DFG Collaborative Research Centre SFB 837
Interaction Modeling in Mechanized Tunneling

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Mechanized tunneling is an established flexible and efficient technology for the construction of underground infrastructure. It is characterized by a dynamic advancement of tunnel boring technologies, increasing TBM diameters and a broadening range of applicability. This rapid development in association with the inherent heterogeneity of the underground and the uncertainty of ground parameters, poses new challenges to reliable prognosis models. Such models are indispensible for the limitation of tunneling risks in the design and construction phases, particularly for difficult conditions in terms of geology or tunneling have to be considered.

Considering this background, the subject of the new Collaborative Research Centre SFB 837 "Interaction models for mechanized tunneling" installed at the Ruhr University Bochum is the research and development of models, methods and design concepts, which, when adequately interlinked, can deal with the manifold complex interactions of the components (ground, shield machine, support measures, tunnel lining, existing buildings) and processes (advancing and excavation process, construction operation) involved in mechanical tunneling. This research centre was set up by a decision of the German Research Foundation (DFG) on 18 May 2010 and will start at 1 July 2010. Collaborative Research Centres (SFBs) are scientific competence centres where cooperative research, often in an interdisciplinary context, is supported by the DFG for periods of up to twelve years. The SFBs are evaluated every four years by a 10- to 15-person expert committee.

Objectives and research perspectives of the Collaborative Research Centre

The objective of the SFB 837 is the determination of the essential interactions between the tunnel excavation, the ground, the tunnel lining and existing structures through scientifically secured computational models and methods as well as laboratory tests. The individual partial objectives of the research project, for which four project areas have been set up (Fig. 1), are:

- To increase the reliability of the interpretation of advance investigation measures, and determine the ground properties and face stability by means of new methods and models (Project section A),
- Model-based concepts for tunnel linings and the support of the annular gap (Project section B),
- Holistic and realistic computational simulation of the excavation and tunneling processes for various geotechnical and machine-related constraints (Project section C),
- Modelling of the risk of damage to existing buildings and ensuring of the interoperability of all partial models through a consistent integration level (Project section D).

The developed computer models are highly interlinked so that, in addition to supporting the design work for a tunnel project, they will also permit real-time forecasts during construction and allow for a continuous support of the shield supported excavation process. The provision of efficient design and tunneling strategies in mechanized tunneling, and, particularly, to comply with the high quality requirements placed on the construction process and the tunnel structure, require the following:

- Realistic modelling and the integration of all relevant system components (ground, advance, lining, surroundings) for various design variants including the multitude of interactions during the tunneling process, considering variable geological conditions,
- measurements and advance investigations during tunneling and
- continuous updating of the computational models and partial models, respectively, to take into account the local conditions and constraints as they become known during tunneling.

In the SFB 837, all the essential components of mechanized tunneling in the planning, design, and construction phases are taken into account. Also considered are the ground including the advance investigations during tunneling, the tunnel boring machine, the tunnel lining including the grouting of the annular gap and the effects of tunneling work on existing structures. The associated processes (excavation, tunneling and logistics) are also depicted by numerical models and integrated into an overall information management system. These computer-supported interaction models are related to the design phase and also to the construction phase, with aspects of operation and lifetime also being partially considered. The maintenance and repair of tunnel structures, however, is not directly part of the current project.

Description of the research programme

The altogether four project sections of the collaborative research project are derived from the categorisation of the tunneling process into three sections, "Ground and Tunneling Machine", "Lining and Support Materials", and "Process Modelling" and contain, with the project section D "Information Management and Risk Modelling", a linking, inter-SFB methodical element that ensures the consideration of reliability and risk models as well as the integration of all partial models into a consistent system of information management.

The SFB 873 includes in the first phase 14 sub-projects (Table 1), which are managed by 15 scientists at the Faculty of Civil and Environmental Engineering Sciences and the Faculty of Geosciences at the Ruhr University Bochum. The overall coordination of the Collaborative Research Centre is in the responsibility of Prof. Günther Meschke, Head of the Chair of Structural Mechanics at the Ruhr University Bochum, who is supported by the members of the Executive Board (Prof. R. Breitenbücher, Prof. H. Steeb, Prof. T. Schanz, Prof. M. Thewes) and coordinator assistant J. Sahlmen. The available project budget for the first project phase is about 8 million €.

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Table 1. Sub-projects in the first phase of the Collaborative Research Centre SFB 837

No.	Description	Project Leaders
1	Ground investigation through the analysis of TBM data	Prof. M. Alber Prof. M. Thewes
2	Advance investigation concepts using acoustic methods	Prof. K. Hackl Prof. W. Friederich Prof. T. Nestorovic
3	Investigation of face stability	Prof. M. Thewes Prof. H. Steeb
4	Material models for the description of destructured soil behaviour	Prof. T. Schanz
5	Optimized structural segments for durable and robust tunnel lining systems	Prof. R. Breitenbücher Prof. P. Mark
6	Damage analyses and concepts for damage-tolerant tunnel linings	Prof. G. Meschke
7	Development of annular gap grout considering the interactions with the surrounding ground	Prof. R. Breitenbücher
8	Multi-scale infiltration models for the annular gap grout	Prof. H. Steeb
9	Process-oriented simulation models for mechanized tunneling	Prof. G. Meschke
10	System identification methods for the adaptation of numerical simulation models	Prof. T. Schanz Prof. D. Hartmann Dr. M. Baitsch
11	Model- and monitoring-based optimisation and quality assurance of the tunneling process	Prof. M. König Prof. M. Thewes
12	Simulation models for the cutterhead-ground interaction	Prof. K. Hackl Prof. G. Meschke
13	Software engineering for system integration and process interoperability	Prof. D. Hartmann Prof. M. König
14	Model-based risk analysis for heterogeneous existing structures	Prof. P. Mark

Forward and inverse modelling for seismic reconnaissance in tunnelling

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Various methods have been developed to explore the mechanical properties of soil and rock beyond the headwall of a tunnel during the excavation process using seismic waves. Most of them are borrowed from reflexion seismics and attempt to image disturbances like faults, voids or inclusions from reflected or scattered waves. Often, several simplifying assumpions are made: only one wavetype is considered (compressional waves), the medium between source and scatterer/reflector is assumed to be homogeneous or only allowed to vary parallel to the tunnel axis, wave fronts emitted from the source are spherical, and finally the influence of the tunnel itself on the wave field is ignored. In particular for shallow tunnels, the above assumptions are not valid because the medium surrounding the tunnel exhibits layering or even complex 3D structure. Moreover, the free surfaces of the tunnel have a major impact on the wavefield emitted from sources on the tunnel headwall or sidewalls. Finally, previous work has demonstrated that consideration of other wave types like shear waves, tunnel surface waves and conversions between them might be much more promising for reconnaisance than P-waves.

This paper reports on research aiming at a better understanding of wave propagation in complex tunnel environments and the development of imaging methods that account for the presence of the tunnel as well as the geological structure of the tunnel surroundings and make use of the complete recorded wavefield. We have started to use spectral finite element approaches (SEM) established in seismology to model wave propagation in the tunnel environment. Since SEM is restricted to hexahedral elements making meshing awkward in case of complicated geological structures, we have developed a nodal discontinuous Galerkin approach (NDG) which allows tetrahedral elements and hence, automated meshing in most cases. To solve the inverse problem, we rely on iterative linearized waveform inversion based on waveform sensitivity kernels. They can be calculated for any 3-dimensional reference medium and tell how the wavefield changes given a perturbation of the elastic material properties of the reference medium. Recently, we devised a way to focus sensitivity of the recorded waveforms to selected spatial regions of interest. This approach avoids solving an inverse problem and could be used to monitor whether the selected region exhibits deviations of material properties from the assumed reference medium.

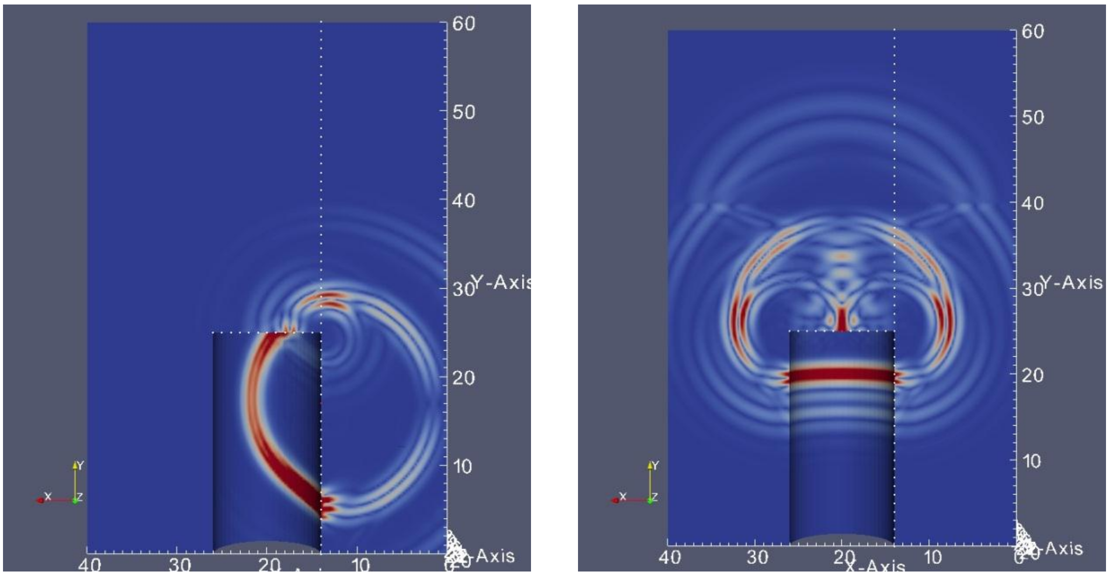

Figure 1: *Left:* Seismic waves emitted from a vertical single force acting perpendicular to the sidewall of a cylindrically shaped tunnel. *Right:* Seismic waves emitted from a single force acting perpendicular to the headwall of the tunnel. Note strong tunnel surface waves and the discontinuity at y=40 m.

Study on the load-bearing behaviour of steel fiber reinforced concrete under localized compression

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Precast tunnel lining segments are subjected to various loads during production, construction and service stages. Especially due to impact loads and local stress concentrations during construction, concrete damages, in the form of cracking and spalling, are likely to occur on the periphery of the segments. Therefore, it is necessary to improve the impact resistance and ductility of this quasi-brittle material in order to avoid the concrete damages above-mentioned and enhance the durability of the entire tunnel lining system.

By means of adding steel fibers into concrete matrix, concrete properties such as tensile strength and fracture toughness can be considerably improved, since fibers bridging the cracks can transfer the stresses across these cracks and retard the crack opening or propagation. Furthermore, the fatigue and impact resistance of the material can also be improved. Thus, fiber reinforced concrete has a distinct advantage in comparison with conventional concrete.

The main objective of this research work is to experimentally investigate the mechanical behaviour of steel fiber reinforced concrete (SFRC) under concentrated loading. To simulate the precast lining segments subjected to local forces (such as point load from the rams of the Tunnel Boring Machine during the assembly process), a specific test-setup was developed. The partial load was transmitted on the upper surface of the prismatic specimens through a steel block. By use of LVDTs the deformations of the specimens as a result of local load were measured.

Parameters controlling the behaviour of SFRC under localized compression, such as fiber type, dosage, fiber orientation, loading area and eccentricity etc., have been varied and investigated. From the experimental results, effects of those parameters on stress versus displacement, failure mode, crack distribution and width etc. were analyzed and discussed.

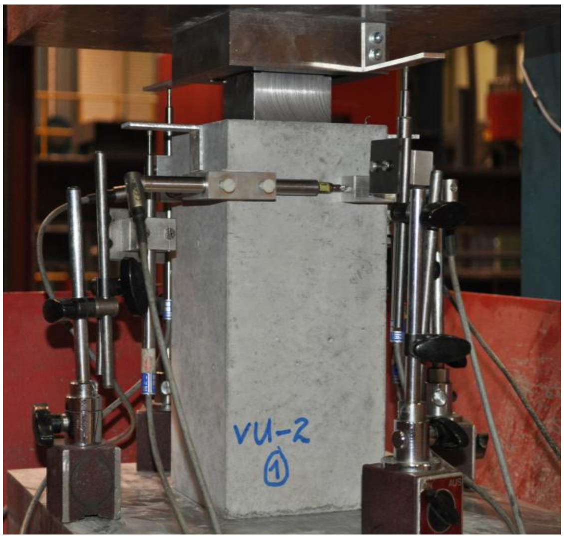

Figure 1: Test-setup for partial loading test

Figure 2: Specimen after partial loading test

A multiscale oriented modeling concept for steel fiber reinforced concrete material for numerical analysis of segmental tunnel linings

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In comparison with plain concrete, steel fiber reinforced concrete (SFRC) is characterized by significantly enhanced ductility in the situation of tension-dominant load; therefore, it is particularly effective in rigorous environment, for example in tunnel linings, where the local damage control of the segments plays an important role. In order to design and construct lining systems with optimal SFRC composite, experimental investigation is essential; in addition, numerical modeling provides powerful support, by means of fast and low-cost simulation and optimization of the material and structures.

In this research, aiming at the development of a simulation and optimization platform of tunnel linings made of steel fiber reinforced concrete, in conjunction with conventional reinforced concrete, a multiscale modeling concept is proposed (Figure 1):

- At the micro level, the pull-out behaviour of single steel fiber in concrete matrix is described by means of analytical or numerical models. The variety of the pullout problem is considered, which is parameterized by the fiber property, the concrete strength, the embedment and loading situation.
- At the meso-scale, a representative volume element (RVE) containing a number of distributed fibers is used to describe the mechanical property of the composite material. The bridging effect of a growing crack is obtained by the integration of the pullout response of all the fibers intercepting the crack.
- At the structural (macroscopic) level, applying the Embedded Crack approach with the interface law and the material property of the intact parts obtained from the analysis of the RVE, the Finite Element Method is used to simulate the structural behaviour and to capture propagating cracks.

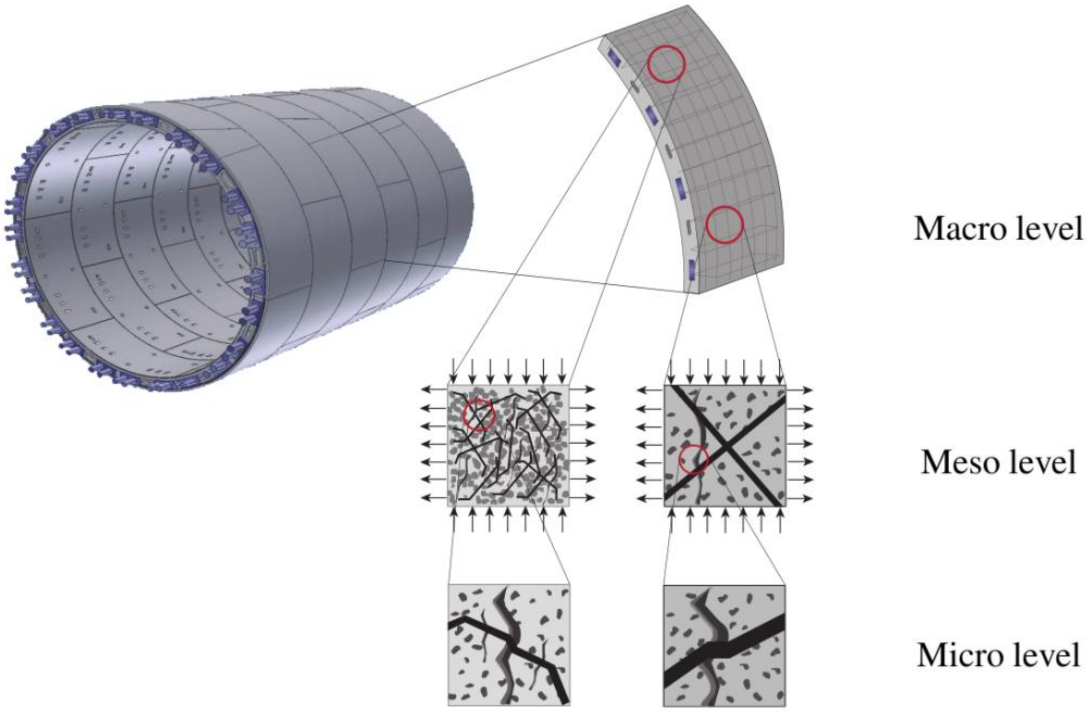

Figure 1: Multiscale modeling concept of segmental tunnel linings made of steel fiber reinforced concrete.

Simulation of the backfilling process of annular gap grouting mortar

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It is well known, that the application of a macroscopical hydraulic gradient to a fluid-saturated cohesionless soil causes seepage flow. Furthermore, the microstructure of the porous skeleton dominates the physics of infiltration processes of complex fluids (fluid & fines) and thus the evolution of the hydraulic and mechanical properties of the soil [1]. The transportation process of fines through the pore network strongly depends a) on the mentioned hydraulic boundary conditions and b) on the microscopic topology of the pore space. From a modeling point of view, approaches taking into account the macro- and the micro-scale physics are yet not well established.

The aim of this work is to develop a continuum multiphase model to describe infiltration processes for cohesionless soils. For this purpose, a Representative Volume Element (RVE) is considered and described by the continuum mixture theory extended by the concept of volume fractions (Theory of Porous Media - TPM). The thermodynamically consistent TPM is a macroscopical multiphase modeling approach, extended from classical single-phase continuum mechanics [2,3].

In the present context, we further extend the concept of volume fractions by certain distribution functions of microscopical quantities. Initially, the fluidizable fraction of the soil is determined from the Grain Size Distribution (GSD) curve [4]. Implementing this multi-scale approach into a Finite Element code, the computational expense of the method is one of the key points.

In the present contribution we discuss a specific approach which could be used in multiphase FEM models. The resulting numerical model is applied to different infiltration applications. One specific application of the proposed model is situated in mechanized tunneling. In that case, the infiltration of grout in the surrounding soil leads to the evolution of hydraulic properties of the soil and is finally responsible for deformations on the surface.

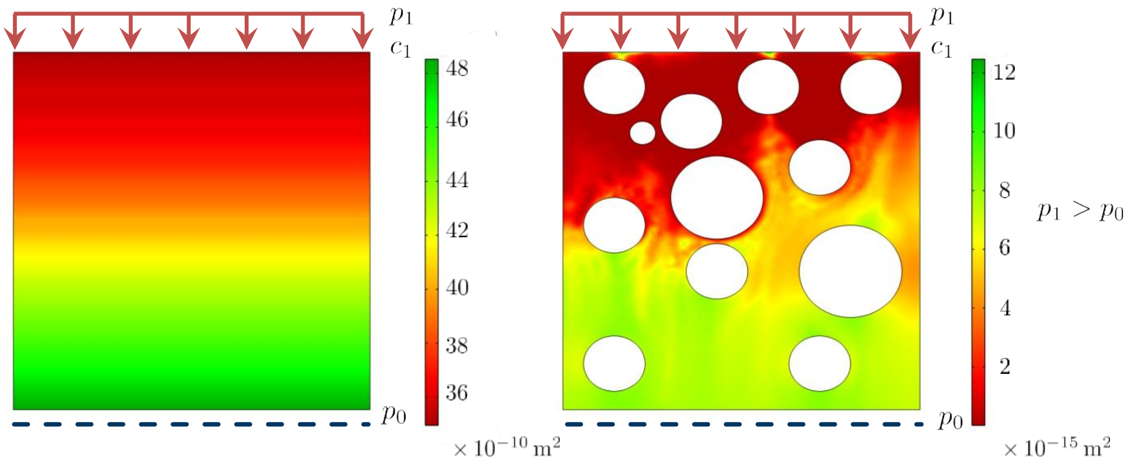

Figure 1: Distribution of the permeability $k^s(\mathbf{x})$ for a) homogeneous and b) heterogeneous domain.

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Aspects of model interaction in mechanized tunneling

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During a tunneling process, many different sub-processes like soil excavation, annular gap grouting, supply chain logistics, etc. work together to create an efficient and smooth tunneling design (see Fig. 1). In the design phase, each sub-process is investigated by its own simulation software without considering other sub-processes although strong dependencies exist. Neglecting these dependencies can result in incorrect computations which increase the risk of economical deficits or even loss of human lives. Thus, a paradigm is necessary to realize interactions between different sub-processes of mechanized tunneling. Therefore, two main components are needed, an object-oriented product model (OOPM) which is the data management component and a tunneling interaction platform to realize the interactions between the different simulations.

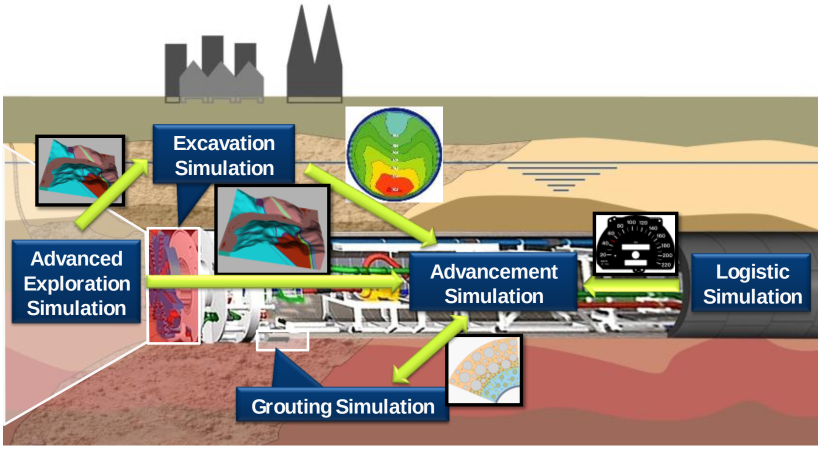

Figure 1: Exemplary interactions in mechanized tunneling

The proposed object-oriented product model consists of many individual product models whereas the three main models can be identified as Ground Data Model (GDM), Tunnel Boring Machine Model (TBMM) and Tunnel Model. So far, two of these three models have been developed, the GDM and the TBMM.

The GDM has to store all kind of ground information and create a geological model of the region where the tunnel is excavated. Additionally, one of the main requirements of the GDM and each model of the OOPM is the ability to store simulation results and process these results such that they can be reused by other simulations. Therefore, a hybrid GDM has been developed consisting of two sub-models. On the one hand, the GDM includes of a surface-based Boundary Representation model and, on the other hand, a decomposition model which consists of many small volumetric elements structured as an octree.

The TBMM has been developed using the data modeling framework Industry Foundation Classes (IFC) which is used in the Building Information Modeling field. The TBMM has to store two kinds of data, product and process data. The product data describes the TBM including a geometric representation and semantic data, such as the degree of openings of the cutting wheel, to specify individual elements. By applying existing classes and adding new classes to the IFC framework a product model for modeling tunnel boring machines has been created.

The complexity of the interactions between the different simulations mentioned above necessitates a formal description of the interactions between these simulations. The complete tunneling system is analyzed, its components are formally described and the interactions between the components of the system are described using SysML. SysML (Systems Modeling Language) is applied as a visual modeling tool to describe the semantics of the interactions between the different components of the tunneling system. SysML structure diagrams are used to describe the components of the tunneling system and the relations between them whereas the behavior diagrams describe the interactions between these components. Formal description of the interactions helps to understand the dependencies and enables improved communication between the components.

If identifying interactions and describing them formally form the first step of Interaction modeling, coupling the identified component interactions form the second step. Since there are many different types of interactions, they have been classified into common categories so that general solutions to couple them can be applied. Furthermore, the coupling solutions available are also categorized such that similar coupling solutions can be used for the interaction problems.

Process Simulation in Mechanized Tunneling

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Tunnel projects vary significantly regarding alignment, dimensions, geotechnical formations, ground water table and other factors. In addition to this, tunneling in urban area is highly influenced by the need to avoid impacts on existing buildings and infrastructure due to the excavation process. To achieve this goal, tunneling with a tunnel boring machine (TBM), having an active face support, is a very common construction method. The design and construction of a machine must consider numerous project specifications, geological conditions and of course the diameter of the designed tunnel. The very high initial costs of tunneling projects result primarily from the combination of the described degree of individual requirements, the complexity of the TBM system and the sometimes enormous dimensions. In the course of TBM projects, a change of project conditions, either evoked by unforeseen ground conditions or by deficiencies in logistical processes, is frequently observed. In case the anticipated production rate of a tunneling system cannot be maintained due to the mentioned variances in project constrains, very high follow-up costs might eventuate. For this reason, the adaption of the TBM system, which might occur at various points within the core processes or the supply chain, can be observed.

Furthermore, the sequential character of the production sequence of excavation and installation of lining entails the issue that disturbances and downtimes of single elements have significant influence to the performance of their successors. Prolongations may result from failure of machine components, wear processes, organizational deficiencies and other causes. These disturbances can have such a big impact on the TBM production sequence, that further modifications of the tunneling system become sensible.

Therefore, the overall performance of the machine is not determined by one single process, but rather to their appropriate interaction and the coordination of required supplies as provided by the supply chain. Additionally the influence of disturbances must be investigated and their occurrence reduced to a minimum by a robust and sophisticated machine design.

For this reason, a powerful tool to transparently evaluate the design of a TBM system including an adequate supply chain and to compare possible alternatives will facilitate the design phase. Although very useful to overcome the mentioned deficiencies of the design phase, computer-based simulation is currently used only sporadically to support the planning of TBM tunneling projects. Within this paper, an approach is presented to accomplish the aforementioned challenges by combination of several simulation paradigms in one simulation model of a shielded TBM. In the field of shielded machines, the Earth Pressure Balance Shield machine (EPB-shield) is the most widely used type with many recent innovations and for this reason in the focus of this publication.

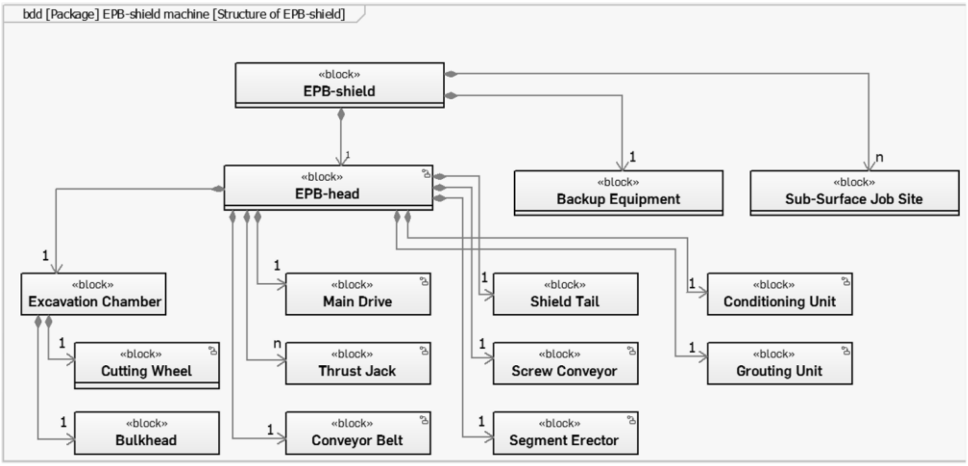

Figure 1: Block definition diagram for structural elements of an EPB-shield

Soil Conditioning for EPB-Shield Tunneling

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Earth Pressure Balance (EPB-) Shields usually use the extracted soil as support medium and were originally used in soils with a content of fines (d < 0.06 mm) of at least 30 M-% [1]. Coarse-grained soils cannot guarantee the required properties of this medium, so that the material has to be conditioned with foams, polymer foams, polymer suspensions or suspensions with a high content of fines.

In laboratory research, suitable testing methods were used to determine the main properties of conditioned soils like their workability, compressibility and water permeability. Firstly, tests were done to identify the properties of different soil-foam-mixtures. Therefore, the grain size distribution curves and foam injection ratios (FIR) were systematically varied. Based on the analysis of these tests new application ranges of EPB-Shields with foam as conditioning agent were developed depending on the grain size distribution curve of the soil and on hydrological aspects. In addition to laboratory research with soil-foam-mixtures, tests with different soils and conditioning agents (polymers, polymer suspensions, suspension of fines and combinations of these agents including foam) were done, the properties of the support medium determined and application ranges estimated.

This laboratory research leads to new application ranges for EPB-Shields in coarse-grained soils based on systematical and reproducible test methods. The results of this laboratory research are a step towards making the use of Earth Pressure Balance Shields in coarse-grained soils more efficient.

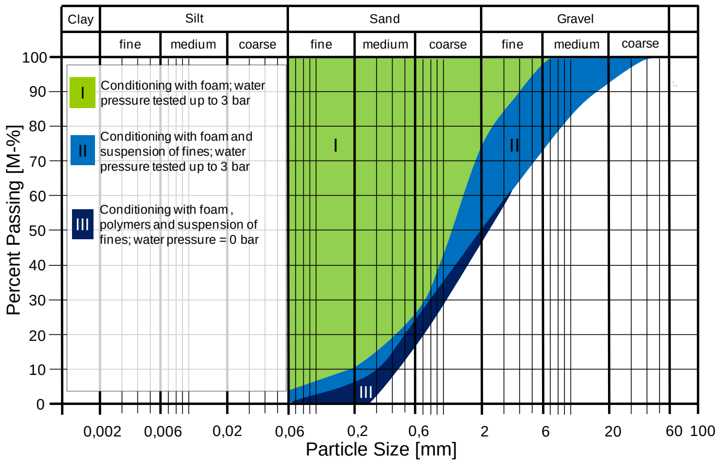

Figure 1: Application ranges for EPB-Shield based in coarse soil based on laboratory research [1]

Different methods were used for laboratory research to determine the main properties of conditioned cohesionless soils with adequate conditioning agents. Tests with soils with widely varied grain size distribution curves and different conditioning agent were carried out. Mainly, the workability, compressibility and water permeability of the support medium are important to define the application range of EPB-Shields in coarse-grained soils. A large number of tests were done with different soils using foam, polymers, polymer suspensions and suspension of fines as conditioning agent. The analysis of the test results lead to an extension of the application ranges of EPB-Shields. Modified application ranges for EPB-Shields in coarse-grained soils based on laboratory research were developed [2].

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