as to consequently perform the risk management on the chosen alignment, allowing the project managers to take full control of the decision-making process. The design process is usually divided into different design phases, starting from feasibility studies and preliminary design, passing through the detailed design phase, delivered for construction and ending with the tunnel construction (for-construction design). For each design phase (feasibility studies, preliminary, detailed and for-construction design), together with the project drawings and reports, the evaluation of costs and time is mandatory. Range and parametric construction costs and time are generally used for such an estimation in the early design phases (feasibility studies and preliminary design). On the contrary, a detailed bill of quantities and a detailed construction time estimation are used for detailed and for-construction design. For estimative computations, to take into account properly the cost level foreseen by the client for each specific work, cost lists should be provided by the client to the designer and the designer will provide his cost estimation by including production rates for materials, manpower, equipment and sustainability analysis.

The decision strategies, corresponding to the so-called conceptual design, may be implemented by employing probabilistic risk/statistical analyses, which offer the possibility of quantifying the project reliability by mathematically modelling the variability and uncertainty of the key parameters involved, and assessing the impact of parameter variations on time and costs (Chapter 7). Realistically, in tunnelling risks cannot be totally avoided and the detailed design should be developed on the basis of reducing risks. Nowadays, there is a need to manage the design process more efficiently, comparing the various alternatives from the very beginning, thus allowing the project managers to take full control of the decision-making process and construction process, rather than employing reactive crisis management, without disregarding the communication processes with the stakeholders and the populations involved in the construction (Chapter 13). It is clear that all the design choices require a set of basic information related to the tunnel's functional requirements, defined by the client according to the scope for which the tunnel is to be built; the geological and geotechnical properties of the ground encountered by the alignment (Chapters 3 and 4); the constraints due to the local environmental conditions (Chapter 5); and health and safety issues during construction (Chapter 6). The available design tools are used by the engineer to forecast the behaviour of the ground and its response to the excavation process, and to minimize the hazards by applying suitable countermeasures (Chapter 7).

In the early design phase, the excavation methods, the support tools and technologies, and the available ground reinforcements and improvement techniques have to be accounted for and critically compared, with the aim of checking their advantages and disadvantages with reference to the specific geotechnical context of the project

(Chapter 8 and Volume 2). Structural section types have to be defined, and preliminary calculations have to be performed by using simplified approaches. For the final detailed design, each structural section of the tunnel should be verified by using suitable computational methods (Chapter 10). In the past, tunnel design approaches were mainly focused on estimating the magnitude and distribution of loads applied to the tunnel supports and then individuating a lining capable of bearing these loads. Today, the design process starts from the identification of the main hazard scenarios and its development is governed by the aim of addressing and managing them. Therefore, nowadays the design is aimed not only at preventing catastrophic collapses and excessive loads on the structures, but also at ensuring structural durability throughout the tunnel's service life, by considering long-term hydro-chemo-mechanical phenomena and accidental loads (such as fire and earthquakes), without disregarding the influence of the construction method on the stability and final quality of the tunnel, and also by designing a proper maintenance and refurbishment policy (Chapter 12).

In conclusion, the designer has to assess what is the goal, in terms of risk reduction related to each mitigation measure (that is, the engineering design process), and then to discuss how to achieve, from the technological point of view, that goal (technological choices and design). Observation and monitoring during work (Chapter 11), which have also to be defined in advance for the specific project, allow the detection of any deviations of the tunnel's progress from the expected behaviour and therefore the adjustment of the project by applying the foreseen designed countermeasures. This procedure has to be considered as a planned design method, named the observational method (Chapter 10), and to be seen as a strategic approach for the management of the risks and for minimizing construction time and costs.

AUTHORSHIP CONTRIBUTION STATEMENT

The chapter was jointly developed by the authors.

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