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Recurrent neural networks and proper orthogonal decomposition with interval data for real-time predictions of mechanised tunnelling processes

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ABSTRACT

A surrogate modelling strategy for predictions of interval settlement fields in real time during machine driven construction of tunnels, accounting for uncertain geotechnical parameters in terms of intervals, is presented in the paper. Artificial Neural Network and Proper Orthogonal Decomposition approaches are combined to approximate and predict tunnelling induced time variant surface settlement fields computed by a process-oriented finite element simulation model. The surrogate models are generated, trained and tested in the design (offline) stage of a tunnel project based on finite element analyses to compute the surface settlements for selected scenarios of the tunnelling process steering parameters taking uncertain geotechnical parameters by means of possible ranges (intervals) into account. The resulting mappings of time constant geotechnical interval parameters and time variant deterministic steering parameters onto the time variant interval settlement field are solved offline by optimisation and online by interval analyses approaches using the midpoint-radius representation of interval data. During the tunnel construction, the surrogate model is designed to be used in real-time to predict interval fields of the surface settlements in each stage of the advancement of the tunnel boring machine for selected realisations of the steering parameters to support the steering decisions of the machine driver.

1. Introduction

Mechanised tunnelling is an efficient tunnelling technology for the construction of new underground infrastructures, in particular in urban environments. During the construction process, it is required to reduce the tunnelling induced settlements or to avoid that tolerances with respect to settlements, which eventually may result in damage of existing structures, are exceeded. The settlements can be controlled by adjusting the process parameters such as the face support pressure at the tunnel face, the grouting pressure of the grouting material injected into the gap between the tunnel lining and the surrounding soil, and the advance speed during the tunnel advancement [1]. Currently, decisions affecting the steering of tunnel boring machines (TBMs) are based upon engineering expert knowledge and monitoring data. However, using monitoring data implies that information (data) related to already passed situations is used to extrapolate on the future behaviour of the soil-tunnel interactions. In this paper, an approach is presented, in which a computational model is used to support TBM steering by providing predictions on the expected settlement field in real time during the construction. Epistemic uncertainties of the geotechnical parameters are taken into account by means of interval data.

In recent years, numerical methods, in particular the finite element method, have become a standard tool for predictions of interactions between the tunnel construction and the surrounding soil in the design phase of mechanised tunnelling projects. A large number of 3D finite element simulation models have been developed to represent the staged tunnelling process, characterised by a repeated sequence of soil excavation, advancement of the TBM and the installation of a new ring of lining segments (see [2–5] and references therein). More recently, a process oriented 3D numerical model for shield-supported tunnel excavation in fully saturated soft soils has been developed in [6], taking into account the most important components of mechanised tunnelling and their mutual interactions. In this computational model, a realistic representation for the soil excavation process following arbitrary alignments is enabled by means of an adaptive re-meshing technique [7]. Using this numerical model, uncertain geotechnical

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conditions and the interaction of the relevant components involved in the construction process have been investigated in [8,9]. Considering the large computational effort for realistic tunnelling models, parallelisation techniques are addressed in [10].

Information on the geotechnical situation, such as the topology and specification of the soil layers and the soil material parameters, can only be obtained from a few borehole data in the design stage of a project. This uncertainty resulting from limited information has to be adequately considered, when mechanised tunnelling simulations are used as the basis for the tunnel design. Stochastic numbers can be used to quantify aleatoric uncertainty considering spatial variability of geotechnical parameters by random fields, see e.g. [11,12]. However, a sufficiently large number of samples is required to select an adequate stochastic model and estimate the corresponding model parameters. In geotechnical reports of tunnelling projects, however, often only a few number of samples are provided to quantify the uncertainty of soil parameters. Moreover, the correlation function and the correlation length within random field approaches must be defined, which, due to insufficient data, are often based on assumptions without physical meaning. An alternative to stochastic approaches are non-stochastic or polymorphic uncertainty models, see e.g. [13]. Non-stochastic approaches such as methods based upon ranges (intervals) of parameters are frequently used in geotechnical engineering and tunnelling in the context of rock mass classifications within the rock mass rating system [14] or by means of fuzzy models [15]. A comparison of geotechnical analysis using stochastic numbers and intervals is contained in [16]. Polymorphic uncertainty models using probability boxes (p-boxes) have been applied within a random set finite element analysis for reliability assessment of tunnel construction according to the New Austrian Tunnelling Method in [17]. A holistic concept for reliability analyses in mechanised tunnelling with polymorphic uncertain data based on stochastic, interval, fuzzy, and imprecise probability approaches is presented in [8] and applied to a mechanised tunnelling simulation with fuzzy stochastic and fuzzy soil parameters in [9].

In this paper, a non-stochastic approach based on interval data is proposed for real-time predictions of tunnelling induced surface settlements. Thereby, the ranges for expected geotechnical parameters of the soil layers given in the geotechnical reports are directly quantified as intervals without requiring any further assumptions, e.g. in terms of stochastic distributions or fuzzy membership functions.

In order to support TBM steering directly at the construction site, the simulation results are required in real-time. "Real time" means a duration for the analysis, which is significantly smaller compared to the time required for one construction stage, consisting of an excavation and machine advancement step, the segmented tunnel ring installation and the tail void grouting. The time required for one construction step depends on the geological situation and is typically in the range between 2 and 4 h. Hence, a real time prediction should be performed in the range of seconds to a few minutes. Moreover, the TBM steering assistant system, which is currently developed within project C1 of the Collaborative Research Center SFB 837 "Interaction Modeling in Mechanised Tunnelling" aims to provide predictions for user-defined realisations of the steering parameters in a few seconds. Evidently, for such real-time predictions, surrogate models are inevitable to substitute the expensive and complex finite element simulation model in mechanised tunnelling. Different methods can be used for generating simulation based surrogate models, including regression models [18], artificial neural networks [19,20], stochastic approaches such as Kriging or spatial correlation models [21,22], response surface methods [23], or proper orthogonal decomposition (POD) [24]. A study on the performance of different surrogate modelling techniques (quadratic polynomial regression, moving least squares, POD with radial basis functions (RBF), and an extended version of POD-RBF) for application in mechanised tunnelling problems is presented in [25]. In [26], a procedure for the steering of TBMs based upon artificial neural networks used as surrogate models has been proposed. However, in this method, parameter uncertainties have not been considered.

In this paper, a hybrid surrogate modelling strategy proposed in [27] is used to support decisions related to the steering of the TBM during tunnel construction in real time, taking uncertainties of geotechnical parameters into account. The hybrid strategy is based on a combination of Recurrent Neural Networks (RNN) and Gappy Proper Orthogonal Decomposition (GPOD) methods and can predict (extrapolate) tunnelling induced uncertain time and spatially varying surface settlements. Based on RNN predictions at selected monitoring points of the settlement field, the GPOD method is used to predict the whole surface field of settlements induced by the mechanised tunnelling process. In [27], an optimisation approach based on Particle Swarm Optimisation is utilized to predict the interval bounds of tunnelling induced settlement fields, considering uncertain soil parameters by means of intervals. However, this requires one to two hours on a standard notebook or parallel runs on a computing cluster to reduce the computational time, which limits its practical application for real-time predictions at construction sites. Therefore, the objective of the new surrogate modelling approach is to provide interval surface settlement predictions in real-time, i.e. in a few seconds using a standard notebook computer. This paper is based upon [28], where the calibration of the hybrid surrogate model with monitoring data and an application for real-time predictions on a standard notebook computer has been presented. As an extension, this paper includes additional research on computing the hybrid RNN-GPOD surrogate model with interval data based on the midpoint-radius representation to directly account for uncertain geotechnical parameters when performing the analysis. The RNN and GPOD surrogate models are split for midpoint and radius computations of the interval data, respectively. While the midpoint computations are identical to the approach presented in [28], the radius computations are restricted to positive numbers. To account for this constraint, we propose using Non-Negative Matrix Factorisation for the GPOD part and adequate activation functions in the RNN part of the hybrid surrogate model.

The remainder of this paper is organised as follows. Section 2 gives a brief description of the process-oriented finite element model for numerical simulations of mechanised tunnelling processes, which is used for the training of the surrogate model. In Section 3, the mapping and computation of processes with interval data is introduced for time variant settlement field predictions in mechanised tunnelling. The new RNN-GPOD surrogate modelling approach for interval data is presented in Section 4. The verification with an analytical solution and an application example are finally shown in Section 5.

2. Finite element model for mechanised tunnelling simulation

In this paper, the process-oriented finite element simulation model `ekate` [29] is used for the simulation of the shield tunnelling processes in fully and partially saturated soft soils. The simulation model `ekate` has been developed within the object-oriented finite element framework KRATOS [30]. The finite element model considers all relevant components of the tunnel construction process (soil and groundwater conditions, tunnel lining, the TBM with shield and hydraulic jacks, tail void grouting and various types of face support) and their (time dependent) interactions, as shown in Fig. 1.