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Optimization of site exploration program for improved prediction of tunneling-induced ground settlement in clays

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ABSTRACT

Excessive settlement caused by tunneling during construction often damages adjacent infrastructures and utilities. Such excessive settlement can also present a challenge in the maintenance of subways during their operation. Thus, it is important to be able to accurately predict tunneling-induced settlement. The uncertainties in geotechnical parameters, however, can lead to either an overestimation or an underestimation of the tunneling-induced settlement. Such uncertainties can arise from many sources such as spatial variability, measurement error, and model error; in this paper, the focus is on the geotechnical parameters characterization from site exploration. The goal here is to determine an optimal level of site exploration effort so that effective predictions of the tunneling-induced settlement in clays can be achieved. To this end, a Monte Carlo simulation-based numerical model of site exploration is first established to generate artificial test data. Then, a series of parametric analyses are performed to investigate the relationship between the level of site exploration effort and the accuracy of the tunneling-induced ground settlement prediction. Through the assumed different levels of site exploration effort, statistics of soil parameters are estimated using the maximum likelihood method and the tunneling-induced ground settlement is then analyzed using the probabilistic method, and finally the effect of site exploration effort is assessed. The knowledge generated from this series of analyses is then used to develop the proposed framework for selecting an optimal site exploration program for improved prediction of the tunneling-induced ground settlement in clays. Examples are presented to illustrate the proposed framework and demonstrate its effectiveness and significance.

1. Introduction

With the advances in tunneling technology and machines, shield-driven tunneling has become a method of choice throughout much of the world for the construction of metro systems and underground expressways in urban areas. The shield-driven tunneling-induced ground settlement in soft clays, however, is a major concern in the construction and operation of these tunnels in urban areas, as the excessive settlement and/or differential settlement can often damage existing infrastructures and utilities, and create maintenance problems during their operation. Although the subject of tunneling-induced ground settlement in soft clays and its impact on surrounding infrastructures has been extensively studied (e.g., [1,2,29]), little effort has been made and reported on the effect of site exploration on the accuracy of the ground settlement prediction. The variation in the predicted tunneling-induced ground settlement can be caused by many factors such as tunneling parameters, the ground water table, and surcharge, in addition to the uncertainties in geotechnical parameters. In this paper, the focus is on the characterization of geotechnical parameters from site exploration. The characterized statistics of geotechnical parameters can be affected by many factors (e.g., spatial variability, measurement error, model error, etc.). In this paper, however, the focus is placed only on those caused by inadequate site explorations. As is presented later, we propose a framework for selecting an optimal site exploration effort for improved predictions of tunneling-induced ground settlement in clays.

Characterization of geological anomalies is an important geotechnical problem, although only a few studies on this subject have been reported (e.g., [18,25,26]). In addition to the statistical characterization, artificial neural networks [12] and Monte Carlo simulation-based modeling [11] have been used to characterize geotechnical parameter uncertainty. In this paper, we want to take a step further to investigate the effect of the level of site exploration effort on the variation of the tunneling-induced settlement prediction. The goal is to determine an optimal level of site

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exploration effort so that improved prediction of the tunneling-induced settlement in clays can be achieved.

Prior to site exploration, only some rough estimate of the geotechnical property can be made based on prior knowledge (such as local experience and knowledge revealed in the published and unpublished reports); the "true" information is of course not known. Thus, the site exploration program has to be optimized based on this available prior knowledge or *assumed* true information of soil property. Nevertheless, the subject of how the site exploration program is influenced by the *assumed* true information of soil property is seldom reported. Therefore, this study is aimed at investigating how to optimize the site exploration effort under the assumed true information of soil property.

This paper is organized as follows: first, the method for predicting the tunneling-induced ground settlement, proposed by Loganathan and Poulos [15], is summarized; second, a numerical model of site exploration is presented, followed by the statistical characterization of soil parameters using the maximum likelihood approach [7]; third, an effective approach is introduced to appraise the validity of candidate site exploration programs; fourth, the framework for optimizing the site exploration program is developed; and lastly, an illustrative example is presented to demonstrate the proposed framework for site exploration optimization.

2. Tunneling-induced ground settlement

The tunneling-induced ground settlement can be estimated using empirical methods, analytical solutions, numerical approaches, and modeling tests. In the empirical approach, the ground settlement is computed with empirical formulae based on field observations (e.g., [21,22]). However, the empirical approach does not consider *explicitly* the geotechnical and tunneling parameters, the factors that are known to have a significant effect on the tunneling-induced ground settlement. To overcome the limitation of the empirical methods, analytical solutions have been proposed, which were derived using elastic theory (e.g., [27]) or elastic-to-plastic theory (e.g., [17]). Furthermore, the tunneling-induced ground movement is a complex 3-D problem, which often necessitates the use of numerical approaches (e.g., [19]) or model tests (e.g., [20]). Nevertheless, the empirical approach and/or analytical approach are often methods of choice owning to their simplicity and decades of experience in the practice.

The method proposed by Loganathan and Poulos [15] for predicting the tunneling-induced ground settlement is adopted herein as a basis for the study of the effect of site exploration. Of course, any similar models for predicting the tunneling-induced ground settlement can also be used. The Loganathan and Poulos model can be treated as a combination of the closed-form analytical solution [27] and the 3-D numerical model [13], which has been shown to be effective. In this method, the ground surface settlement in the "greenfield" site is expressed as (shown in Fig. 1):

$$u_z = 4R^2(1-\nu_u)\frac{H}{x^2+H^2}\,\frac{4Rg+g^2}{4R^2}\,\exp\left\{-\left[\frac{1.38x^2}{(H+R)^2}\right]\right\} \tag{1}$$

where R = tunnel outer radius; ν_u = undrained Poisson ratio of soil; H = depth of the tunnel springline measured from the ground surface; x = horizontal distance measured from the tunnel centerline; and g = gap parameter, defined as [13]:

$$g = G_p + U^*_{3D} + \omega \tag{2}$$

where G_p = physical gap; U^*_{3D} = 3-D elastoplastic deformation into the tunneling face; and ω = workmanship factor. The parameter G_p is estimated using the following equation:

$$G_p = 7\text{–}10\%\ (2\Delta + \zeta) \tag{3}$$

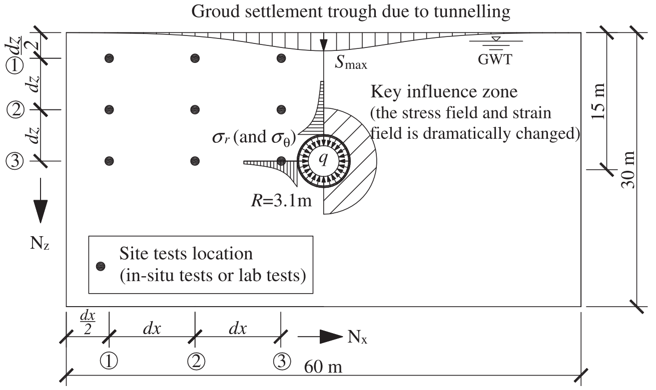

Fig. 1. Schematic diagram of tunneling-induced ground settlement, shown with an example site exploration plan.

where Δ = thickness of the tailpiece of the shield driving machine; ζ = clearance for the erection of tunnel segments; and the reduction factor of 7–10% is often applied to account for the grouting effect. The term U^*_{3D} in Eq. (2) is evaluated by:

$$U^*_{3D} = \frac{1}{2}\frac{\Omega R P_0}{E_u} \tag{4}$$

where E_u = undrained Young's modulus of soil; P_0 = total stress removal at the tunneling face; and Ω = dimensionless displacement factor estimated from the stability factor N, which is defined as [13]:

$$N = \frac{\gamma H - P_i}{c_u} \tag{5}$$

where γ = soil unit weight; c_u = undrained shear strength of soil; and P_i = support pressure at the tunneling face. P_0 in Eq. (4) is calculated by:

$$P_0 = K_0(P'_v + P_w) - P_i \tag{6}$$

where K_0 = coefficient of earth pressure at rest, $K_0 = 1$ is usually adopted for undrained soft clay; P'_v = vertical effective stress at the tunnel springline; and P_w = pore water pressure at the tunnel springline. The parameter ω in Eq. (2) is estimated as:

$$\omega = \min\left(0.6G_p, \frac{u_i}{3}\right) \tag{7}$$

where u_i = elastoplastic plane strain displacement at the tunnel crown, which is suggested by Lo et al. [14]:

$$\frac{u_i}{R} = 1 - \left(1\bigg/\left\{1 + \frac{2(1+\nu_u)c_u}{E_u}\left[\exp\left(\frac{N-1}{2}\right)\right]^2\right\}\right)^{\frac{1}{2}} \tag{8}$$

3. Numerical modeling of site exploration

Four geotechnical parameters, including the soil unit weight (γ), undrained Poisson ratio (ν_u), undrained Young's modulus (E_u), and undrained shear strength (c_u), are required in the Loganathan and Poulos model [15] for predicting the tunneling-induced ground settlement. Compared to the Young's modulus and shear strength, less uncertainty is associated with the soil unit weight [23]. Meanwhile, the variation of Poisson ratio of undrained clay is often negligible [8], thus the undrained Poisson ratio is assigned as a fixed value of 0.5 in this paper. Furthermore, the undrained Young's modulus is strongly correlated with the undrained shear strength [4]:

$$E_u = \alpha c_u \tag{9}$$