Chapter 9

Conclusions

9.1 Summary and concluding remarks

9.1.1 Advances in numerical simulation in tunneling

The process-oriented FE simulation model for mechanized tunneling ekate was used and enhanced for modeling the shield tunneling process in partially and fully saturated soil. The computational model includes proper representation of all individual components of mechanized tunneling (soil model, TBM, lining, grouting, face support and hydraulic jacks) and their mutual interactions. This simulation model was compared with the commercial software Plaxis 3D™. In this regard, the effect of mechanized tunneling was investigated for different values of the ratio between horizontal and vertical stresses in the soil ($K_0$) for a reference project, the newly constructed Crossrail line in London, UK. The Plaxis model uses simplified boundary conditions to represent the EPB tunneling process, while ekate represents the TBM as a distinct deformable structure in contact with the soil. The analyses simulated the Crossrail EPB machine and assumed undrained conditions with stiffness and strength parameters typical for the London clay. We compared the results for the cases $K_0 = 1.0$ and $K_0 = 1.5$. The two FE models (Plaxis and ekate) produced similar predictions of surface deformations and lining forces for the $K_0 = 1.0$ case. However, there are large differences in the predicted behavior at $K_0 = 1.5$ that can be directly attributed to the assumed boundary conditions of the two models. The more comprehensive ekate model predicts an ovalization of the tunnel cavity, resulting in smaller surface settlements above the tunnel. Lining forces are quite comparable for both $K_0$ cases, although ekate tends to predict smaller axial thrusts and larger bending moments at the springline for $K_0 = 1.5$ than Plaxis. While comprehensive process-oriented FE models such as ekate are clearly superior for representing (and controlling) the advance of a TBM, the predictions of the simpler Plaxis model appear to provide very reasonable predictions of far-field ground deformations and tunnel lining forces. Furthermore, we demonstrated that accounting for steering by means of hydraulic jacks and for the weight of TBM and machinery affects the tunneling-induced settlements and also enables the calculation of the longitudinal stresses in the lining due to jacking thrust.
The simulation model ekate allows for simulating the real time tunneling process. To this end, in the example presented in this thesis, the resolution of the calculation time steps for simulation of tunnel advance was addressed. The consolidation time depends on the hydraulic and mechanical properties of the soil as well as the overburden. Therefore, for clayey soils, the consolidation process takes days or months, while for sandy soils, the consolidation occurs on the same time scale as the TBM advance process. The simulation of this effect is enabled using a three-phase (or two-phase) soil model for partially (or fully) saturated soil to account for migration of pore water pressures in soil pores. Using a proper boundary condition and proper time resolution for the consolidation sub-steps between two TBM advance steps, it was possible to accurately capture the effect of dissipation of pore water pressures in time.

Furthermore, the soil model, combined with a two-phase grouting model with time-dependent stiffness and permeability made it possible to model the pressurization of the tail gap behind the machine and the de-watering of the grout. In combination with a sophisticated four-phase model for the infiltration of the grout, this enables the update of the permeability of the grouting material according to real infiltration processes occurring between soil and pressurized grout.

Having a sophisticated 3D simulation of the tunnel advance process that accounts for time-dependent water pressure distribution, stepwise advancement of TBM, installation of the lining structure and support by means of pressurized grouting with time-dependent properties, it is possible to extract the forces acting on the lining in the construction phase. For consideration of the pressure acting on tunnel lining, a modified contact formulation on the interacting surfaces between the lining and grouting element is applied. The loading on lining was obtained as a normal contact force acting on the lining surface. In the presented example, we investigated the evolution of the loading on the lining for different soil conditions, boundary conditions and initial soil in situ stress states. It is shown that the acting loading on the lining depends on both earth and grouting pressure and that it is highly dependent on soil mechanical and hydraulic properties as well as prescribed support (boundary) conditions. Furthermore, the loading acting on the tunnel lining depends on the load history, due to time-dependent mechanical and hydraulic properties of the grout material in combination with the resulting evolution of stresses in the surrounding soil. Regarding the influence of the material properties of the grout material, in the presented example, a different loading history leads to strain “freezing” under different loading conditions and consequently to a different final total stress state around the lining, although the water pressures finally always dissipate to the hydrostatic stress state.

Moreover, in our simulation model ekate, the segmental lining can be modeled including the joints between the segments. Hence, the segment-wise installation of tunnel lining and the reduced bearing capacity of the lining due to the presence of joints can be simulated. Finally, overlaying structures were modeled using substitute models: a building is modeled as a shell element with corresponding substitute elastic stiffness \( E \), height \( H \) and weight \( \rho \) obtained from more sophisticated models and inverse analysis. The interaction with the soil is accomplished via a mesh-independent surface-to-surface algorithm. The building model accounts for different interaction modes (sagging and hogging) and the building weight.
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9.1.2 Embedded pile model and applications

A finite element model for the numerical representation of pile foundations in 3D geotechnical simulations was proposed. The model allows to consider an arbitrary number of piles with arbitrary orientations independent of the spatial discretization of the soil, of frictional contact between the pile skin and the soil along the height of the pile and also of the tip resistance. The individual piles are modeled as beam elements, which are connected to the finite elements representing the surrounding soil with frictional contact based on control points located on both elements to detect contact conditions. All interaction conditions are defined in the integration points of the beam elements representing the piles. The integration points are projected to respective control points of the respective volume elements crossed by the pile elements. Hence, the soil can be discretized using arbitrary element geometries, and an arbitrary number of piles may intersect one soil element. Special focus was on the computational efficiency of the formulation. To this end, a frictional point-to-point contact algorithm was proposed, using a tangent plane approximation as an effective way to describe the kinematics of multi-directional slip in the embedded beam elements and a consistently linearized contact tangent matrix. In addition to the consideration of skin contact and friction, also the tip resistance at the pile foot was accounted for by enforcing appropriate impenetrability conditions.

The proposed formulation for embedded beams was verified and numerically validated by means of two benchmark examples related to axially and laterally loaded piles, adopting a fully 3D model for the pile and the soil as a reference model. It was shown that the embedded pile model allows for an accuracy of the results concerning the pile-soil interaction comparable to fully 3D pile-soil models at only a fraction of the required efforts, both with respect to the computational cost and the model generation. We investigated the stress distribution in the vicinity of the pile. Although the sharp gradients of the stresses in the soil observed in the immediate vicinity of the pile for the 3D reference model could not fully be replicated, the magnitude of the stresses were in satisfactory agreement with the results from the reference model. Discrepancies observed in the case of tensile stresses at the surface of the soil are connected with the detachment of the pile skin from the soil, which is not accounted for in the embedded pile model, and the fact that an elastic material model was used for the soil in this benchmark analysis. However, this discrepancy would be reduced or even eliminated if a realistic inelastic material model was used for the soil, limiting tensile stresses through the constitutive formulation. In general, the small remaining local discrepancies decreased fast and almost became zero at horizontal distances larger than two times the pile diameter from the pile axis.

The embedded pile model was implemented in our process-oriented finite element model for the simulation of the construction processes in mechanized tunneling considering soil-structure interaction. Using this model, the applicability of the embedded pile formulation to be used in large scale problems was demonstrated by the numerical simulation of a shield-driven tunnel construction underneath a high-rise residential building resting on a pile foundation. Comparing the results with the outcome of an analysis assuming a plate foundation of the structure, we provided a quantitative assessment of the influence of the piles on the stiffening of the foundation-soil system.

In the second example, the embedded beam model was used for the representation of grouted
anchors and pipe roofs often used in tunneling as primary support after excavation in NATM. To this end, a full 3D model FE model of the Bočac tunnel was created, incorporating all relevant elements of primary and secondary support in hard rock tunneling and considering the staged excavation sequence. We demonstrated that the anchors significantly reduce the displacements of the tunnel lining at the crown and the bench of the tunnel. More importantly, more than 600 grouted anchors and roof-pipes modeled in this case study could appropriately represent the soil improvement without a large increase of the total computational costs.

Finally, a modified embedded beam formulation was applied for modeling of fiber-reinforced concrete, where the beam element represents steel fibers interacting with the concrete matrix. In this formulation, in addition to the frictional contact interface between the beam and the solid, a nonlinear bond-slip law was proposed to account for initial bonding of the fibers with the surrounding matrix. For modeling of concrete behavior, an isotropic damage model including the IMPL-EX scheme was implemented in KRATOS. The damage model introduces a softening law based on the Rankine criterion that solely captures tensile material behavior and is also sufficiently suited for a description of concrete cracking. The capabilities of the proposed method were shown in a numerical example, where the effect of fiber distribution and orientation on the overall response was investigated. The model is able to qualitatively capture major effects of fibers distribution on the induced damage within the concrete specimen.

9.1.3 Simulation and monitoring-supported steering

A prototype concept for the simulation and monitoring-based support of the steering of tunnel boring machines in real-time was proposed. It consists of two stages: first, an efficient method for updating a computational model for mechanized tunneling according to monitoring data obtained during construction, and second, the back-analysis of optimal operational parameters according to prescribed limits for the target settlements. Due to the real-time requirements, meta models that provide a response within a few seconds were employed for the steering support during construction, substituting the computationally demanding, process-oriented finite element model. This finite element model is used, however, in the design stage for the training of the meta model based on the available information on the geological conditions.

To this end, a fully automated computational procedure for the generation of a simulation-based meta model with capabilities of prediction, parameter identification and process optimization was developed. For the generation of a meta model, two different ANNs are proposed: Backpropagation Artificial Neural Network and Recurrent Neural Network. As mentioned, the input data for the training was generated with the advanced computational model ekate for a given set of material, model and operational parameters related to the steering of the TBM. The meta model was then trained using a PSO-optimized ANN learning procedure.

Selected numerical applications show that it is possible to predict the spatio-temporal evolution of settlements with high reliability with the proposed simulation-based ANN model even for more complex geological conditions characterized by two soil layers with an inclined boundary. For a selected portion of the tunneling project and a fixed set of relevant input and output parameters, the meta model fully substitutes the finite element model during construction.
The trained meta model was used for updating the model parameter during construction on the basis of information obtained from monitoring. For the inverse analysis, PSO was used. In two numerical examples (using synthetic measurements instead of monitoring data), the performance of PSO for the identification of material parameters of the soil and topology-related parameters (such as the inclination angle of the boundary between two soil layers) was demonstrated. On average, less than 30 iterations were required to identify the unknown parameters. Furthermore, the choice of PSO for global optimization in the inverse analysis allows to easily consider physical limits for parameters to be identified.

A procedure for the simulation-based steering of the tunneling process was developed based on the updated meta models. Using inverse analysis, the operational parameters related to the steering of the TBM (e.g. grouting or the face pressure) are determined such that certain target values (e.g. surface settlements) to be expected within the next few excavation steps are kept below an acceptable limit. For the inverse analyses of the selected operational parameters, again a combination of ANNs and PSO was used successfully. It was shown that only a few (10–15) iterations were necessary to identify the optimal steering parameters with sufficient accuracy.

The advantage of this method is that using the meta model for the evaluation of the Fitness function in the PSO algorithm, the identification process is executed within a few seconds on a standard PC—or possibly also on mobile devices—and therefore is well suited to support decisions during the tunnel construction.

It should be noted that the proposed procedure is based on the assumption that the soil conditions do not change abruptly during further advancement of the TBM from the current location to the next excavation step. To overcome this drawback of the meta model-based steering, a novel strategy for a hybrid meta model and simulation-supported steering of TBM parameters for the reduction of the surface settlements induced by tunneling was proposed in this work. In this method, the process-oriented finite element model is directly employed for forward analyses during tunnel advancement, however, provided with updated geotechnical parameters and with optimized process parameters obtained from meta models accompanying the simulation during tunneling in each excavation step. The predictions from the finite element model in each excavation step are used as the basis for the generation of a new set of process parameters for the next analysis step.

Both computational strategies for the steering of TBM operational parameters (meta model-based and FE-supported steering) have been applied to data of the WHL metro project in Düsseldorf, Germany.

9.1.4 Case study: metro Wehrhahn-Line

The two strategies for meta model-based and FE-supported steering of the TBMs are demonstrated by means of real project data of the Wehrhahn-Line metro. The simulation model for the tunnel project was created based on the project data obtained from the TPM for the chosen tunneling section. The real advance rates of the TBM were properly implemented in the simulation model, allowing to account for time-dependent effects such as pore water pressure distribution on the tunnel face and around the TBM and consolidation of the surrounding soil. In order to improve the quality of the performed back-analysis, a sensitivity analysis was conducted for parameter ranges...
obtained from the geotechnical report to preselect the most influencing parameters before creating the meta model. Having the meta model based only on the effective parameters as a basis of the back analysis, the material parameters of the soil were determined. The model prediction of surface settlements shows very good agreement with real in situ measurements.

In the presented examples, the support and the grouting pressure are continuously updated during the advance of the TBM to keep the tunneling-induced settlements below tolerated limits during all excavation steps. The steering of TBM has been accomplished by means of the two mentioned strategies: meta model-based steering and FE-supported steering. In the first strategy, computationally very cheap meta models are used for real-time model update and the optimization of the process parameters. Secondly, a novel strategy for a hybrid meta model and simulation-supported steering of the TBM parameters is employed, where the predictions from the finite element model in each excavation step are used as the basis for the generation of a new set of process parameters for the next analysis step.

Both meta model-based steering and FE-supported steering strategy have satisfied the objective of minimizing the surface settlements in all points within tolerated limits. Although the meta model-based steering approach provides instantaneous optimization satisfying the objective, the FE-supported steering strategy has shown better performance w.r.t. the global solution of the problem. The advantage of using the simulation model directly for the generation of optimized process parameters is the correct model response (independent of the range of geotechnical parameters) and the adjusted optimization of the TBM parameters during the advance based on this correct response. Furthermore, in contrast to the meta model-based strategy, one can assess the influence of the chosen parameters on all components of the tunneling project represented in the numerical simulation model. Compared to the meta model, the required computation time is higher. However, since the model is used during the tunnel advance for each excavation step, the required response time for one excavation step in the range of $\sim 5$–30 minutes can be achieved even for large models using appropriate parallelization.

Due to the minimal computing time required for the determination of operational parameters, the meta model-based steering is well suited for the consideration of uncertainties of the soil parameters ahead of the tunnel face. This then allows to provide a range of suitable operational parameters, instead of a deterministic value obtained from the proposed (deterministic) approach.

When higher accuracy is necessary, the FE-supported steering strategy can be employed, however, requiring addition computational resources and incurring a longer execution time. It should be emphasized that the FE-supported steering method can be extended by adding multiple criteria for triggering and controlling the process optimization, including safety against loss of face stability, the stress state in lining, etc. Furthermore, a priori information on parameter sensitivity available from the design stage may also be used in the parameter identification process performed during the advancement process to govern the choice and/or magnitude of the optimized TBM parameters.
9.2 Outlook

The process-oriented simulation model ekate implemented in the FE framework KRATOS allows for flexible extension of the existing components and the implementation of new features. For the work presented in this thesis, further developments can be done in terms of material modeling of the structural components, development of new formulation for modeling of soil improvement and furthermore:

Assessment of structural damage induced by tunneling

In the presented work, buildings are modeled using a linear-elastic material interacting with the soil either through elastic-perfectly plastic or a COULOMB friction interface. In Section 3.4, the use of surrogate building models was motivated. This approach has advantages in terms of low computational costs within the tunnel simulation model, but still requires extensive numerical and inverse analysis in order to establish building surrogate models based on far more accurate numerical models and measurements. Furthermore, although it is possible to capture the soil-structure interaction effects on the tunneling induced settlements, it is not yet possible to assess the damage induced in buildings. Therefore, implementation of models that are able to incorporate damage or cracking of quasi-brittle materials is required. In the studied cases of buildings subjected to tunneling-induced settlements, the damage was mainly due to tensile and shear stresses, and therefore the focus is on modeling of tension and slipping modes. Therefore, the fundamental requirement is to account for reduced bearing capacity in tension either by adopting simple constitutive models characterized by low tensile strength and high strength in compression or by using advanced models accounting for masonry tension softening behavior, which is necessary for a realistic post-peak stress redistribution.

Modeling of segmental lining

In Section 3.3, the basic concept for modeling the segmental lining is introduced. In the scope of this thesis, the concept for segment-wise installation of the lining within the computational model based on flexible and efficient activation of longitudinal and ring joints was proposed. This model requires an extension in two directions: a more realistic modeling of the joints accounting for nonlinear behavior and an appropriate representation of the segments by means of material laws accounting for the damage induced in concrete. In general, for the structural response of the lining, it is often sufficient to account only for nonlinearity of the joints. However, for the assessment of robustness and durability of the lining the modeling of the damage induced in concrete is needed. Generally, it is not required to use such models in full-scale simulation models, but rather for models of individual segments/rings loading with jack forces and/or earth pressure. In terms of joint modeling, the nonlinear responses of the longitudinal joints manifests in a reduced rotational stiffness after the joint experiences maximal bending bearing capacity, while for the normal stiffness, it is valid to use a linear relation (CAVALARO AND AGUADO 2012). On the other hand, for the ring (circumferential) joints, it is more typical to consider a nonlinear relation for shear after reaching the maximal bearing capacity, accounting for the stiffening of the shear behavior with an increase of the
normal (jacking) force. Applying a proper model for segment and ring joints within the simulation of the construction process would result in a more accurate simulation of the structural response of the lining and of the resulting redistribution of the stresses in the surrounding soil acting as a loading on lining (see Section 3.2). Having the real loading acting on the tunnel lining during the construction process (jacking forces and earth pressure) is an essential input for detailed modeling of the lining segments by means of sophisticated constitutive laws for concrete.

**Soil improvement by means of jet grouting**

Jet grouting is a technology used for improvement of the stiffness of the ground during geotechnical interventions such as tunneling in order to reduce induced settlements of the ground. In standard engineering analyses, jet grouting is usually simulated by changing the material properties of the FE domain representing the jet-grouted material. Jet grouting at the beginning leads to negligibly small strength and the stiffness of the grouted material due to destroyed microstructure of the soil. The increase of the hydrostatic pressure in the soil during jet grouting can be modeled by adding a hydrostatic stress state $\Delta p$ to the initial stress state. Compensation grouting is often used in urban tunneling, whereas increasing the hydrostatic pressure induces a heaving of the soil and “compensates” settlements caused by tunneling. An FE model for jack grouting, which has to consider all main phenomena occurring during the jet grouting, but also satisfy the requirement of minimum computational costs, can be developed in KRATOS. The embedded beam model can be used as a basic framework and be extended to account for time-dependent stiffening and pressurization caused by jet grouting. The beam element with pressure nodes, i.e. the “jet grouting element”, can be embedded in the soil specimen independent of the discretization of the soil, where the contributions to the surrounding soil due to grouting by means of change of the soil strength and pressure can be achieved by interpolation.

**CAD and BIM based modeling**

Complex simulation models require a large amount of project-specific information that is usually available in the form of dispersed resources such as drawings, spreadsheets, diagrams or heterogeneous databases. Nowadays, information about the geometry of the models is usually given in some CAD format, while more recently, BIMs were used to collect, classify, structure and visualize all relevant information about design and construction. Clearly, the interaction between information and numerical models is a key feature for better integration of numerical models for prediction and design in a real projects. The information models (CAD, BIM etc.) can be used to support generation of FE models based on the project data and eventually reduce efforts needed for creating geometry, FE mesh and simulation scripts. On the other hand, the predictions obtained for computational models could be implemented in information models and enable better understanding of the interactions and effects induced by the construction. Recent advances in BIM bring the new concept of multi-scale modeling of the systems w.r.t. level of details by means of geometry, process modeling and monitoring information. This concept could be directly connected with simulation models where numer-
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Ical models can be be also generated according to given levels of abstraction in BIM model. For instance, depending on the design targets in different design stages, a numerical model can be represented from an abstract level such as a model of the tunnel advance by means of the volume loss method, to models containing all sophisticated components for machine, lining segments with joints, building, etc. In terms of CAD models, the future development goes towards the direct use of the CAD geometry for the numerical model, which is nowadays possible with isogeometric analysis (Hughes et al. 2005).

Process control and real-time steering using numerical models is not yet applied in practice. In order to use such techniques, first of all, the strategies, methods and their applicability has to be demonstrated and validated on existing project data. In order to enhance the proposed techniques, three major steps could make the techniques more robust, flexible and adaptable to a wide range of scenarios:

**Learning from in situ measurements**

In the presented concept, the application of simulation-based meta models and meta model update based on measurement data was proposed. The meta models are based on the geometrical, material and process parameters and their corresponding ranges predefined in the design phase. Therefore, the meta models are limited to the amount of knowledge from that period. It has already been mentioned that the real in situ conditions and the construction process parameters often differ from the ones in the design phase and additionally change with the advance of the project and due to “learning from experience”. Therefore, additional accuracy of the meta model can be obtained if it is re-trained “live” with the data obtained from the constant monitoring of the surface settlements, buildings, hydrological conditions, underground deformation and TBM process parameters during the construction process. Retrained meta model would be a more solid basis for forthcoming steps such as the model update and steering of machine process parameters.

**Consideration of parameter uncertainties**

Geotechnical parameters are spatially-variant uncertain data in terms of both stratification of the soil (geometry parameters of the simulation box) and the material behavior of the individual layers (material parameters of the soil models). This uncertainty could be quantified with intervals or fuzzy variables. Hence, from the data obtained from the discrete boreholes along the tunnel trace, a fuzzy location-variant geometry and material parameters can be established based on geostatistical methods like Kriging. Kriging is a method for the interpolation based on regression against given values of surrounding data points, governed by prior covariances. This method can be developed for polymorphic uncertain data and combined with stochastic and non-stochastic methods to simulate the spatial and parameter variability of the model. The TBM process parameters (face pressure, support pressure, advance rate etc.) are generally measured on a very fine time scale (seconds), while such a high resolution is not suitable for a numerical models due to the extreme computational costs. Therefore, transfer of the deterministic measurement data with the fine time-scale to the coarse simulation time scale is required. Accounting for both material and process parameters as uncertain non-stochastic or
stochastic data consequently leads to a model response containing the effects the uncertainties. Therefore, the predictions are no longer given as discrete values, but instead can reflect the probability of certain response to happen.

**Multi-objective steering criteria**

The research presented in this thesis w.r.t. computer-aided steering of the tunneling process is mainly focused on the minimization of the tunneling-induced surface settlements. Although these settlements are one of the best indicator of the global stability and safety of the system (i.e. large settlements almost always relate to the potential collapse of the underground or the existing infrastructure), this is not the only important aspect of tunneling and not the only cause responsible for hazards. Other important measures of the system safety are face stability, global stability of the tunnel lining, overlaying structures etc. Therefore, in future work, a concept for multi-objective steering of the mechanized tunneling process can be developed and validated using measurements of real tunnel projects. In Section 7.5, a new concept for multi-objective steering of TBM process parameters was proposed. This concept is to be more extensively tested and extended by means of the conditioning of the process parameters based on their sensitivity. Alternatively, a multi-objective meta model combined with multi-objective optimization strategies can be developed.