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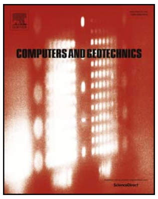

Research Paper

Mechanized tunneling induced building settlements and design of optimal monitoring strategies based on sensitivity field

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ABSTRACT

This study adopts the local and global sensitivity analyses to study the influence of the soil-tunnel-building system characters (e.g. soil properties, building's stiffness and position, tunnel volume-loss and embedment depth, soil-building interface properties) on the settlement and tilt of building. To properly update the design parameters during tunnel construction, a field sensitivity analysis is proposed to find the optimal position of the sensors in a priori to increase the quality of measurements (less uncertainty) which leads to efficient identification of the soil parameters from the measurements. The validity of this methodology is justified by applying it to a case study.

1. Introduction

Mechanized shield tunneling is a widely applied underground excavation technology that has significantly developed due to the urbanization process. The shield excavation method is an efficient and economic approach compared to the traditional tunneling method that not only increases the excavation speed, but also minimizes the tunneling induced deformations at the ground surface. In this approach, the soil is excavated by a cutting head and the machine advances by a thrust force provided by jacks reacting on the installed structural linings. In the urban environment, many buildings supported by shallow or deep foundations might be affected by underground tunneling. Tunnel excavation inevitably induces unloading due to soil mass removal and stress relaxation in the soil domain around the tunnel that leads to stress redistribution in the soil system. Consequently, the induced deformations can jeopardize the integrity of foundations themselves [13]. Thus, the effects on buildings in the vicinity of the tunnels should be evaluated to ensure that their influences do no exceed the allowable capacity of the structure.

The process of building damage assessment is usually conducted from preliminary evaluations to simple conservative approaches, and eventually to detailed procedures as introduced by Mair et al. [24]. In the preliminary stage, the zone where the ground surface settlement is induced by tunneling is determined. In the second stage, empirical-analytical methods, namely limiting tensile strain method and relative stiffness method, are utilized to calculate the strains and distortions in the buildings to determine the possible structural damages. The limiting tensile strain method was originally developed by Burland et al. [6] and further modified by Boscardin and Cording [4]. In this approach, the greenfield displacements are imposed to a simplified beam model of the building. The maximum bending strain, maximum diagonal strain and beam horizontal strain are evaluated. After that, the total strain can be calculated to be compared to the limit values to determine the damage class. It should be noted that in this approach, the soil-structure interaction is not considered. Due to this reason, Potts and Addenbrooke [30] proposed the relative stiffness method for improving the limiting tensile strain method to include the soil-structure interaction, and this method was further developed by Franzius et al. [12] and Son and Cording [40]. In their approach, the relative stiffness of the building compared to the soil is evaluated. The modification factors are defined to associate the specific features of the building and its behavior (deflection ratio and horizontal strain). The third step of a detailed assessment is necessary if there are buildings in the second step being classified in the damage category. Accordingly, an accurate analytical or complex numerical analysis that accounts for details of the building and soil-structure interaction should be conducted [13].

In order to investigate the realistic ground behavior during tunneling, Shahin et al. [37] conducted 2D model tests on tunnel excavation beneath an existing building. They also conducted non-linear finite element analyses in accordance with their model tests. They revealed that surface settlement was highly dependent on the distance between tunnel and building where the building might be significantly affected even by deep tunneling. Elsaied [9] studied the influence of tunneling on settlements induced in adjacent building by considering variable tunnel diameters, overburden depths and horizontal distances between the tunnel and building in a 2D numerical model. However, the

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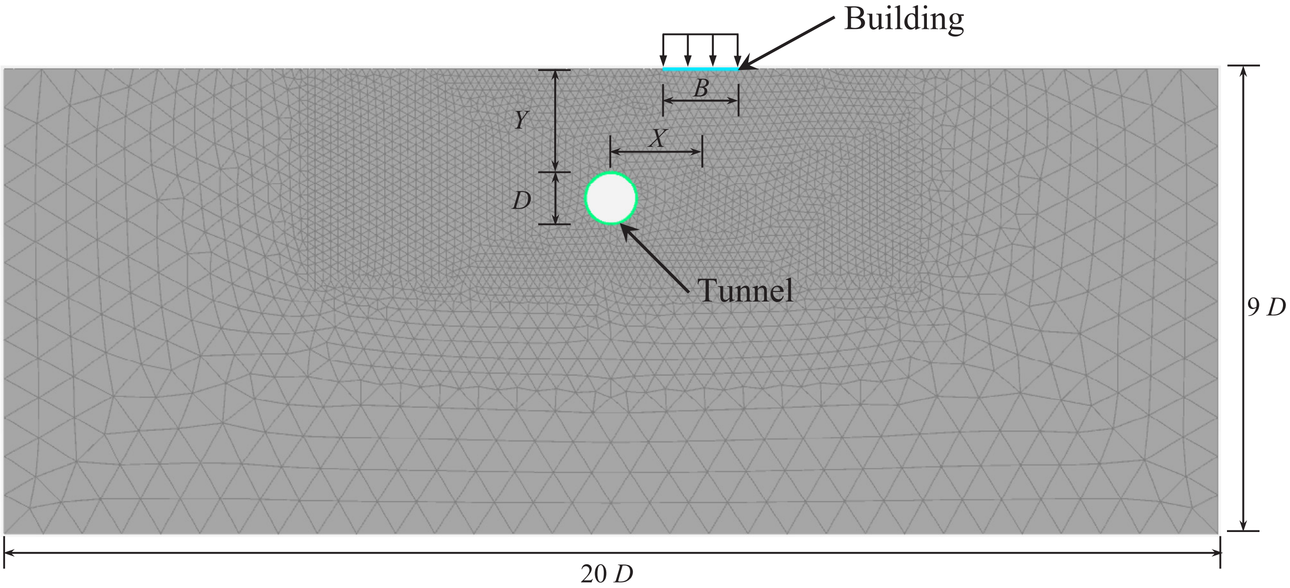

Fig. 1. Geometry and mesh discretization of the tunneling model (where $D = 8.5\,\text{m}$ is tunnel diameter, $B = 1.5D$ is building width, X is horizontal distance between the centers of the tunnel and building, Y is the overburden depth).

interaction between the building and soil was not taken into account. A critical review on idealization and modeling of soil-structure interaction conducted by Dutta and Roy [8] indicated the crucial role of such interaction under the influence of both static and dynamic loading in order to accurately estimate the design force quantities. Generally, these researches investigate the influence of one or several important factors on the model responses individually whilst the coupling effects between these factors are not taken into consideration. Due to this reason, this research aims to study these influencing factors which may affect the building behavior synchronously by employing an adequate numerical model, and to evaluate the relative importance of these influencing factors by using global sensitivity analysis method. To be specific, the possible influential factors (e.g. inherent material properties, geometrical and tunneling parameters), such as soil stiffness and shear strength, tunnel overburden depth, distance between the tunnel axis and the building, soil-structure contact properties, volume loss around the tunnel due to excavation, stiffness of the building, and structural loads acting on the building are considered to study their effects on the building behavior by the use of an adequate FE numerical model.

In spite of the fact that numerical simulation method is capable to predict the building behavior by considering all the details, the uncertainty embedded in soil and tunneling parameters cannot be captured by FE-model in a deterministic approach [28]. Due to the natural variability of soil characteristics, the measurement error in quantifying the soil properties and diminutive fraction of the investigated soil volume in comparison with the whole affected soil domain [19], the soil parameters are associated with inevitable uncertainties. Furthermore, some constitutive parameters have no physical meaning and they are difficult or even not possible to be determined by laboratory tests or in situ investigations which significantly enhances the uncertainty of system responses as well. In numerical simulation, the uncertain parameters are normally assumed in a preliminary study. Afterwards, back analysis is widely applied to identify the model parameters and to update the values of uncertain parameters on the basis of the real measurements. During this process, reliable field measurements are essential for parameter identification/update. Additionally, defining the appropriate monitoring arrangement (i.e. type and location of the sensors) based on the physical behavior and hydro-mechanical interactions in the system can significantly enhance the quality of parameter identification through inverse analysis. Therefore, an optimum design for the sensor locations is necessary and can be decisive to enhance the quality of identified parameters. However, the methodology of Design of Experimental (DoE) is not well established in the field of geotechnical engineering yet. Hölter et al. [15] conducted a research on an optimal design of monitoring strategy for appropriate parameter identification in soft clays using global sensitivity analysis. They concluded that an optimal arrangement in terms of the type and position of the sensors can be determined by evaluating the sensitivity field in the relevant geometrical area. This study follows the same methodology and evaluates the optimal sensor locations to measure the soil deformations for the purpose of constitutive parameter identification and model update. Furthermore, a case study of tunneling model tests is conducted to validate this methodology of optimal sensor location.

2. Numerical analysis

2.1. Model description

Finite Element Method (FEM) has become a popular and powerful tool in both engineering practice and academic research, the recent applications on tunneling problems can be found in Potts and Zdravković [29], Möller and Vermeer [27], Zhao et al. [46], and Lavasan et al. [22]. In the early years, most of the simulations were conducted in 2D conditions, which was related to the limitation in computational resources and lack of information to validate the numerical model. With the development of computer technology, nowadays 3D simulation of complex tunneling problems is applicable. Compared to realistic 3D simulation, the most significant deficiency in plane strain condition is that the staged excavation process and subsequent 3D arching effect cannot be captured. However, the 3D simulation is often complex and requires excessive computational efforts and time. In the present study, since intensive evaluation of the FE-model is required in the parametric study and this research mainly focuses on the final building behavior due to tunnel excavation, a series of 2D numerical simulation have been conducted to simulate the tunneling by the use commercially available software PLAXIS. The appropriate dimension of the model in terms of its influence on both stress and displacements fields is determined by a number of preliminary trial analyses. The geometry of the problem, the discretization pattern and the geometrical parameters in this research is shown in Fig. 1. The mechanical boundary conditions on the bottom and outer boundaries of

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