1 Introduction

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Abstract

This book summarizes the main results from research performed within the Collaborative Research Center "Interaction Modeling in Mechanized Tunneling" installed at Ruhr University Bochum, Germany. Topics being covered include all relevant aspects of mechanized tunneling ranging from digital design to steering support during tunnel construction. One subject area is concerned with the characterization and modeling of ground conditions, advance exploration methods as well as face support measures. A second subject area covers novel segmental lining designs with enhanced robustness and the interaction between the grout and the surrounding soil. A third subject area is concerned with computational simulation of tunnel advancement, logistics and excavation processes including monitoring strategies and digital models for real-time support of TBM construction. Finally, risk analysis and tunnel information modeling are completing the large range of topics. The individual research topics are each supported by computational models, experimental research and in situ monitoring.

In order to meet the growing demand for an efficient and environmentally friendly transport infrastructure, the use of the subsurface is often without alternative. Major projects, such as the Alpine transversals (e.g. Brenner Base Tunnel), but also the construction or expansion of inner-city underground transport lines to reduce the above ground traffic illustrate the growing importance of tunnel construction, as can be vividly seen in Fig. 1.1.

Mechanized Tunneling has proven itself as an economical and flexible construction method that continues to undergo a dynamic evolution process; shield diameters are con-

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G. Meschke et al. (Eds.), *Interaction Modeling in Mechanized Tunneling*,
https://doi.org/10.1007/978-3-031-24066-9_1

Fig. 1.1 Metro-systems improving the quality of life in urban areas: Example Vienna before [Source: https://de.wikipedia.org/wiki/Kärntner_Strasse] (left) and after (right) completion of the metro system in the city center [Source: https://commons.wikimedia.org/wiki/]

stantly increasing (an example can be seen in Fig. 1.2, right), and the range of scenarios in which tunnel boring machines are deployed is continuously expanding, from clays to granular soils to highly fractured or monolithic rock masses, from partially to fully saturated ground, and from alpine mountain ranges with high overburden pressures to sensitive urban areas with low overburden (Fig. 1.2, left). Today, the application range of tunnel boring machines is being extended to an ever increasing variety of geotechnical conditions.

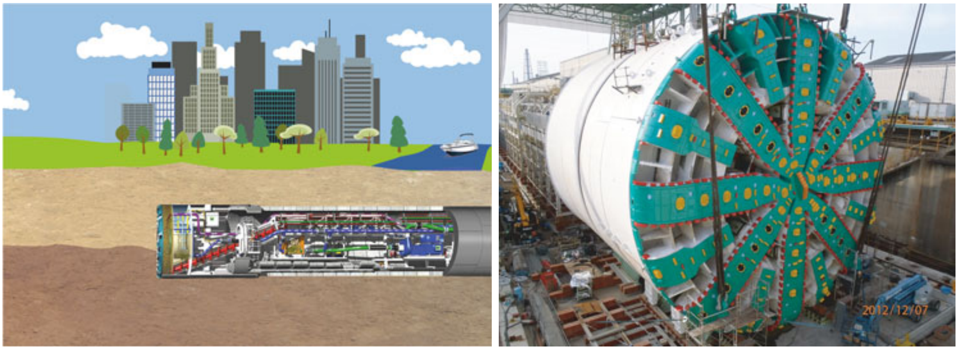

Fig. 1.2 Illustration of mechanized tunneling in urban areas (left), breakthrough of a 17.5 m Tunnel Boring Machine in Seattle [Source: Washington State Department of Transportation (WSDOT) – https://www.flickr.com/photos/wsdot/8260834957/] (right)

Mechanized tunneling is characterized by a number of advantages over competing tunneling methods. As a result of the shield casing, a high level of work safety is guaranteed; due to the prefabrication, a high quality of the segment elements can be ensured and the intended tunnel profile is maintained with great accuracy, without unintended additional excavation. In addition to very high investment costs, these advantages are offset above all by a lack of flexibility with regard to adjustments during tunneling to changing ground conditions, e.g. marl-limestone alternating bedding or difficult geological conditions, such as swelling clay rock.

The reliable, economical and environmentally compatible planning and construction of tunnels on the basis of mechanized driving requires reliable knowledge of the expected effects of tunnel driving on the existing infrastructure and environment, but also of the effects of the geological conditions or existing infrastructure on the tunnel driving process. The generally heterogeneous geological conditions and the often only vaguely detectable ground properties place special demands on prognosis models compared to other engineering tasks. However, such models are indispensable for limiting driving-related risks during the planning and driving stages, especially in the case of difficult geological and tunneling conditions and special boundary conditions, for example, when tunneling underneath existing buildings.

Research goals Heterogeneous geological conditions and often only approximated ground parameters create, in contrast to other engineering projects, special challenges. These circumstances and the constant expansion of the range of deployment of shield-supported tunneling as well as the tendency to always larger shield diameters demand the exploration of new problems that can only be effectively solved through truly interdisciplinary research. Open problems demanding fundamental research arise in almost all aspects of the mechanized tunneling process. Examples are the characterization of the ground properties ahead of the tunnel face, the efficiency of the face support pressure in Earth Pressure Balanced, slurry or variable density machines, the actual mechanism in which the support fluids infiltrate the ground, tool wear, the efficiency of the cutting process in heterogeneous ground conditions or the optimization of design and construction processes based on real-time interactive digital tools. Understanding the relevant aspects and components of the mechanized tunneling process and their interactions is a prerequisite for developing new concepts and improved technological solutions.

Due to the high degree of automation and the interlocking of a large number of subprocesses and components, malfunctions and the failure of individual components often cause delays in the process or even complete shutdowns. On average, tunnel boring machines achieve only 30%–50% of their theoretical performance capacity (Fig. 1.3, left). Deficiencies in design are among the most common causes of failures in underground construction (Fig. 1.3, right).

This and the constant expansion of the range of deployment of shield-supported tunneling to various ground conditions, the tendency to ever larger shield diameters and the strict

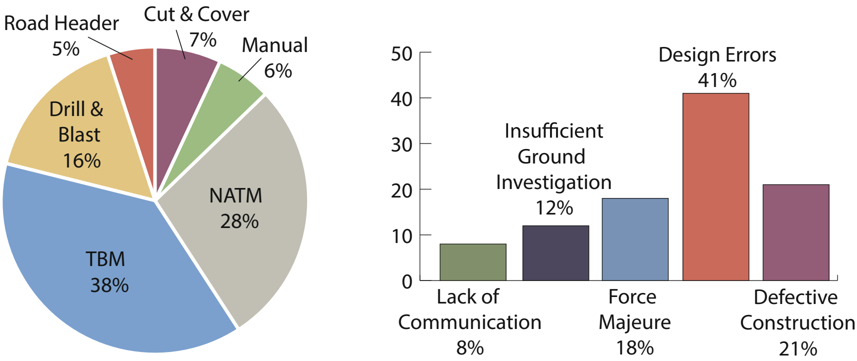

Fig. 1.3 Causes of damage in mechanized tunneling [redrawn according to N. Bilgin, H. Copur & C. Balci. TBM excavation in difficult ground conditions: Case studies from Turkey, Ernst & Sohn, 2016] (left); Frequency of damage events depending on the construction method [redrawn according to T.K. Konstantis. Tunnel projects: Risks exposure, risk management and insurance coverage – A realistic roadmap, Proceedings of the World Tunnel Congress 2017, 2017] (right)

requirements posed by society in regard to safety and impact on the environment during construction, sustainability of the design and durability of the constructed tunnel necessitate new insights into the manifold interactions between individual components, planning phases and partial processes involved in mechanized tunneling. Innovative solutions can only be effectively solved through truly interdisciplinary research.

The transformation to a green economy also induces a strong motivation in the underground construction sector to develop novel designs for segmented tunnel shells with less material consumption and thus a reduced CO_2 footprint of the tunnel linings without sacrificing safety or robustness. In the same spirit, innovation in the design of cutter heads and novel materials for excavation tools both lead to a better wear resistance, and thus to an improved efficiency of the tunnel advancement and less energy consumption. A key ingredient in reducing unexpected standstill in tunnel processes is the knowledge of the ground conditions ahead of the tunnel face, necessitating reliable methods of ground advance exploration.

In order to maintain low settlements, and to ensure an economically feasible as well as environmentally friendly construction process, realistic computational models are indispensable for providing reliable prognoses during the planning and construction stages of a tunnel project. These models become especially critical in difficult geotechnical environments as well as under special boundary conditions, such as driving under existing, possibly fragile constructions. A prerequisite for a reliable numerical prognosis is the assessment of the interactions between the components involved in mechanized tunneling, the surrounding site, the ground, and any pre-existing structures. To render use of complex 3D modeling feasible within a digital workflow requires a smooth integration of all interacting tools.

Digitalization The use of digital tools places specific demands on the planning processes in tunnel construction, addressing the problems generated by decentralized data management and separate submodels by adequately linking heterogeneous data sources via tunnel information models. Although information model methods were first developed to be applied to improve the organization of above-ground building projects (Building Information Models, BIM), they have been, and currently are, being extended to tunneling projects.

Standardized exchange formats such as the Industry Foundation Classes (IFC) are being developed to ensure a universal data structure, coherent data exchange and interoperability among projects partners. The capability of the Tunnel Information Model (TIM) to connect information databases and graphical representations based on parametric 3D models allows a better visualization, coordination, and management of construction projects and helps to reduce planning errors and project costs. Recent developments in software platforms for tunnel information modeling have enabled a multi-level information representation of the built environment with an adequate Level of Detail (LoD) and collaborative design, and a parameterized analysis of alternative designs (Fig. 1.4).

In the future, tunnel information and simulation models will be used interactively, beyond the visualization of project data, also by real-time analyses of route variants and accompanying risk forecasts, especially in inner-city tunnel construction. This places demands not only on the efficiency of numerical simulation models and a seamless connection to digital tunnel information and logistics models, but also on the real-time capability of complex tunneling and process simulation models.

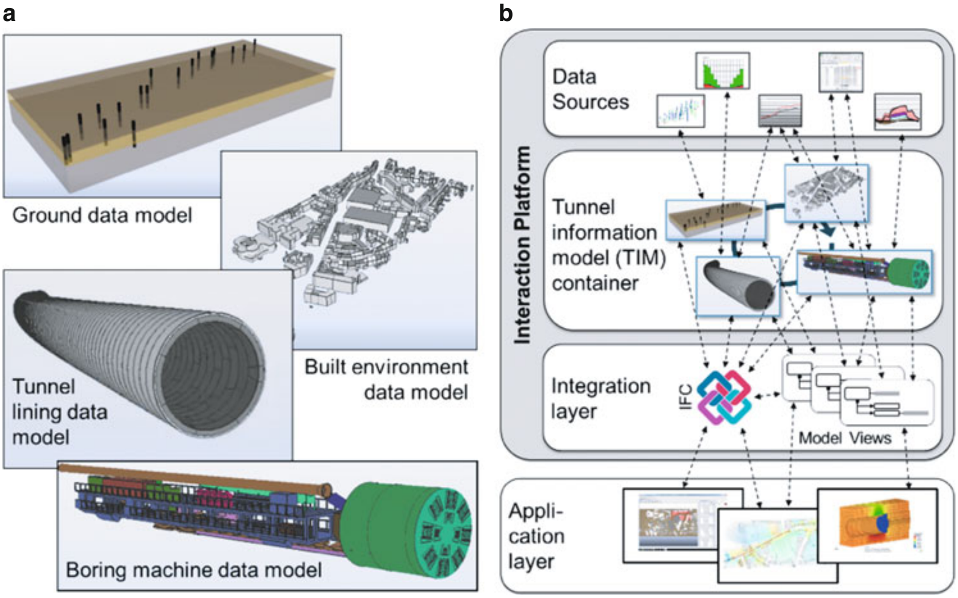

Fig. 1.4 Illustration of the tunnel information modeling framework: Main subdomain data models (**a**), the unified interaction platform and application layer (**b**)

The SFB 837 In this context, the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) established the Collaborative Research Center "Interaction Modeling in Mechanized Tunneling" (Sonderforschungsbereich 837, SFB 837) at Ruhr University Bochum since 2010. Collaborative Research Centers are interdisciplinary scientific research groups in which cooperative research is conducted under the umbrella of a central research theme. Within the 20 subprojects of the SFB 837, a range of design concepts, numerical models and new excavation technologies concerning mechanized tunneling have been developed.

While research during the initial project phases focused mainly on tunneling in soft ground, more recent research concentrated additionally on tunneling in difficult geological conditions, which nowadays sets the limits on the application range of mechanized tunneling. Among other topics, research was concerned with the exploration of significant, as yet unexplored factors that control tunneling processes in expansive soils as well as with the design of novel deformation-tolerant tunnel linings to be used in such situations. From interdisciplinary research between material scientists and geophysicists, essential insights have been gained into the wear of excavation tools and the efficiency of excavation in such difficult geological conditions. Simulation and risk models for the excavation, advancement and logistics processes developed in the SFB 837 will enable improved, environmentally-friendly and low-risk planning and construction processes. These models have been extended to enable real-time prognoses and to provide a platform for the interactive digital design of urban tunneling projects. In doing so, the SFB 837 aims to create new perspectives for innovative participative planning instruments in tunneling. Furthermore, by developing continuously updated real-time models, the SFB 837 has taken an important step towards computer-aided steering of the mechanized tunneling process.

The research goals of the SFB 837 are concerned with relevant planning and construction aspects of the many components of the mechanized tunneling process. They are organized into four project areas (Fig. 1.5). Project area A is concerned with the characterization and modeling of the in-situ ground and the disturbed ground conditions in the vicinity of the cutting wheel as well as with advance exploration methods. The topic of research in project area B is the modeling of novel segmental lining designs with enhanced robustness and the interaction between the grout and the surrounding soil. Project area C is concerned with the simulation of the advancement process and real-time prognosis methods to support the TBM steering, as well as with optimal monitoring strategies, the simulation of logistics processes and the modeling of the cutting process and the material transport into the excavation chamber. The last project area D is concerned with research on risk analysis in urban tunneling and model integration. These research themes are each supported by computational models and are all included in an SFB encompassing tunnel information model that was developed in the first period of the SFB.

Furthermore, interaction groups were formed in order to integrate and combine the results of different submodels and analyses. These originated partially through prototypical cause-and-effect relationships, and partially from applications to actual reference tunneling projects.

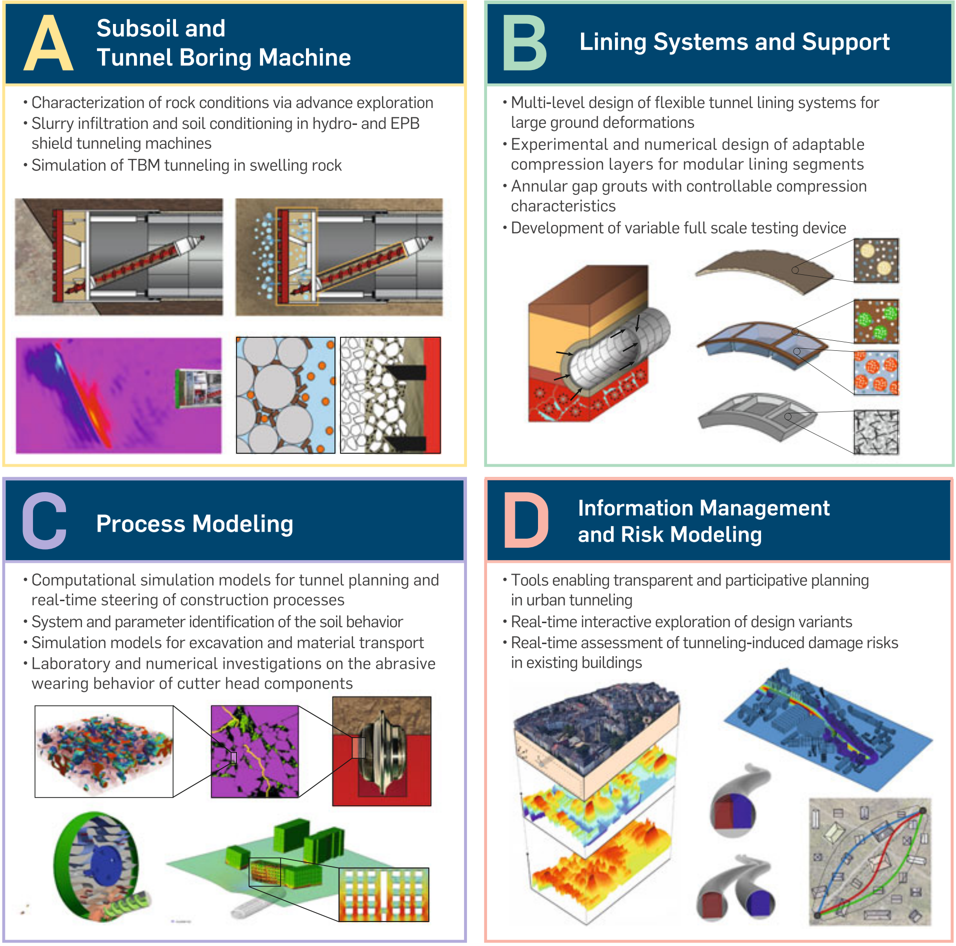

Fig. 1.5 Components and processes involved in mechanized tunneling and their representation within four project areas (A–D) in the SFB 837

Structure of the book This book summarizes the main results from the SFB 837 related to the four project areas included in Fig. 1.5:

A: Characterization of the subsoil and the face support mechanisms;
B: Lining systems and support;
C: Modeling and computational simulation of the tunnel construction processes including the excavation and logistics and
D: Tunnel information modeling and risk assessment in urban tunneling.

Evidently, research within these project areas is highly interlinked. This leads to the structure of this book, which organizes the developed concepts, methods, models for mechanized tunneling in soft ground and rock conditions as well as the findings from experimental research into 6 chapters.

Chapter 2 is concerned with the characterization of the ground ahead of the tunnel face based on geophysical exploration methods in association with computational methods for the identification of joints and obstacles in the ground.

In Chap. 3, computational models for the analysis of excavation processes at the tunnel face in soft, hard and mixed ground conditions along with the experimental and model-based analysis of wear processes in the cutting tools are presented.

Chapter 4 focuses on the analysis of infiltration processes involved in the support of the tunnel face and the material transport in Earth Pressure Balance and Hydro Shield Machines.

Chapter 5 is concerned with the design of robust- and damage-tolerant segmented linings and the experimental and model-based characterization of the infiltration and the stiffening behavior of various one- and two-component grouting materials.

Methods and models for digital design in mechanized tunneling are described in Chap. 6. Here, the Tunnel Information Model is introduced to facilitate the management of heterogeneous and distributed data and the interoperability of various submodels involved in the design process. Furthermore, computational methods for the modeling of tunnel-ground interaction within a digital workflow, and risk models for existing infrastructure are described. Combining these submodels, a method for the interactive assessment of tunnel alignment variants in urban areas is introduced.

Finally, Chap. 7 presents computational models for the support of the construction process in real-time. This concerns a real-time prediction scheme for the logistics processes and a software for the steering of tunnel boring machines considering different steering targets, such as minimizing the damage risk in existing buildings. Uncertainties, of both epistemic and aleatoric nature arising in mechanized tunneling are considered in the prediction models.