8 Conclusions and recommendations

8.1 Conclusions

In this research, the influence of the most important sub-systems, namely volume loss, tail void grouting, lining installation and progressive excavation on the model responses are studied. Special attentions are paid to the tunneling induced ground movements and the associated building’s behavior. Tail void grouting induced time- and space-dependent stiffness and permeability of ground domain in the near field around the tunnel are considered in the hydro-mechanical coupling (consolidation) analyses of tunnel excavation in saturated soil. Three advanced process simulation techniques are proposed for the purpose of saving computational cost especially in parametric study. Finally two tunnel case studies are conducted. The main derived conclusions are categorized as follows.

Effects of sub-systems

Tunneling induced surface volume loss is triggered by the tunnel volume loss, the difference between them is attributed to the soil volume change which depends on the soil elasticity and plasticity parameters. The empirical Gaussian distribution curve can be modified based on the effect of tunnel volume loss on the surface settlement trough. Surface volume loss ratio and settlement trough width parameter can be respectively expressed as quadratic and linear equations of tunnel volume loss ratio. The value of $K_0$ governs the deformation mode of soil above the tunnel crown, higher value of $K_0$ may induce less settlement at the ground surface. When there is building on the ground surface, soil’s friction angle, tunnel volume loss and horizontal distance from the tunnel are the dominant parameters in determining the building’s settlements. While the overburden depth of tunnel as well as the soil-building contact properties highly affect the tilt of the building. By applying the sensitivity analysis in the entire domain of the model, it is found that for the purpose of identifying the soil’s stiffness and strength, the optimal sensor locations to measure the vertical and horizontal displacements in the present study are (1) $D/2$ to
out the outer side of the tunnel with respect to the position of the building, (2) below or above the tunnel, and (3) 1D below the building and 2D horizontal distance to the inner side of the tunnel towards the intermediate zone between the tunnel and building. Consecutive and simultaneous consolidation schemes are developed as two numerical simulation methods for hydro-mechanical coupling analysis of tunneling problem. The consecutive scheme allows full generation of the excess pore pressure during excavation, which is preferred for tunneling in low permeable soil with high advance speed. Whilst the simultaneous scheme is preferred for slow advancing in high permeable soil due to the fact that consolidation and drilling coincide in each excavation step. The infiltration of grout material does not take place in soil with low permeability, while it strongly occurs due to backfill grouting in soil with high permeability. Neglecting the grouting induced evolution of the permeability and stiffness of ground domain in the near field around the tunnel could underestimate the surface settlements and lining axial forces after passing the TBM.

Advanced process simulation

The innovative adaptive constitutive modeling accounts for constitutive model exchange in the near field sub-domain which is strongly affected by tunnel excavation. The model adaption is suggested to be carried out by taking into account a family of hierarchical constitutive models. The zone which is subjected to loading, unloading and reloading due to tunnel excavation can be numerically simulated by an advanced model while the less-affected far field sub-domain can be sufficiently simulated by a basic model. The distribution and variation of plastic strain at the Gaussian points are used to determine the size of the area where advanced constitutive model is employed. The appropriate size of the near-field sub-domain as well as the hierarchical constitutive models can benefit the design of laboratory tests and in-situ investigation strategy. It is found that the submodeling approach is a powerful tool for detailed analysis in the near field around the tunnel with reduced computational costs in comparison with the conventional simulation method. The applicability of the assumed submodel boundary is suggested to be checked by the strain energy distribution. The submodel may or may not be defined with the same material law in comparison with the global model, and two submodeling techniques, namely fixed block and moving block approaches, are developed for tunneling simulation. The novel computational method hybrid model is proposed for numerical simulation of mechanized tunnel excavation. This approach combines the capacity of a process-oriented submodeling with the computational efficiency of metamodel. It is a powerful tool for parametric study and it is also applicable in optimization of process
parameters in each excavation step without updating the submodel boundary conditions, accordingly the tunneling induced soil deformations can be kept within the tolerated limit with the advancement of TBM.

**Case study**

According to the case study of Western Scheldt tunnel, it is found that sensitivity analysis is a powerful tool to elaborate the relative importance of the model parameters in determining the model responses. Sensitivity of soil deformation to constitutive model parameters are varying for different observation points. Plastic deformation of soil is most sensitive to friction and dilatancy angles. While the elastic deformation is more sensitive to stiffness and is related to friction angle as well. Sensitivity analysis can be used to quantify the model uncertainty and reduce the dimension of the back analysis problem. Optimized parameters within 3D back analysis are adequate in both 2D and 3D models. Validated 3D model provides reliable predictions of the surface settlement profile with the advancement of TBM as well as other model responses that cannot be well captured by 2D model. When the sensitivity information is applied in the entire model domain to form the sensitivity field, it becomes a powerful tool for design of optimal sensor location where instead of arranging all the sensors at the ground surface, less sensors can be conveniently and rationally placed at subsurface level to attain better knowledge on the soil properties with less efforts. This methodology is validated via the case study of tunneling model tests.

**8.2 Works in the next step**

Based on the work of adequate numerical simulation of mechanized tunnel excavation using finite element method conducted in the present study, the very interesting and potential development could be stated as follows:

1. Although the lining stiffness are reduced to take into account the effect of joints, the longitudinal joints in the lining segments could be further considered and explicitly simulated in the numerical analysis, which is more realistic for lining structural design.

2. In the present study, the variable permeability obtained from infiltration theory is manually updated in the simultaneous consolidation analysis. The grout infiltration
induced permeability evolution could be further implemented in the same framework of finite element code which is utilized for consolidation analysis.

3. In adaptive constitutive modeling, the size of sub-domain where advanced model is applied is defined manually based on the incremental plastic strain. This approach could be further implemented in the finite element code. To be specific, when the incremental plastic strain at the Gaussian points using the basic constitutive model (e.g., MC model) fulfills the predefined criteria in certain domain of the model, the basic constitutive model is exchanged to the advanced one (e.g., HSS model). Thereafter, the basic constitutive model is re-assigned to the domain when the criteria of incremental plastic strain cannot be fulfilled.

4. The constitutive model employed in the present study does not account for the complex soil behavior, i.e., anisotropy and destructuration. These features of soil could be further considered in the numerical simulation by developing or employing more sophisticated constitutive models.

5. In the current Hybrid modeling approach, the effect of ground water is not considered. The hydraulic boundary conditions of the submodel can be further studied, and an approximate method can be developed to drive the submodel in Hydro-mechanical coupled analysis.