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Model update and real-time steering of tunnel boring machines using simulation-based meta models

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ABSTRACT

A method for the simulation supported steering of the mechanized tunneling process in real time during construction is proposed. To enable real-time predictions of tunneling induced surface settlements, meta models trained a priori from a comprehensive process-oriented computational simulation model for mechanized tunneling for a certain project section of interest are introduced. For the generation of the meta models, Artificial Neural Networks (ANN) are employed in conjunction with Particle Swarm Optimization (PSO) for the model update according to monitoring data obtained during construction and for the optimization of machine parameters to keep surface settlements below a given tolerance. To provide a rich data base for the training of the meta model, the finite element simulation model for tunneling is integrated within an automatic data generator for setting up, running and postprocessing the numerical simulations for a prescribed range of parameters. Using the PSO-ANN for the inverse analysis, i.e. identification of model parameters according to monitoring results obtained during tunnel advance, allows the update of the model to the actual geological conditions in real time. The same ANN in conjunction with the PSO is also used for the determination of optimal steering parameters based on target values for settlements in the forthcoming excavation steps. The paper shows the performance of the proposed simulation-based model update and computational steering procedure by means of a prototype application to a straight tunnel advance in a non-homogeneous soil with two soil layers separated by an inclined boundary.

1. Introduction

Increasing urbanization and the need for environmentally friendly urban transportation and national and trans-national high-speed mobility has increased the need for underground transportation systems and safe and efficient construction technologies. Mechanized tunneling is a well established construction technology that allows for tunnel advances in a wide range of geological environments, high ground water pressures or small cover depths often met in urban tunneling. It is characterized by a construction process involving complex interactions between the surrounding underground, the groundwater, the support measures at the face and the tail void and the Tunnel Boring Machine (TBM) (Maidl et al., 1996).

Although the continuous increase of efficiency of modern computer technology and the considerable progress in computational structural mechanics have stimulated the development of numerical simulation models in tunneling since the early 1980s, compared to the larger number of models developed in the context of New Austrian Tunneling Method (NATM) (see, e.g. (Beer, 2003) and references therein), only a relatively small number of fully three-dimensional numerical models exist for shield tunneling due to its considerably more complex nature, see, e.g. (Bernat and Cambou, 1998; Komiya et al., 1999; Dias et al., 2000; Swoboda and Abu-Krisha, 1999). These models are based upon a pre-defined excavation path determined by the mesh discretization and do not allow for the simulation of the actual steering process accomplished by the elongation of hydraulic jacks and its effect on the actual movement of the tunnel boring machine in the soil. However, this capability is required if computational methods should be employed to support the steering process in machine driven tunneling.

A prototype for a process-oriented, three-dimensional, finite-element (FE) model for simulations of shield-driven tunnels in soft, water-saturated soil has been proposed by Kasper and Meschke (2004) and successfully used for systematic numerical studies of interactions in mechanized tunneling (Kasper and Meschke, 2006). Based on the simulation model presented by Kasper and Meschke (2004) a model for mechanized tunneling has been

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developed by Nagel et al. (2010), using a more advanced and flexible software architecture (Nagel et al., 2010). The model incorporates realistic models for all relevant components involved in mechanized tunneling (fully and partially saturated soft soils, the shield machine, the segmented lining, the face support, and the tail void grouting) and closely follows the construction stages on site. Furthermore, it is characterized by an automatic model generator (Stascheit et al., 2007) and an adaptive technique for re-meshing in the vicinity of the tunnel face (Alsahly et al., 2013).

However, although modern programming concepts such as object-oriented modeling and parallelization techniques (Bui et al., 2013) are used, the enhanced capabilities and accuracy enabled by such sophisticated 3D FE models have to be paid by a larger effort for the model generation and a higher computational cost for the actual simulation. If numerical simulation models are to be used directly for the support of the tunneling process during construction, real-time predictions are required, which evidently is only possible either using massive parallelization or, alternatively, computationally cheaper meta (surrogate) models. This strategy is adopted in the present paper by proposing Artificial Neural Networks (ANNs) to be trained by means of the full-scale simulation model for a certain project section a priori, i.e. in the design stage to replace the far more expensive 3D numerical simulations for the purpose of real-time predictions of surface settlements, parameter identification and process optimization.

Due to evident need for rapid computation, robustness and adaptability in all areas of process simulations, in the last 20 years simulation-based meta models have been developed to substitute numerical simulations. Meta models (Kleijnen, 2008; Friedman, 1996) are used to represent the dependency between the simulation input and output, learning the multiple relations between different parameters and mapping them to a given output. Different methods are used to provide compact representations for the simulation model, e.g. regression models (Kleijnen, 1979), ANNs (Fonseca et al., 2003), radial basis functions (Hussain et al., 2002), Kriging or spatial correlation models (Kleijnen, 2008; Ankenman et al., 2010), response surfaces (Kleijnen et al., 2000), game theory models (Poropudas and Virtanen, 2010) and proper orthogonal decomposition (Buljak, 2012). Those models are used for simplifying and interpreting simulation models (Friedman, 1996), conducting sensitivity and what-if analyses as well as optimizing the simulation output (Cheng and Currie, 2004). In geotechnical problems, ANNs have been applied as meta models trained with numerical simulations and used for the prediction of the deformations induced by geotechnical interventions (Duan and Sterling, 2002; Tsekouras et al., 2008; Pichler et al., 2003).

Although ANNs have shown excellent performance for mapping given tunneling conditions and parameters to a specified output parameter (such as settlements), there is still the question of the reliability of data used for the training. In geotechnical problems, and in particular in mechanized tunneling, information is usually generated in the design phase based on explorations from a limited number of locations. Consequently, during the construction, the geotechnical conditions may differ considerably from the a priori assumptions in the design stage.

This fact raised an interest in the application of inverse parameter identification strategies and optimization algorithms to geotechnical modeling in order to update the actual material and model parameters at certain stages of the construction. Since such analyses require a large number of simulations and an automated procedure for execution, sufficiently fast computer hardware is required. Therefore, automated techniques of inverse analysis for geotechnical processes have been investigated e.g. in Calvello and Finno (2004), Feng et al. (2006), Schanz et al. (2006), Meier (2008). The difficulty related to methods of inverse analysis like Particle Swarm Optimization (PSO) is that they need a large number of realizations. This problem can be solved by using substitute numerical models for evaluation (Song et al., 2011).

In the paper, a procedure for a simulation-supported steering of tunnel boring machines is proposed, using ANN as a meta (or surrogate) model to substitute the full process-oriented model for predictions made in real time during construction. More specifically, the meta model is used for the update of soil parameters according to monitoring data by means of inverse analysis using PSO. After the model and/or material parameters are updated according to the measurements during the tunnel advance, the combined ANN-PSO model is also used for the optimization of the steering parameters, such as the grouting or the face pressure, according to pre-defined target values for the tolerable settlements in the forthcoming excavation stage.

The remainder of this paper is organized as follows: Section 2 motivates the need for numerical steering of the tunneling process and describes the concept, methods and potential applications of the proposed model. Section 3 describes a numerical experiment for mechanized tunneling based on the process-oriented simulation model `ekate` (Nagel et al., 2010). In Section 4, methods used for establishing meta model and performing a back-analyses of measurement data are described. Finally, in Sections 5 and 6, a numerical example of the application of the proposed method characterized by a straight tunnel advance in a heterogeneous soil is presented.

2. Simulation-supported real-time steering in mechanized tunneling

Mechanized tunneling is an industrial processes with a high degree of mechanization, which is characterized by the repeated sequence of individual steps of the process: the thrust of the TBM through hydraulic jacks, the excavation of the soil at the face by the cutterhead and the installation of the next segment ring while the machine is stopped. In order to ensure the stability of the surrounding soil, minimize settlement and prevent the ingress of groundwater into the tunnel, the boring process is accompanied by a range of support measures: the face is supported in the excavation chamber by a pressurized support medium, the soil stands in frictional contact with the shield skin and the annular gap, which is created between the segment lining and ground, is filled with grouting mortar at the same time as the machine is thrust forward (Fig. 3). The control of TBMs is supported by a vast amount of monitoring data and machine data, gathered more or less continuously during construction. Decisions on TBM operation depend on the experience of the engineering staff.

Having process-oriented computational models for mechanized tunneling in soft soils (Nagel et al., 2010; Meschke et al., 2013) available by now, the question arises if such advanced prognosis tools can be applied to support the steering process during construction. As a prerequisite, two problems have to be solved: firstly, the prognosis obtained from the computational model must be available in real time, i.e. in the range of minutes, and secondly, the parameters used within the model must reflect the actual conditions of the project (i.e. geological situation, existing buildings, etc.).

During the design phase of a tunneling project, geotechnical information is only available from point-wise exploration at discrete boreholes. This information is generally used as the source for determining model parameters for numerical analysis models. Consequently, due to the limited spatial information on the ground properties, the material parameters adopted for numerical analyses in the design stage often do not fully reflect the in situ situation which will be later met during tunnel construction. Since in contrast to the design stage, abundant information from continuous monitoring is available during tunnel construction, these data