Chapter 6

Conclusions

Numerical Modeling of tunneling along arbitrary alignment

Within the first part of this thesis, a new computational framework for the simulation of the advancement and the excavation process of tunnel boring machines (TBMs) during mechanized tunneling was proposed using the finite element method. Within this framework, the TBM advancement and excavation processes are simultaneously simulated in such a manner as to enable the efficient and realistic three-dimensional modeling of the tunneling process for an arbitrary alignment. The step-wise excavation process is modeled by means of an adaptive spatial discretization strategy used in conjunction with a steering algorithm. This combination of algorithms provides a high resolution of the stress and deformations in the direct vicinity of the TBM and thus also a realistic kinematic description of the movement of the TBM during advancement. The coupled re-meshing – TBM steering procedure embedded in the simulation model takes the actual deformations of the soil and the TBM-soil interactions into account. The stresses induced in the soil, the lining and the TBM during arbitrarily aligned tunnel drives can therefore be more accurately assessed. This method automatically corrects "drift-off" phenomena, as are often observed in TBM tunneling, and continuously keeps the TBM on the desired course during the simulation.

The applicability and effectiveness of the proposed computational framework for the advancement and excavation process was demonstrated and verified by 3D numerical simulations of tunnel drives along both straight and a curved tunnel paths. The thrust force distribution predicted by the proposed adaptive re-meshing and steering strategy along the shield of the TBM has been shown to be in good agreement with the observed field data for both cases. The machine drives along a zig-zag pattern around the target alignment, which corresponds well with data collected from TBM guidance systems. A major advantage of the proposed computational model as compared to existing models is the combination of two strategies (TBM steering and adaptive re-meshing) in a single numerical framework, as this removes the needs of a complex pre-processing. The applicability of the proposed technique is shown by means of a case-study in which the a TBM was driven along a curved alignment. This study has shown that the proposed framework is able to realistically simulate the motion of the TBM and the TBM-soil interactions along an arbitrary path with minimum effort.
by the user in the preprocessing stage. Additionally, the effect of different process parameters, i.e. the alignment of the driven path, the over-cut, and the coefficient of sliding friction, was investigated. It was shown that the influence of these process parameters on shield behavior, e.g. shield tilting and orientations, can be realistically described by use of the proposed computational model.

An innovative software platform that enables the automatic generation of a Finite Element simulation of the mechanized tunneling process was presented. This software platform was developed on the basis of the computational framework proposed in this thesis and is intended to reduce user effort connected with the generation of simulation models. It supports the coupling and integration of numerical simulation models within Building Information Modeling (BIM) concepts. The platform provides a foundation for a central BIM-based model generation and execution of shield tunneling simulations invoked autonomously via web. Within this platform, the geometry of the tunnel project is modeled, all relevant model components are generated, geotechnical survey data stored in CAD format is extracted, the FE mesh is automatically discretized, and the process flow of the simulation is controlled. The applicability and efficiency of the proposed strategies when used for engineering purposes was demonstrated by means of project data from the WEHRHAHN-LINE (WHL) metro project in Düsseldorf, Germany through a direct comparison of the simulation results to on-site monitoring data. The proposed computational simulation model and its integration into a central BIM databank is well suited to serve as a tool for the analysis of machine driven tunneling along complex alignments and to aid in the pre-evaluation of decisions during the design and the construction processes.

Computational techniques for the assessment of tunnel face stability

In the second part of the thesis, a new approach for the finite element analysis of shear failure was developed. The technique was applied to accurately assess tunnel face stability and to predict potential tunnel face collapse mechanisms. This approach consists of i) a novel strategy for the global tracking of strong discontinuity surfaces and ii) the enhancement of the kinematics of those finite elements which are identified by the tracking procedure and which satisfy the necessary condition for localization. The proposed tracking algorithm exploits the information obtained from the enhanced parameters computed by using the Enhanced Assumed Strain (EAS) method. Observing that these parameters are associated with a deformation field characterized by opposite bending curvatures across a potential shear band, a proper inter-element continuous scalar function $\chi(x)$ of the enhanced parameters was constructed. The locus $\Gamma$ of $\chi(x) = 0$ of this function can be easily determined at the element level. The zero value of this function occurs close to the shear band center plane and is thus interpreted as the location of a potential strong discontinuity surface. The spatial information provided by $\chi(x)$ evolves during loading. It enables the identification of the elements which may be potentially enriched by a strong discontinuity kinematics according to the embedded strong discontinuity approach. The enrichment, however, is only inserted if a proper necessary condition for the formation of a strong discontinuity is also satisfied within the elements crossed by the surface $\Gamma$. The position and the orientation required for the enriched kinematics is then directly provided by $\Gamma$. This potential discontinuity surface is generated locally by checking the sign change of $\chi(x)$ for each element at every time step. Upon detection of a sign change, a new elemental
segment of $\Gamma$ is defined. These discontinuity surfaces are, by construction, continuous across the elements. Although they are locally evaluated and employed in the embedded strong discontinuity method (i.e. at the element level), it is emphasized that the EAS-based tracking method proposed in this work has a global character. Hence, in contrast to alternative tracking methods, neither a separate solution of a level set equation nor the solution of another auxiliary field equation at the global level is needed.

The performance of the proposed tracking algorithm was evaluated by means of three 2-D benchmark examples and one 3-D application using different structured and unstructured meshes with different sizes and orientation biases of the finite elements. The new proposed approach was shown to be capable of capturing slip lines that are almost exactly aligned with the analytical solutions available for the adopted $J_2$ and Drucker-Prager plasticity models, independently of the chosen mesh configuration. Neither the mesh size nor the mesh orientation had an influence on the predicted topology of the strong discontinuity surface and on the load-displacement curve. Remarkably, as was shown in the numerical applications, the tracking algorithm correctly predicts the localization surface already in early loading stages, even before the localization condition is fulfilled. Hence, there is no need to include any artificial delay between the detection of the potentially localized elements and the insertion of the strong discontinuity kinematics during the analysis.

A method for a numerical assessment of the safety factor against face collapse in selected stages of the advancement process, was introduced by means of the Strength Reduction Technique (SRT). The coupling of the error based re-meshing technique and SRT has been proven to be highly effective in capturing the shear failure mechanism that evolves during the parameter reduction by providing a higher mesh density along the shear band. A combined error indicator is incorporated in the re-meshing algorithm during the excavation process to enhance the accuracy and to improve the reliability of the numerical model. Furthermore, the performance of the Enhanced Assumed Strain (EAS) formulation in numerical analysis of the tunnel face stability was investigated and compared with standard low-order elements. The results have demonstrated the capability of the enhanced kinematics to capture the localized shear failure mode at the tunnel face even for relatively coarse meshes due to the enhanced kinematics of the EAS elements. Furthermore, the combination of the EAS formulation and the Strength Reduction Technique (SRT) is proven to be effective in capturing the shear failure mechanism and in predicting a more reliable safety factor as compared with standard low order finite elements. This indicates that the enhanced kinematics can be used as a powerful tool for the assessment of safety factor, especially in complex cases, when analytical methods cannot be used, such as when different soils layers with different angles of internal friction and cohesion, are present.