Computers and Geotechnics 68 (2015) 38–53

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A probabilistic analysis of subsoil parameters uncertainty impacts on tunnel-induced ground movements with a back-analysis study

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ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form 25 February 2015
Accepted 28 March 2015
Available online 11 April 2015

Keywords:
Mechanized tunneling
Finite element simulation
Surrogate modeling
Global sensitivity analysis
Reliability analysis
Bayesian updating

ABSTRACT

In this paper a probabilistic-based analysis is presented for evaluating the influences of subsoil parameter uncertainties on tunnel-induced ground movements in mechanized tunneling. The procedures of the tunneling process using Slurry Shield Tunnel Boring Machine are numerically modeled and simulated by utilizing a finite element code. To keep the computational cost of the presented simulation model low, an efficient and reliable surrogate modeling technique is used to substitute the original simulation model. The input parameter uncertainties are mathematically represented by adequately chosen probability density functions within their extreme lower and upper bounds. Subsequently, a variance-based global sensitivity analysis is conducted for quantifying the impact of each uncertain parameter on different system responses that are considered in this study. Afterwards, the propagation of parameter uncertainties are evaluated by performing a Monte Carlo-based simulation using the computationally inexpensive surrogate model. At this stage, the variations of system responses, which result from input parameters propagating uncertainties, are compared with predetermined threshold values and, based on that, failure criteria of the tunneling system are defined as well as probabilistically quantified. In a last step, a Bayesian updating procedure is employed for reducing subsoil parameter uncertainties by utilizing recorded synthetic measurements.

1. Introduction

The safety and stability of tunnels as well as surface and subsurface adjacent structures and facilities are of utmost importance for a successful tunnel project. Therefore, the ground movements initiated by the tunneling process should be minimized and not be larger than admissible limits. In particular, large movements of the ground next to the tunnel can result in differential displacements of nearby structures and, consequently, can cause damages and fractures with the risk of failure.

In shallow tunnels, in particular, the tunneling-induced ground movements represent dangers and are a challenge that requires control and mitigation. Hereby, the movements of the ground are consequences of the redistribution of stresses and changes in pore water conditions around the tunnel face and tunnel cavity [1,2]. These movements are functions of the hydro-geological conditions of the ground, tunnel depth, tunnel geometry, and the excavation method [3]. A variety of analytical methods have been developed by several researchers for the prediction of these movements [4–11,2,12]. Furthermore, with the advancement of computational methods and computing power, numerical approaches are being widely used in simulating tunnel excavations and the consequent ground behavior. Among others, the reader is referred to [13–18]. In comparison with the analytical methods, the numerical methods, in particular 3D finite element simulations, are able to provide a comprehensive view of stress and strain distributions in the ground domain affected by the tunnel. Moreover, the numerical methods can explore the impact of additional supporting measures (such as anchoring and soil exchange) that are employed to further stabilize the tunnel.

In mechanized tunneling using tunnel boring machines (TBM) different methods and technologies are employed for reducing the ground displacements by supporting the tunnel face and cavity. Technologies such as mechanical support, compressed air, earth pressure balance, and slurry support are employed to back up the tunnel face [1]. The tunnel cavity, on the other hand, is supported by a TBM-shield followed by precast concrete segments together with grouting material injected to fill the gap between the segments and the excavated ground [1]. With these

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http://dx.doi.org/10.1016/j.compgeo.2015.03.012
0266-352X/

technologies the natural stress state of soil can be retained to a large extent and, as a result, the settlements can be reduced.

In spite of the aforementioned supporting approaches, ground movements are especially significant in shallow tunnels in soft soils. Here, the mechanical properties of the soil play a substantial role on these movements and their predictions. In particular, the soil characteristics are associated with inevitable uncertainties that result from: (i) the natural variability of soils, (ii) the measuring errors in quantifying the soil properties by site and laboratory tests, and (iii) the diminutive fraction of the investigated soil volume in comparison with the whole affected soil domain. According to [19], the fraction of the investigated soil using boreholes is only about 10^{-6} to 10^{-9} of the total site volume. In addition to that, accessibility to sufficient site exploration might be restricted because of surface overly or lack of permission [20]. To this end, studying the propagation of uncertainties in subsoil mechanical properties to tunnel-induced ground movements is essential for a reliable assessment of these movements. Furthermore, a systematic reduction of the aforementioned uncertainties by employing an appropriate inverse analysis methodology is vital for the tunnel project success. In this respect, back analysis methods in geotechnical engineering were first formulated and utilized in [21,22]. They were used, moreover, for estimating and identifying system parameters in many geotechnical applications, such as [23–28].

Mollon et al. [29] present a comprehensive study and methodology for evaluating the influences of soil parameter uncertainties on tunnel-induced ground movements that were predicted using a 3D finite element simulation. In this study we use an alternative approach for predicting the tunnel-induced ground movements with an advanced elasto-plastic soil constitutive model with isotropic hardening, namely the Hardening Soil Model (HS-Model) [30,31]. Moreover, the representation of the uncertain soil properties as random variables with probability density functions is discussed on the basis of introducing lower and upper extreme values. Additionally, a Bayesian back analysis approach [32] is adopted to reduce the uncertainties of soil properties during tunnel excavation and, consequently, to reduce the potential risk of uncertainty propagation to the ground movements. This work extends a recent paper [18] focused on a global sensitivity analysis of the same mechanized tunnel computational model.

The structure of this paper is outlined as follows: Section 2 includes a detailed description of the 3D finite element simulation of the shallow tunnel along with the predicted ground settlements and displacements. The probabilistic representation of input parameter uncertainties is discussed in Section 3. In Section 4 a surrogate model based on quadratic polynomial regression is introduced along with the variance-based global sensitivity analysis. In Section 5, a reliability analysis is performed for evaluating the impact of subsoil parameter uncertainty representations on the probability of failure through limit state functions. As a last step, in Section 6, a sequential Bayesian back analysis approach is conducted to update the subsoil parameter uncertainties based on synthetic data. The paper ends with a summary and conclusions in Section 7.

2. Mechanized tunnel 3D finite element simulation

2.1. Description of the simulation model

A three dimensional finite element software PLAXIS 3D, version 2012, is employed for simulating the mechanized tunneling process. In this simulation the excavation of homogeneous soil by means of a *Slurry Shield Tunnel Boring Machine* is modeled. Herein, an advanced elasto-plastic soil constitutive model with isotropic hardening, the *Hardening Soil* Model (HS-Model), is used. The parameters of the HS-Model are described in Table 1.

Fig. 1 illustrates the 3D FE-model of a shallow tunnel 90 m long in the *X*-axis direction, 45 m wide in the *Y*-axis direction, and 45 m deep in the *Z*-axis direction. These dimensions represent only one-half of the subsoil model, due to the symmetry of geometry, material properties, and initial and boundary conditions with respect to the vertical plane *X*–*Z* normal to the *Y*-axis. A discretization with a total number of 22,542 10-node tetrahedral elements and 34,841 nodes has been adopted after a preliminary study of the impact of different mesh sizes. The excavation length of this tunnel equals 60 m and its diameter *D* is 8.5 m. As the overburden is equal to $1 \times D$, the considered tunnel corresponds to a very shallow tunnel that is expected to result in large ground movements in real world projects [29]. The groundwater table is not considered in this study, however, it can easily be included in the numerical simulation. The shield of the TBM is taken to be 9 m long and simulated, besides the tubing that consists of annular precast concrete segments (1.5 m), as circular plate elements with a linear elastic model. The material properties of both the lining elements and the TBM-shield are given in Table 2.

Modeling the effect of the grouting material, which is injected in the gap between the excavated soil and the erected lining segments, is performed by a non-uniformly distributed load increasing with the depth. This load is directly applied to the soil elements that are located between the TBM shield and the last assembled tubing section. In a similar manner, the face support pressure, which is applied to counteract any active failure ahead of the TBM, is modeled as a non-uniformly distributed load that grows linearly from the tunnel crown to its invert. The contact area between the shield skin and the tubing with the adjacent soil is modeled by a 40% reduced shear strength of the enclosing soil. Hereby *interface elements* [33] are utilized. The tunnel excavation is performed by a step-wise procedure (45 steps). Further details about the developed simulation model can be found in [18,34].

2.2. Tunneling-induced ground movements

Most of the existing literature dealing with tunneling-induced ground movements discusses the distribution of surface settlements as a result of the tunneling process. These settlements, in the case of tunnel excavation in homogeneous soil, shape a trough that can be described by the longitudinal settlement along the tunnel axis, as well as the transversal settlement along a cross-section perpendicular to the tunnel axis. This is illustrated in Fig. 2. The maximum value of these settlements occurs at the tunnel axis behind the TBM-face in the stabilized area of the soil. In addition to surface settlements that constitute the major part of the ground movement induced by the tunneling process, other movements

Table 1
The description of hardening soil model parameters.

HS-model parameters	Description
ϕ (°)	Friction angle
ψ (°)	Dilatancy angle
c (kN/m^2)	Cohesion
E_{oed}^{ref} (kN/m^2)	Tangent stiffness for primary oedometer loading
E_{50}^{ref} (kN/m^2)	Secant stiffness in standard drained triaxial test
E_{ur}^{ref} (kN/m^2)	Unloading reloading stiffness
p^{ref} (kN/m^2)	Reference stress level
m (–)	Exponent of the Ohde/Janbu law
R_f (–)	Failure ratio
ν (–)	Poisson's ratio
γ_{unsat} (kN/m^3)	Unit weight (unsaturated)
R_{inter} (–)	Strength reduction factor for interfaces