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A hybrid finite element and surrogate modelling approach for simulation and monitoring supported TBM steering

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ABSTRACT

The paper proposes a novel computational method for real-time simulation and monitoring-based predictions during the construction of machine-driven tunnels to support decisions concerning the steering of tunnel boring machines (TBMs). The proposed technique combines the capacity of a process-oriented 3D simulation model for mechanized tunnelling to accurately describe the complex geological and mechanical interactions of the tunnelling process with the computational efficiency of surrogate (or meta) models based on artificial neural networks. The process-oriented 3D simulation model with updated model parameters based on acquired monitoring data during the advancement process is used in combination with surrogate models to determine optimal tunnel machine-related parameters such that tunnelling-induced settlements are kept below a tolerated level within the forthcoming process steps. The performance of the proposed strategy is applied to the Wehrhahn-line metro project in Düsseldorf, Germany and compared with a recently developed approach for real-time steering of TBMs, in which only surrogate models are used.

1. Introduction

Mechanized tunnelling is a flexible and efficient technology for the construction of underground infrastructure, which is characterized by a dynamic technological progress of tunnel boring machines (TBMs) and an increasing range of applicability to various ground conditions (Maidl et al., 2012). During TBM-driven tunnelling in urban environments, in particular in the presence of sensitive buildings, the risk of damage caused by construction-induced settlements needs to be limited. To this end, computational models are required to efficiently and reliably predict the expected response of the ground and existing infrastructure to the tunnel drive.

Engineering decisions during the construction process are based, besides the (often limited) a priori knowledge from analyses made in the design stage of the project, mainly on the interpretation of data from on site monitoring including data related to soil deformations, pore pressure and machine performance. However, the capacity of computational models to quantify the effect of engineering decisions on stability and safety at the construction site during the tunnel drive is not exploited.

The mechanized tunnelling process involves complex spatio-temporal interactions between the TBM, the tunnel structure, the surrounding soil and the existing infrastructure. In addition to empirical and analytical relations for the description of surface and subsurface settlements induced by tunnelling (Peck, 1969; Rowe et al., 1983; Pinto and Whittle, 2013), 2D and 3D numerical analyses have been applied (see Swoboda and Abu-Krisha (1999), Komiya (2009), Meschke et al. (2013), Do et al. (2014) and references therein) to model the tunnelling process and the physics behind it more accurately.

Numerical analyses of geotechnical problems are characterized by a large number of problem-dependent model parameters related, among others, to the geotechnical specifications of the ground. In case of tunnelling, these parameters may have a significant spatial variability (Phoon and Kulhawy, 1999). Furthermore, in the design stage, only limited information on the specific soil parameters is available from distinct boreholes, which limits the quality of the model parameters based upon these data. Therefore, in geotechnical analysis, to reduce the uncertainty of model parameters, back analysis based on in situ measurements is often used for the calibration of numerical models to determine more reliable

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updated model parameters. Several authors have addressed inverse analysis for geotechnical processes, see e.g. Calvello and Finno (2004), Schanz et al. (2006), and Meier (2008). If optimization algorithms such as Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995) are used for inverse analyses, often a large number of realizations is required. Since this is connected with a prohibitively large effort if large-scale 3D finite element models are used, often surrogate models (alternatively also denoted as meta models) are employed for the evaluation of the objective functions (Deng and Lee, 2001; Pichler et al., 2003). In Ninić and Meschke (2015), this approach is used for back analysis of material parameters and steering of the mechanized tunnelling process.

Surrogate models are a compact representation for the simulation model, and can be generated based on different methods, e.g. regression models, Artificial Neural Networks (ANNs), Proper Orthogonal Decomposition (POD), etc. (see Ninić and Meschke (2015), Khaledi et al. (2014) and references therein). In geotechnical problems, ANNs have been applied as surrogate models trained by means of numerical simulations and used e.g. for the prediction of the deformations induced by geotechnical interventions (Pichler et al., 2003) or for the prediction of tunnelling-induced settlements (Kim et al., 2001; Suwansawat and Einstein, 2006; Ninić et al., 2013; Ninić, 2015; Stascheit et al., 2013a). Hybrid surrogate modelling approaches in mechanized tunnelling combining POD and ANNs are presented in Cao et al. (2016) and Freitag et al. (2015).

For computational prognoses during construction (almost) real-time predictions are required. If numerical simulation models would be employed, the required continuous model update during the tunnel drive would only be possible using massive parallelization. This is not feasible for most practical applications. To overcome this obstacle, an approach to support the TBM steering based upon surrogate models has been proposed in a recent paper by the authors (Ninić and Meschke, 2015). Feedforward neural networks have been used to substitute the computationally demanding 3D finite element simulation models. Evidently, this approach only provides an approximation of the tunnelling-induced settlements, which relies on the a priori parameterization of the surrogate model. It is not able to provide detailed information on the tunnel-ground interaction with a resolution comparable to an advanced numerical simulation model. Therefore, in this paper, a novel hybrid FE-surrogate modelling strategy is proposed for the support of the TBM steering during construction with model parameters updated according to monitoring data in association with adequately designed surrogate models used to determine optimized steering parameters. In contrast to Ninić and Meschke (2015), Recurrent Neural Networks (RNNs) (Freitag et al., 2011) are employed, which are able to account for history-dependent processes. This approach combines the advantage of surrogate models to provide fast computations needed for the numerous realizations involved in the parameter identification and the iterative determination of optimal steering parameters with the accuracy provided by a process-oriented finite element model in regards to the consequences of the tunnel drive on ground deformations, buildings, lining stresses, etc.

The proposed strategy is demonstrated by means of real project data from the Tunnelling Information Model (TIM) (Amann et al., 2013) of the Wehrhahn-line (WHL) metro project in Düsseldorf. Based on the project data, sensitivity analysis are conducted first to preselect a set of relevant material and machine-operational parameters, which are then used to set up numerical simulations using a process-oriented 3D Finite Element (FE) simulation model for mechanized tunnelling (Meschke et al., 2013; Nagel et al., 2010) in order to generate the surrogate model. In this work, an RNN surrogate model (Freitag et al., 2011) is applied, which is trained using an optimized back-propagation algorithm (Ninić and Meschke, 2015).

The remainder of the paper is organized as follows: Section 2 introduces the overall concept for simulation-supported steering in mechanized tunnelling, the RNN and the hybrid FE-surrogate modelling approach. In Section 3, the 3D FE model for a selected section of the Wehrhahn-line metro project in Düsseldorf is presented. Using a complete data set of the selected project section, the generation of the surrogate model, the parameter identification and the model-supported steering is demonstrated in Section 4. In this section, also a comparison with a recently proposed approach for real-time steering based on surrogate models only is provided.

2. TBM steering concept combining surrogate models and finite element simulations

Prior to the construction of a TBM-driven tunnel, the parameters of the tunnel boring process to be used in the project are determined in the design stage according to geological explorations to satisfy design objectives such as tolerated surface settlements, safety against loss of face stability and other specific construction requirements. However, during tunnel construction, due to on site ground conditions, which differ from the original assumptions, the settlements often exceed tolerated values. This is of particular importance in tunnelling in urban areas, where the existing infrastructure may be affected by damage caused by tunnelling-induced ground settlements. Controlling the TBM process parameters, denoted in the following also as steering parameters (i.e. the support pressure, grouting pressure, advance rate, etc.), it is possible to control the surface settlements and to reduce or even prevent damage of existing infrastructure.

The conceptual outline of simulation-supported process control in mechanized tunnelling is illustrated in Fig. 1. It contains the generation of surrogate models in the design phase, the model update based on monitoring data and the determination of optimal steering parameters to keep the ground settlements below tolerated values.

After the selection of the relevant project sections, in which the steering support will be needed, surrogate models are generated in the design phase of the project especially for these sections.

A 3D numerical model of a tunnelling project characterized by a complex geotechnical situation generally requires a large number (from around ten to more than 100) parameters to characterize the geotechnical model, the alignment, the TBM and the lining shell, including a number of operational parameters and parameters related to the existing infrastructure. Some of the model parameters are well determined (geometry of TBM and lining), while geotechnical parameters such as the topology of soil layers and material parameters of the soil are usually associated with uncertainties and hence are provided in general only as a set of admissible ranges.

If all uncertain parameters are taken into account, it would be extremely time consuming to reach a good quality of the surrogate model. Therefore, prior to the generation of the surrogate model, a sensitivity analysis has to be conducted to determine a set of important parameters sensitive to the output of the model (Ninić and Meschke, 2015). Based on pre-selected important parameters, a reliable surrogate model is generated in the design phase as shown in Fig. 1. The algorithm for the generation of reliable surrogate models for tunnel sections is summarized in Appendix A (Table 3). In this paper, an RNN is used for the generation of the surrogate model. RNNs (in contrast to feedforward ANNs) are able to represent space-time dependencies, which is essential to consider time-dependent processes occurring during the mechanized tunnelling. The RNN model is described in the following Section 2.1.

The surrogate model is used for the update of geotechnical parameters according to monitoring data acquired on site during