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Model validation and calibration via back analysis for mechanized tunnel simulations – The Western Scheldt tunnel case

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ABSTRACT

In this research, Finite Element (FE) method is applied to simulate the shield supported mechanized excavation of Western Scheldt tunnel in the Netherlands. Both 2D and 3D numerical models are created to predict the system behavior. Sensitivity analysis and parameter identification techniques are utilized to calibrate and validate the model based on field measurement. The mechanical behavior of the soil is modeled by an advanced elasto-plastic model, namely Hardening Soil model correlating small strain stiffness (HSS). Global sensitivity analysis is carried out in this paper to evaluate the relative sensitivity of model response to each input parameter. Thereafter, a parameter identification technique (back analysis) is employed to find the optimized values of the selected parameters. To accomplish this, the computationally expensive FE-model is replaced by a meta-model in order to reduce the calculation time and effort. Moreover, a soft soil constitutive model based on the modified Cam-clay model deals with primary compression of fine grained soils, is assigned to the clay layer to further improve the numerical prediction of system behavior. Due to the importance of model subsystems, such as face pressure and volume loss, the sensitivity of model response to subsystems has been evaluated. The results show that optimized parameters obtained via back analysis make the numerical simulation capable to well predict the ground settlement.

1. Introduction

Shield supported tunneling by Tunnel Boring Machine (TBM) has become a well-established tunnel construction method in various ground conditions [1]. One of the most important objectives of mechanized tunneling is to keep the ground deformation, especially the surface settlement, as small as possible. Numerical simulation is widely applied before and during tunnel construction to provide reliable prediction of soil deformation which is highly dependent on the constitutive model and its parameters used along the investigated tunnel length.

Sophisticated constitutive models have been employed in the past to consider the complex interactions between the soil and the TBM. However, such models contain large numbers of constitutive parameters. Some parameters are difficult to obtain due to the complex and expensive in situ or laboratory tests. It means uncertainty is embedded in the constitutive parameters. Moreover, the constitutive models have their own assumptions, e.g., soil is treated as an isotropic material in Hardening Soil model correlating small strain stiffness even though the anisotropic behavior during test is commonly observed. In other words, there are uncertainties in the models as well as in the measured data. In order to confirm that the physically right model is used, it is necessary to conduct model validation. Since some input parameters are still uncertain, calibration is carried out to conduct parameters identification to minimize the discrepancy between measurement and numerical predictions. Calvello and Finno [2] calibrated the elasto-plastic Hardening Soil model by minimizing the value of objective function based on experimental data and field measurement.

When the constitutive model is implemented in the numerical simulation, uncertainty of model response is generated due to the propagation of input parameters uncertainty, assumptions used in constitutive model, etc. This paper mainly focuses on uncertainty of input parameters. In order to evaluate how the uncertainty of model response can be distributed to the uncertainty of input parameters, Sensitivity Analysis (SA) technique

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can be applied. By conducting SA, the key parameters that govern the model response can be identified, and it is valuable to evaluate the importance of input parameter with considering the expense of laboratory or in situ investigation. Sensitivity analysis has been also employed in geotechnical applications. Miro et al. [3] conducted global sensitivity analysis to detect the key subsoil parameters that influence the output of mechanized tunneling finite element simulation using synthetic measurements.

It is to be noted that even the regular soil parameters may not be characterized properly using the experimental data (due to the influence of the accuracy of experimental instruments, operation skill of the experimenters, etc.). However, back analysis can be applied in any case to identify the values of the uncertain parameters based on the field measurements, such as displacement or pore pressure observed during construction. Back analysis technique as a practical engineering tool is nowadays widely used in engineering problems. It has been used to identify soil parameters in laboratory or in situ tests [4], excavation support systems [2], excavation of tunnel in rock [5] and embankment construction on soft soils [6]. Meier et al. [7] concluded that back analysis offers a promising tool for gaining information of material and geometrical features in different geotechnical projects. To summarize, it can be concluded that in case of tunneling simulation, it is difficult to obtain the values of all constitutive model parameters, as this is related to the expensive or time-consuming in situ and laboratory tests as well as because not all parameters can be directly derived from the test data. To determine the soil properties, iterative back analysis is applied as indirect method to conduct parameter identification based on less experimental data.

The methodology illustrated in this paper is outlined as follows: Numerical model is created to overall evaluate the model response with initial guess of model parameters. Sensitivity analysis is applied to rank input parameters' importance to reduce the dimension of the back analysis problem. Back analysis is used to conduct parameter identification. Model calibration and validation are conducted based on the measured data. This methodology can be applied to any practical engineering problem. In this research, mechanized tunnel excavation is simulated to demonstrate this methodology.

Mechanized tunneling is a complex engineering problem involving various processes such as consequential excavation, grouting and lining installation [8]. Kasper and Meschke [9] presented a 3D finite element model to take into account all relevant components of the construction process (e.g. the hydraulic jacks, the steering of the TBM). However, for the practical design purpose, one may focus on the most important factors of the excavation process. For the sake of simplicity and robust prediction, the 3D numerical model of the Western Scheldt tunnel takes into account the consequential advancement of the TBM, face support, grouting of the annular gap due to conical shape of the TBM-shield and the overcut zone.

Compared to 3D model, 2D numerical simulation of mechanized tunneling does not take into account the inclination of the tunnel, consequential advancement of the TBM and face support. However, it provides a good approximation of the model response for a defined observation section and it is popularly applied in engineering practice [10]. For the comparison of model responses in 3D and 2D models, a simplified 2D FE-model is created to simulate the construction of Western Scheldt tunnel. In order to evaluate if the optimized parameters obtained within 2D back analysis are adequate in predicting the model response, they are used in both 2D and 3D models to check the discrepancy between numerical results and measured data. In addition to the surface settlement, other model responses, such as lining force and stress path are also compared.

2. Methodology

2.1. Numerical simulation of shield supported tunneling

The Western Scheldt tunnel (Dutch: Westerschelde tunnel) is a shallow twin road tunnel under the estuary of the Scheldt river in the Netherlands and it was constructed by slurry shield machine. The east line is the one investigated in this paper. The geology along the tunnel is made up of different sand and clay formations. The mechanical properties of the soil layers around the excavation zone were obtained based on conventional in situ and laboratory tests. The groundwater level is influenced mainly by the North Sea and it is about 1.5 m below the ground surface during tunnel excavation. Ground settlements above the excavation domain were measured during the tunneling process.

To simulate the staged construction process, finite element code *PLAXIS* (version 2013[11]) is utilized. The excavation in clay and sand layers is modeled by means of slurry shield TBM. A length of 88 m tunnel excavation is simulated to conduct model calibration and validation. The tunnel has a diameter $D = 11.33$ m and an inclination of 4.3%. Furthermore, the TBM-shield including the cutter head is defined to be 12 m long. The tunnel lining consists of ring-shaped prefabricated concrete segments. After a preliminary study of boundary effects, the 3D FE-model is set up with dimensions of 150 m (almost 13D) long in *X*-axis direction, 100 m (almost 9D) wide in *Y*-axis direction and 71 m (almost 6D) deep in *Z*-direction (Fig. 1). These dimensions only represent half of the model due to the symmetry condition assumed with respect to the vertical plane that goes through the tunnel crown and invert. In the first step, a reference model was created by applying very fine finite element discretization. The solution in terms of ground settlements at the observation points was further considered as the "true" solution. In the next step, a model with coarser spacial finite element mesh was generated and the mesh coarseness factor in the area nearby the tunnel was varied until the maximum discrepancy between the current solution and the "true" solution became less than 0.5%. This last finite element mesh was further adopted in the presented hereafter analysis. The spacial discretization with a total number of 78,639 (10-node tetrahedral) elements and a typical shape of the mesh generated for the numerical simulation are shown in Fig. 1. Moreover, a constant water level of 1.5 m below the surface is assumed in numerical simulation.

When installing the lining segments, an annular gap remains between the lining segments and the soil [12,13]. In order to prevent large deformation of the surrounding soil, the gap is filled with grouting material. In the numerical simulation, the grouting pressure is modeled by a uniformly distributed load acting on the soil elements that directly follow the TBM-shield to avoid the collapse of surrounding soil. In this research, the value of grouting pressure is chosen as 150 kN/m^2 based on the measured data. The face support pressure is applied to avoid collapse of the soil at face of excavation [14,15]. In case of Western Scheldt tunnel construction, the face pressure distribution was varying during excavation process. Based on the geotechnical report, the measured face support pressure remained at a low level for the first several excavation steps. Thereafter, the pressure began to increase and finally the pressure reached a relatively high level compared to the face pressure applied at the beginning. This happened due to the fact that the overburden increased with the advancement of TBM. In initial numerical simulation, the pressure is simulated by a non-uniformly distributed load that increases from the tunnel crown (137 kN/m^2) towards the tunnel invert (250 kN/m^2) and this distribution is kept constant with the advancement of TBM. The value is defined according to the average face pressure during