PROCESS ORIENTED NUMERICAL SIMULATION OF MECHANIZED TUNNELLING USING AN IFC-BASED TUNNEL PRODUCT MODEL

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ABSTRACT: *The use of underground space is a prerequisite for maintaining mobility and infrastructure in today's crowded urban areas. In order to minimize risks and mitigate hazards, reasonably accurate numerical simulations of the tunneling process are required. The authors have previously proposed a comprehensive process-oriented 3D finite element simulation model. Information on tunnel projects, however, is usually only available in a heterogeneous and dispersed form, preventing complex simulation models from easily being employed in practice. In this contribution, an IFC-based product model for mechanized tunneling is presented that is used to automatically create a complex numerical simulation model. A model mapping procedure is proposed that links IFC representations of the ground, the tunnel, and the shield machine with the corresponding input of the parametric simulation model. The proposed approach is demonstrated by means of a parameter study for a metro tunnel excavation in Düsseldorf, Germany.*

KEYWORDS: *Mechanized tunneling, Numerical simulation, Product modeling, IFC, Data exchange*

1. INTRODUCTION

The increasing demand for the use of underground space has been fostering the tunneling industry in recent years. With more challenging projects, also the demand for advanced numerical simulation tools for the prediction of tunneling-induced ground movements and possible hazards for surface structures has increased.

A comprehensive 3D finite element simulation model accounting for partially saturated soil, segmented tunnel lining, tail void grouting, a deformable shield skin and thrust/steering jacks has been preliminarily proposed by the authors (Meschke et al. 2011). Such complex simulation models, however, require a large amount of project-specific information that is usually available from dispersed resources such as drawings, spreadsheets, diagrams or heterogeneous databases. For this reason, complex numerical analyses are still not commonly employed in current practice.

In this contribution, a unified, IFC-based product model for mechanized tunneling is presented that is directly linked to the numerical simulation software. The IFC tunnel product model basically features three sub-domains: the ground, the tunnel, and the shield machine. Based on that, the simulation model can automatically be created and invoked. The advantage of this automated simulation procedure is the on-the-fly generation of new simulation results for any given changes in specifications or data such as updated design, deviations in ground conditions, occurrence of hazards, and disruptions in the tunneling workflow. Finally, the product model and its link to the FE simulation software are demonstrated simulating the excavation process of a metro tunnel in Düsseldorf, Germany.

2. BACKGROUND

2.1 Current practice

In mechanized tunneling, design documents are usually available in many different formats and databases. Furthermore, the type of data differs widely (e.g. CAD drawings, text reports, spreadsheets and diagrams). This complicates the generation of Finite Element (FE) simulation models, because required data has to be organized from multiple resources, and documents have to be searched for appropriate parameters. Additionally, these

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parameters usually have to be manually integrated and updated in case of design changes. Thus, in tunneling practice, numerical simulation is still not used to the extent that the possibilities of current simulation models would suggest. This is mainly due to the enormous effort in the manual modeling process and, in particular, in the procedure of gathering all available information on the project in a form that can be easily adopted for the model generation (Guglielmetti et al. 2008).

2.2 Current research efforts

2.2.1 Numerical simulation in mechanized tunneling

Guglielmetti et al. (2008) have suggested applying realistic numerical simulations for the computation of settlements to accurately predict the influence of the tunnel construction on the built environment. For the generation of realistic numerical models, linking CAD tools and numerical simulations has become a popular issue in recent years. In particular in industrial design, this has become state of the art, for example in the automotive sector, and is a matter of ongoing research (Franciosa et al. 2013). For geotechnical applications, Liao et al. (2005) have developed an interface for transforming geological profiles into finite volume models in FLAC3D by means of the ANSYS pre-processor. In an attempt to incorporate site-acquired monitoring data in the validation and improvement of numerical simulations of the shield tunneling process, a tunnel information system has been developed by Chmelina and Rabensteiner (2010). This system is currently being coupled with a process-oriented FE simulation software for mechanized tunneling and that is also employed in the current work. An automated modeling tool (Stascheit et al. 2008) acts as one of the core modules in order to accomplish seamless generation of parameterized simulation models. However, none of these approaches to date has integrated a unified product model that contains the complete design data of a mechanized shield tunneling project with a numerical simulation tool.

2.2.2 Product modeling in mechanized tunneling

Building Information Modeling (BIM) is an up-to-date modeling concept involving the generation and the management of a three-dimensional (3D) digital representation of physical and functional characteristics of a building or construction facility during its entire life-cycle. Building information models are commonly used as shared data and knowledge resources to support planning, construction, management, utilization, revitalization, and demolition activities (Eastman et al. 2008). BIM is often associated with the Industry Foundation Classes (IFCs), which are a data structure for representing complex building information. The IFCs have been developed by buildingSMART as a neutral, non-proprietary and open standard for sharing BIM data (Eastman et al. 2008). Currently, the IFC standard predominantly supports building constructions rather than tunnel construction. There are initiatives to extend this standard and develop an IFC-based model for shield tunnels (Yabuki 2008) and shield machines (Hegemann et al. 2012). However, there is no integrated model available that captures all information necessary to fully derive a FE simulation model.

3. METHODOLOGY

The overall approach is depicted in Figure 1. Within the first step, project relevant data available from dispersed resources are combined and integrated into a holistic product model for mechanized tunneling. Obviously, the creation of the product model takes a significant amount of time which has to be contrasted with the amount of time gained by the automated model generation and mapping process. Moreover, the product model can be used for generating multiple simulation models for different simulations, for example, driving simulation, grouting simulation and advance exploration simulation as well as for the overall data management within the life-cycle of the entire project (Eastman et al. 2008).

For generating the holistic product model we use and extend the IFC. Based on that, the FE simulation model is automatically generated using an ontology-based mapping approach. The focus of this contribution, as highlighted in Figure 1, is on the definition of the IFC tunnel product model (TPM) and the automated model mapping of its properties to the FE simulation model.

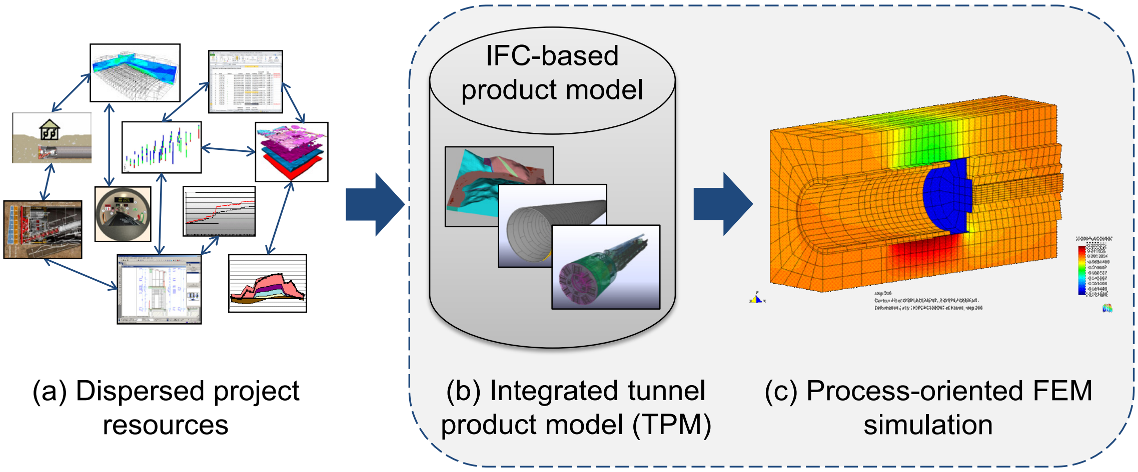


Fig. 1: Method overview (paper focus emphasized).

3.1 IFC-based tunnel product model (TPM)

To achieve a holistic product model an IFC-based approach is applied. It enables the link between individual objects of the model and captures both geometric representation and semantic information of an object. Furthermore, by generating an object-oriented data model an efficient structure can be provided to capture the different data types in a tunneling project. To cover all required information in mechanized tunneling, the holistic IFC product model consists of three partial models: the ground data model (GDM), the tunnel model (TM), the tunnel boring machine model (TBM), for now neglecting a model of the built environment (Fig. 2).

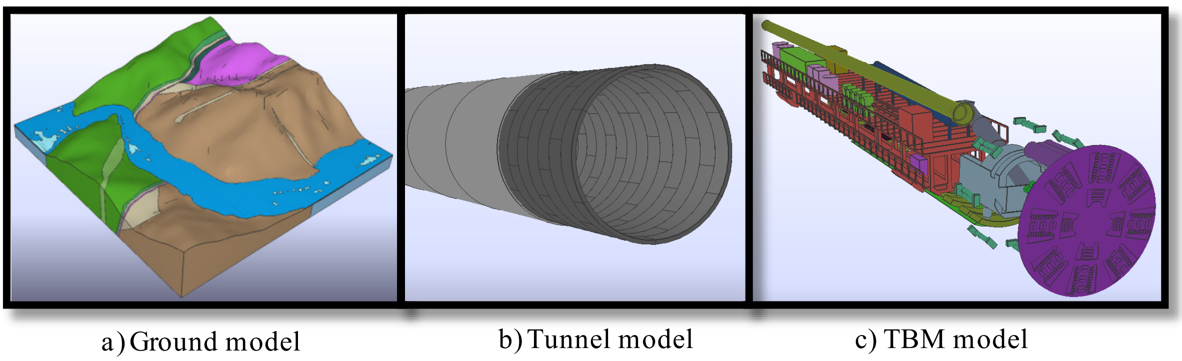


Fig. 2: Components of the proposed IFC tunnel product model: (a) the ground data model (GDM), (b) the tunnel model (TM), (c) the tunnel boring machine model (TBM).

In general, the GDM stores subsurface information including the shape of a ground layer and its material parameters. The TM captures information on the tunnel alignment, the lining segments, and the annular gap grouting. The TBM contains information about the dimension and the characteristics of each individual shield machine component, for example, the shield and the thrust jacks. Due to the missing extensions of the IFC regarding ground data, objects of the GDM are represented as IFC proxies. A proxy class is a generic container defined by its associated geometric and semantic properties (BuildingSMART 2011). For example, if a ground layer should be stored, a new proxy element is added to the partial ground model. The proxy has attached both a geometric representation defining the region of the layer and semantic information on the material properties by means of so-called property sets.

On the other hand, the TM is designed based on an approach recently presented by Borrmann and Jubierre (2013) (Fig. 3b). It provides individual classes to model different aspects of a tunnel, for example, the lining (*LiningSpace*), the segmental rings (*IfcRingSegments*), and the annular gap grouting (*AnnularGapSpace*). Each provided class can have attached both a geometric representation defining the geometric boundaries of its respective element and semantic information to characterize its properties by means of so-called property sets.

For the TBM, a similar approach has been previously presented by the authors (Hegemann et al. 2012) (Fig. 3a). Here, the IFC are extended for the purpose of describing the geometry (e.g. the dimension of the shield and the cutting wheel), the semantics (e.g. material properties and manufacturing information) as well as the process information (e.g. performance and operating data) of a tunnel boring machine. In accordance with the TM, the TBM can be divided into two parts, the spatial and the element part. The spatial part contains new classes to describe the spatial structure of the TBM, needed, for example, by visualization components (e.g. *IfcTbmHead*). The element part, on the other hand, specifies certain elements needed to describe the operation and behavior of a boring machine (e.g. *IfcTbmCuttingWheelElement*).

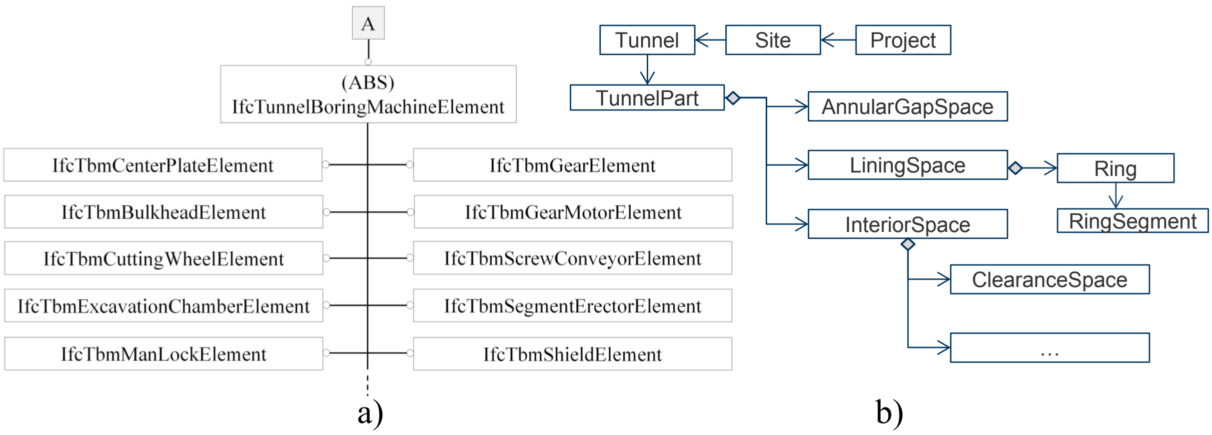


Fig. 3: IFC extensions: (a) classes for the TBM (Hegemann et al. 2012), (b) classes for the TM (Borrmann and Jubierre 2013)

3.2 Process-oriented Finite Element simulation

Mechanized tunneling comprises various process components such as the excavation of the ground, the advance of the shield machine, the installation of lining segments and the grouting of the annular gap evolving behind the shield. Furthermore, construction measures like heading face support by means of earth muck or support fluids play an important role. The process-oriented FE simulation model employed in this contribution has been developed in the attempt to account for all relevant components of the shield tunneling process with the required level of detail to cover their effects on structural loading in the tunnel as well as the impact of the tunnel excavation on the surroundings. Details of the model and its implementation can be found in (Meschke et al. 2011).

Since the manual generation of complex FE simulation models is a very time-consuming and error-prone task and in order to allow for a direct link of the simulation model with a tunnel product model, the model components have been combined to a parameterized model that can be created by means of an automated preprocessing tool (Stascheit et al. 2008). Figure 4 depicts the main geometrical parameters of the simulation model that have to be assigned by the model mapping scheme. Based on these parameters, a numerical simulation model instance can be automatically generated and executed.

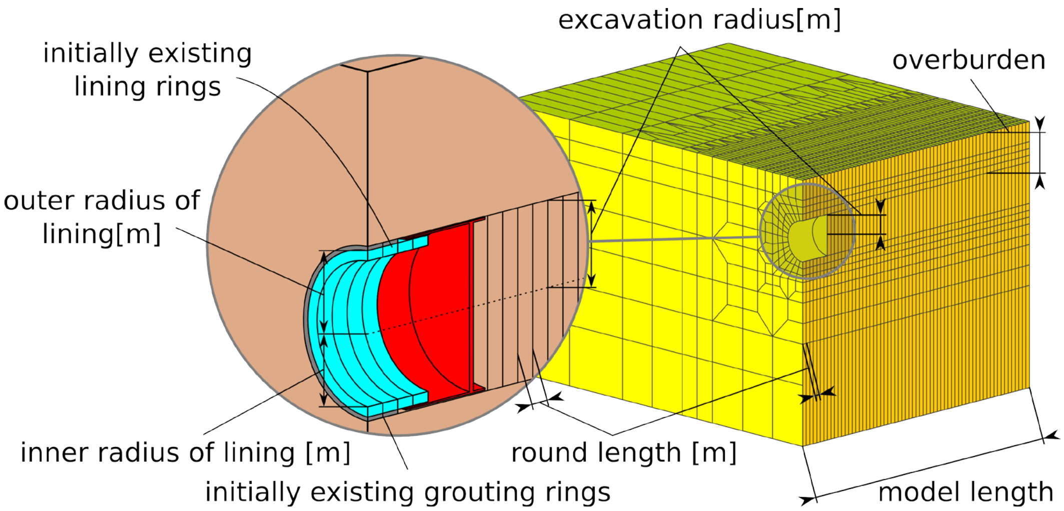


Fig. 4: Geometrical parameters of the FE simulation model.

3.3 Automated model mapping

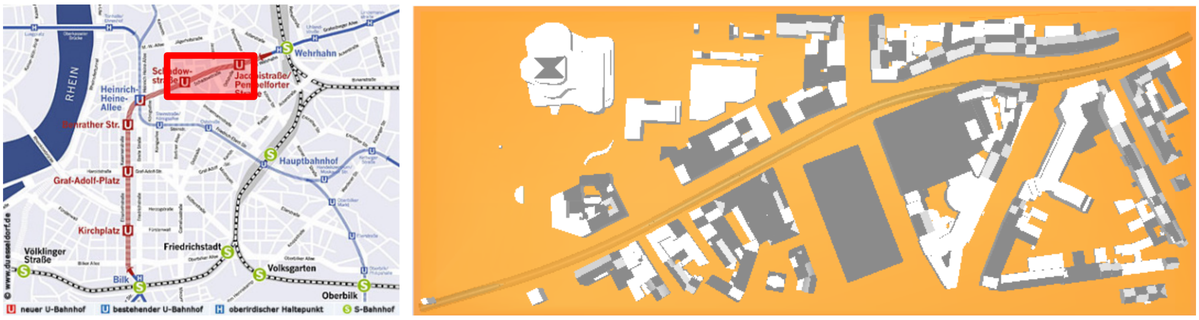
Automated mapping between different models always implies the problem of a different nomenclature of identical parameters within individual models. For example, the porosity of a ground layer is called "layer_porosity" within one simulation model, but "porosity" in another one. Therefore, a mapping is necessary defining that these different expressions describe identical parameters. Ontologies are commonly used to solve this problem. They create a pool of ordered terms, restrictions and rules to formally describe objects and their interrelations. For our purpose, an own XML-based ontology schema has been developed. This schema establishes a connection between the different parameter names of the simulations by assigning an umbrella term. Additionally, both the resource location of the parameter value inside the TPM and the target location inside the parametric simulation model are stored for automated data reading and writing, respectively.

However, the mapping of required parameter values from the TPM is a challenging task and can be divided into two categories. In the first category, the required parameter value is available in the TPM, exactly as needed. In the second category, the product model does not contain the requested value directly, because the partial models only contain raw information provided by several design parameters. In this case, pre-defined algorithms referring to existing parameters in the TPM are employed for calculating required values. For example, the overburden of the tunnel is needed at a specific position of the tunnel lining. Therefore, an algorithm calculates the distance from the tunnel lining (TM) at the specific position to the ground surface based on the ground geometry (GDM)

4. IMPLEMENTATION AND CASE STUDY

The proposed IFC based tunnel product model has been implemented using the Open IFC Tools (Open IFC Tools 2012). The process-oriented FE simulation model has been implemented in the open source multi-physics finite element framework KRATOS (Davdand et al. 2010). This tool has been chosen due to its open modeling interface. However, also any other FE framework which allows the generation of simulation models by using input files can be applied. For geometrical modeling, meshing and assignment of boundary conditions, the customizable pre- and post-processor GiD (www.gidhome.com) is employed. A collection of Python scripts is used to batch-control GiD and to prepare the model data for the simulation. The model mapping has been implemented by means of XML schemas.

To demonstrate the capabilities of the proposed model mapping technique, a tunnel excavation in Düsseldorf, Germany has been modeled using the tunnel product model (Fig. 5). The complete project, running from 2007 till 2014, comprises 2.3 km of shield driven tunnels and various deep excavations. Figure 5a shows a city map of Düsseldorf with the complete alignment of the new tunnel. The extract applied and modeled for this case study is highlighted in Figure 5b. It has an approximate size of 724 x 282 x 77 m with a tunnel length of 780 m at a tunnel diameter of 9.4 m.



a) b)

Fig. 5: Case study: (a) map of Düsseldorf, (b) the IFC model visualized.

Based on the project data, a case study has been performed varying two design parameters: the overburden and the support pressure. The former is a geometrical parameter defining the depth of the tunnel whereas the latter is a semantic process parameter defining the amount of heading face support. Figure 6 illustrates the variation of the overburden parameter. Case a) is a shallow tunnel with an overburden of 1.5 diameters while case b) is a deeper tunnel with an overburden of 2.5 diameters. In the first step, a respective box is cut from the global representation of the tunnel product model. Step 2 shows the discretized FE model as a result from the model mapping procedure. In step 3, the simulation results in terms of surface settlements resulting from the excavation are shown. For the deeper tunnel, the support pressure has been varied: one setup has been run with a support pressure that is equal to that of the shallow situation (180 kPa); another setup features an adequately increased support pressure for the deeper tunnel (280 kPa).

The effect of the variation of the two exemplary model parameters is shown in Figure 7. The right plot shows the evolution of the settlements directly on top of the tunnel axis in a fixed monitoring section. As the shield approaches the monitoring section, the settlements are increasing. They reach a maximum after the shield has passed and the annular gap is fully grouted. Finally, the settlements remain constant. The left plot depicts the transversal settlements at three different stages 12 m ahead and behind the shield and as the shield is passing the monitoring section, respectively. From these plots the influence of the two investigated parameters can be seen. The depth of the tunnel has the largest influence on the surface settlements, whereas the support pressure only has a minor impact in this example.

5. CONCLUSION

In recent years, increasing demand for the use of underground space has been fostering the tunneling industry resulting in the need for advanced numerical simulation tools for the prediction of tunneling-induced ground settlements. In this contribution, a unified, IFC-based product model for mechanized tunneling was presented that is directly linked to the numerical simulation software.

The IFC tunnel product model basically features three sub-domains: the ground, the tunnel, and the shield machine. Based on that, the numerical simulation model can automatically be created and invoked. The presented case study revealed the advantages of the proposed approach. Simulation results could be easily obtained for two exemplary parameter variations. This shows the potential to conveniently perform simulation-based predictions for any given changes in specifications or updated designs without the need for manual re-editing of complex FE simulation models.

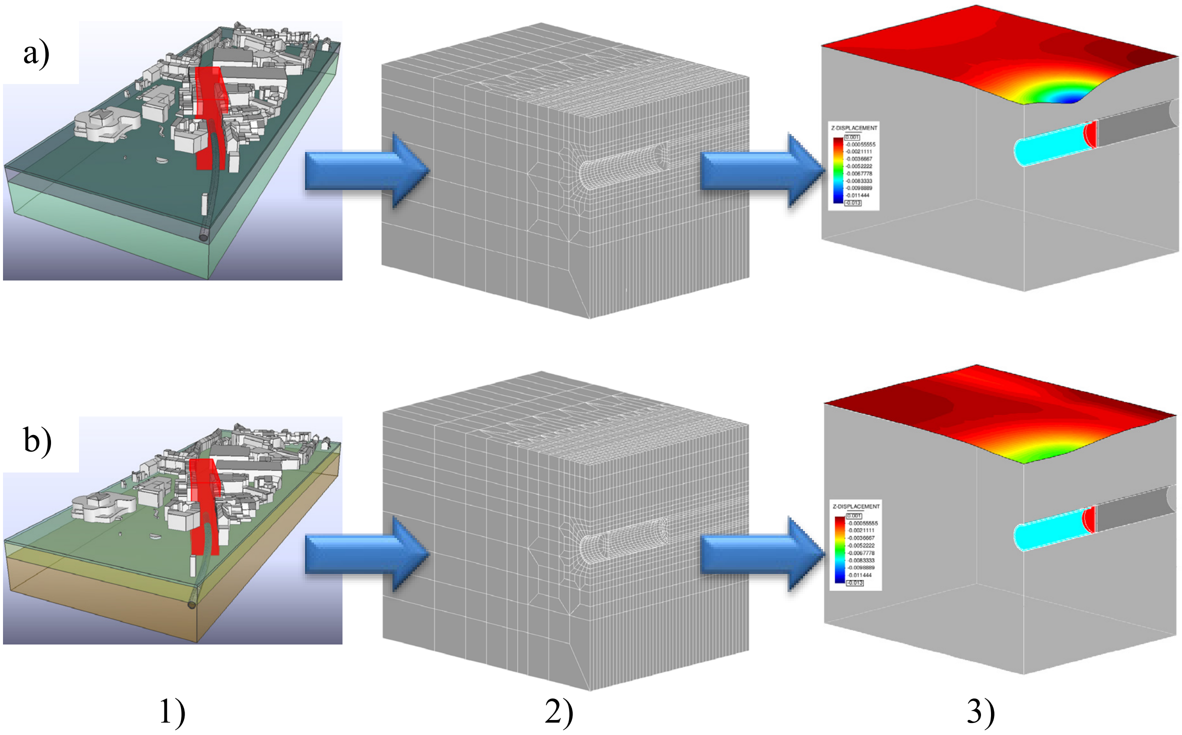


Fig. 6: Workflow (steps 1 to 3) of model mapping for an overburden of 1.5D (a) and 2.5D (b).

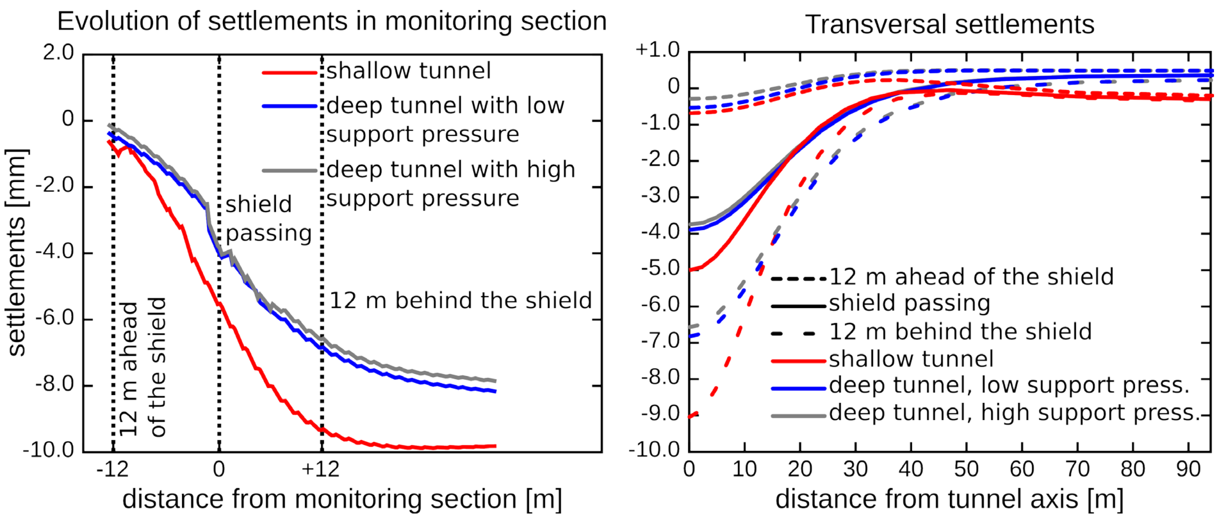


Fig. 7: Evolution of settlements in the investigated tunnel variants.

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