System identification, meta-modeling, global sensitivity analysis, and probabilistic analysis of failure in mechanized tunneling

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Abstract:

The ground model is central to computational tunneling, where, a realistic ground model is crucial for predicting the distributions and magnitudes of the strains and, consequently, reducing the surface settlements caused by the Tunnel Boring Machine (TBM) propagation. However, due to the complex interactions between the ground, the driving machine, the lining tube and the built environment, the accurate assignment of in-situ system parameters for numerical simulation in mechanized tunneling is always bounded with tremendous difficulties. Furthermore, the more accurate these parameters are, the more applicable the responses gained from computations will be. In particular, if the entire length of the tunnel lining is considered, then the appropriate selection of various kinds of ground parameters is accountable for the success of a tunnel project and, more importantly, will prevent serious casualties. As a consequence, only the realization of the system identification approach can result in improved and more sophisticated numerical predictions of the spatio-temporal ground behavior induced by driving the tunnel. In this context, methods of system identification for the adaptation of numerical simulation ground models are presented. These methods consider both deterministic and probabilistic approaches for typical scenarios for variations or changes in the ground model.

In the deterministic approach, measurements of system responses obtained during the tunneling process (e.g. surface subsidence) are compared to their numerical counterparts computed from the numerical simulation (forward calculation). If there is no match, the serious deviations (defects or residuals) are iteratively minimized by applying a different derivative-free optimization algorithm and taking the parameters of the ground model, used in the numerical simulation, as minimizing parameters for the minimization problem (inverse problem). Hereby, the underlying optimization problem constitutes a highly nonlinear as well as non-smooth optimization problem associated with multiple optima (non-standard optimization problem), due to the ground model that represents a complex, mechanically-hydraulically coupled and a three dimensional boundary value problem.

Customarily, the geotechnical applications are associated with uncertainties, where, the significantly scattered material properties (e.g. stiffness, strength, permeability) of the soil, due to the inherent randomness of its nature, yields aleatoric (objective) uncertainty. In addition to that, lack of data, of information about events and processes and of understanding the physical laws results in Knowledge (epistemic/subjective) uncertainty. In order to obtain realistic results and to quantify the underlying uncertainties in the parameter estimation process, a Bayesian probabilistic approach for the inverse problem is introduced. This approach is able to include the prior information about the parameters, which may be captured from bore holes sunken in the target area of the tunnel alignment. To this end, a numerical approximation of the probabilistic solution using Markov chain Monte Carlo is carried out.

In order to make the identification process as efficient and robust as possible, it is favorable to reduce the number of the parameters to be identified (consequently, the number of numerical simulation runs) by performing an effective sensitivity analysis. With this analysis, the importance of each unknown model parameter with respect to the system response is evaluated such that an effective selection of the dominating model parameters is achieved. For this purpose, two global sensitivity analysis approaches, namely elementary effect and variance-based analyses, have been adopted and validated. In the elementary effect approach a strategy for considering the dependencies, which result from a set of constraints between different parameters, is proposed. As a result, the propagating sensitivities of subsoil parameters during the excavation process of the mechanized tunnel are achieved. On the basis of this, an efficient choice of the parameters that have to be identified is enabled.

The computationally expensive finite element tunnel simulation has been replaced by an accurate meta-model. In this regard, and in order to construct robust and reliable meta-models, three meta-modeling approaches have been implemented and tested. These approaches are quadratic polynomial regression QPR, moving least squares MLS, and proper orthogonal decomposition with radial basis functions POD-RBF. Furthermore, an extended version of the latest approach is proposed and implemented. This version constitutes a combination of proper orthogonal decomposition with extended radial basis functions and is abbreviated as POD-ERBF. Its performance has been systematically compared with the three aforementioned methods through a comparative study utilizing pure mathematical test functions. With this study the best performing meta-model, which is the extended version of POD-RBF, is selected to replace the tunneling simulation model in the system identification and global sensitivity analysis.

For the evaluation of influences of subsoil parameter uncertainties on the mechanized tunnel safety and stability, a probabilistic analysis has been performed. In this analysis, the input parameter uncertainties are mathematically represented by adequately chosen probability density functions, consequently, the propagation of these uncertainties are evaluated by performing a Monte Carlo-based simulation of the computationally cheap surrogate model that is developed to replace the computationally expensive finite element tunnel simulation. In addition to that, a global sensitivity analysis is conducted for quantifying the impact of each uncertain parameter on different system responses that are considered in this study. The variations of system responses, which result from input parameters propagating uncertainties, are compared with predetermined threshold values, and based on that, reliability-based failure criteria of the tunneling system are defined and probabilistically quantified. As a result, the influence of subsoil parameter uncertainty representation on failure probabilities is addressed and evaluated.

Short biography – After obtaining a M.Sc. degree in Computational Engineering at Ruhr-Universität Bochum in Germany in October 2010, I started my PhD study in November 2010. My research work is part of the Collaborative Research Center SFB 837 "Interaction Modeling in Mechanized Tunneling", funded by the German Research Foundation DFG. I work within sub-project C2 "System identification methods for the adaptation of numerical simulation models". My research focuses are: System identification considering uncertainties, Bayesian inverse analysis, global sensitivity analysis, meta-modeling, and failure analysis of the mechanized tunnel due to subsoil parameter uncertainties.