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Probabilistic analysis of tunnel longitudinal performance based upon conditional random field simulation of soil properties

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ABSTRACT

Because of the inherent spatial variability of soil properties and the limited number of boreholes that can be afforded in a typical project, the soil properties at given geotechnical sites could not be known with certainty, which leads to an uncertainty in the predicted performance of a geotechnical system. For such uncertain system, probabilistic analysis is often used to assess its performance considering uncertainty. This paper presents a new framework for the probabilistic analysis of tunnel longitudinal performance. Within this framework, the conditional random field theory is adopted to simulate the spatial variation of soil properties along the tunnel longitudinal direction, in which the soil properties at borehole locations can be explicitly considered. Then, the tunnel longitudinal performance is analyzed with an advanced tunnel performance model, in which the influence of tunnel longitudinal behavior on the circumferential behavior of the tunnel cross section can be explicitly considered. With the aid of Monte Carlo simulation (MCS), tunnel longitudinal performance can readily be analyzed in a probabilistic manner; and, the variation of the tunnel performances (i.e., the structural safety and serviceability of the cross section) along the tunnel longitudinal direction could be assessed. The novelty and significance of this proposed framework, compared to the existing methods, are demonstrated through an illustrative example. Further, the influence of the borehole density (i.e., the number of boreholes per tunnel length) on the prediction of the tunnel longitudinal performance is analyzed through a parametric study.

1. Introduction

Shield tunnels, an important component of the modern transportation infrastructures, are being constructed in a fast pace around the world. As a reference, in Shanghai the metro tunnel system currently with a total mileage of 538 km, which takes up approximately 43% of the daily public transportation, is still growing (Huang and Zhang, 2016). From the perspective of a tunnel engineer, tunnel is a slender structure: the longitudinal length could be in hundreds or thousands of meters while the diameter could typically be less than 15 m. The longitudinal variation of the input parameters such as soil properties is quite likely over the tunnel longitudinal length, and the influence of this variation on the *tunnel performances* (measured herein in terms of the structural safety and serviceability of the cross sections) could not be ignored. The longitudinal variation of the input parameters would lead to the longitudinal variation of the tunnel performances, and this effect must be explicitly considered in the analysis and design of tunnels (ATRB, 2000; ITA, 2000; Koyama, 2003; Gong et al., 2015a, 2015b; Huang et al., 2015).

A comprehensive analysis of the *tunnel longitudinal performance*, which is referred to herein as the variation of the tunnel performances (i.e., the structural safety and serviceability of the cross section) along the tunnel longitudinal direction, requires a complete characterization of the input parameters (especially soil properties) along the tunnel longitudinal direction (Gong et al., 2015b). However, the soil properties could only be known at borehole locations and only a limited number of boreholes could be afforded in a specified project; whereas, the soil properties at other positions may have to be interpolated from those at borehole locations. Here, the spatial interpolation methods such as the linear interpolation methods could be employed (Schloeder et al., 2001;

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Kılıç et al., 2006; Samui and Sitharam, 2010). Note that while these spatial interpolation methods have been widely adopted in the current practice, they are deterministic approaches and they are not equipped to consider the inherent spatial variability of soil properties (Fenton, 1999b; Cho et al., 2004). To this end, the random field theory-based site characterization has long been advocated (Jaksa et al., 2005; Griffiths and Fenton, 2009; Gong et al., 2014a, 2016).

Within the random field theory-based site characterization, the statistical information of the random field of the soil property is first calibrated using the soil properties known at borehole locations. Then, the soil properties at the project site are randomly generated with the calibrated random field, the generated soil properties are readily taken as the inputs to the analysis of the performance of the geotechnical system. Although the random field theory is a powerful tool for the simulation of the inherent spatial variability of soil properties, the soil properties collected at borehole locations are not fully utilized in this conventional random field simulation, which may lead to an overestimate of the site variability (Li et al., 2015). For example, in the conventional random field simulation, the soil properties that are randomly sampled at borehole locations may be different from the collected borehole data. This is not ideal as the soil properties at borehole locations are certain; and, the generation of the random field must be constrained to reflect this known information. Hence, within the proposed framework for the probabilistic analysis of the tunnel longitudinal performance, the conditional random field theory (Chen et al., 2012; Li et al., 2015; Li et al, 2016) will be adopted, in which the simulation of the soil properties at borehole locations would be constrained by the borehole data.

It is worth noting that though the significance of tunnel longitudinal performance analysis has long been acknowledged (ATRB, 2000; ITA, 2000; Koyama, 2003), very limited studies have been undertaken to elucidate this aspect. The current tunnel design practice still depends on the deterministic analysis of a few critical tunnel cross sections adopting a plane strain assumption (Wood, 1975; Bobet, 2001; Lee et al., 2001; Lee and Ge, 2001). In this paper, a new framework for the probabilistic analysis of the tunnel longitudinal performance is proposed: (1) the conditional random field theory is adopted to simulate the inherent spatial variation of the soil properties (based upon the collected borehole database) along the tunnel longitudinal direction; (2) the soil properties generated from the conditional random field are taken as the inputs to the analysis of the variation of the tunnel performances (i.e., the structural safety and serviceability of the cross section) along the longitudinal direction; and (3) with the aid of Monte Carlo simulation (MCS), the tunnel longitudinal performance is analyzed probabilistically.

This paper is organized as follows. First, the conditional random field simulation of the soil properties based upon the collected borehole data is outlined. Second, the tunnel longitudinal performance analysis with a full characterization of the soil properties along the tunnel direction is presented. Third, a probabilistic framework for the tunnel longitudinal performance analysis is formulated. Fourth, an illustrative example of the tunnel longitudinal performance analysis is provided, through which the significance of the proposed framework is demonstrated. Fifth, the influence of the borehole density on the prediction of the tunnel longitudinal performance is analyzed through a parametric study. Finally, the concluding remarks are drawn based upon the results presented.

2. Conditional random field simulation of soil properties

It is known that a soil property at various locations (at a project site) is often correlated to some extent in both horizontal and vertical directions, and such spatial correlations generally decrease with the relative distance. This feature of soil properties can best be simulated utilizing the random field theory (Fenton, 1999b; Cho et al., 2004). As mentioned above, the soil properties at borehole locations are "known" through measurements (and thus considered "certain"). To this end, the conditional random field theory (Chen et al., 2012; Li et al., 2016) is adopted in this paper for the simulation of the inherent spatial variability of the soil properties, and the statistical information of this conditional random field will be calibrated from the soil properties collected at borehole locations.

In a typical site investigation, only a limited number of boreholes can be conducted at the site due to budget constraint. For simplicity, the boreholes in this study are assumed to be located at the centerline of the planned tunnel and equally spaced along the tunnel direction. Let $\mathbf{s_{BH}} = [s(x_1,z_1), s(x_2,z_2), \dots, s(x_{nB},z_{nB})]^{\mathrm{T}}$ denote the soil properties that are collected at borehole locations, where n_B represents the number of collected borehole data, and x and z represent the longitudinal coordinate and depth, respectively. In the context of the random field simulation, the statistical information of the random field of the soil property, in terms of the distribution and statistics (e.g., the mean, standard deviation and spatial correlation structure), will first be calibrated using the available borehole data $\mathbf{s_{BH}} = [s(x_1,z_1), s(x_2,z_2), \dots, s(x_{nB},z_{nB})]^{\mathrm{T}}$. Here, the distribution could be derived using techniques such as chi-square test (Nikulin, 1974); and, the statistical information could be determined using probabilistic approaches such as Bayesian method (Ching et al., 2010; Wang et al., 2010; Sujatha et al., 2014) and maximum-likelihood method (Ledesma et al., 1996; Fenton, 1999a; Gong et al., 2014a).

With the calibrated statistical information of the random field (of the soil property) and the soil properties known at borehole locations, the conditional random field of the soil property at the project site could be sampled using various algorithms such as Bayesian method (Li et al., 2015), Kriging-based sampling method (Frimpong and Achireko, 1998; Lloret Cabot et al., 2012; Li et al., 2016) and Hoffman method (Hoffman and Ribak, 1991; Hoffman, 2009; Schöbi and Sudret, 2015). In this paper, the Hoffman method is adopted for sampling the conditional random field of the soil property owing to its simplicity and computational efficiency. With which, a realization of the conditional random field of the soil property is obtained with the following two main steps (Schöbi and Sudret, 2015):

Step 1: sample an unconditional random field of the soil property

The generated unconditional soil field is denoted as $\mathbf{S_{un}} = [\mathbf{S_{BHu}}, \mathbf{S_{Pu}}]$, where $\mathbf{S_{BHu}}$ and $\mathbf{S_{Pu}}$ represent the soil properties that are sampled at borehole locations and those at other locations, respectively. A variety of sampling methods could be available for sampling the unconditioned random field, including the covariance matrix decomposition method, local average subdivision method, fast Fourier transformation method and turning-band method (Fenton, 1994; Fenton and Griffiths, 2008). In this paper, the covariance matrix decomposition method is adopted because it is simple to implement and sufficiently accurate (Luo et al., 2011; Li et al., 2015). In that the soil property is assumed to be lognormally distributed, the unconditional random field $\mathbf{S_{un}} = [\mathrm{S_{un1}}, \mathrm{S_{un2}}, \dots, \mathrm{S_{un\mathit{ns}}}]$, where n_s represents the number of soil elements, could be obtained.

$$\mathrm{S}_{\mathrm{un}i} = \exp(\mu_{\ln s} + \sigma_{\ln s}\cdot\ln\mathrm{S}_i) \tag{1}$$

where $\mathrm{S}_{\mathrm{un}i}$ represents the soil property sampled within the ith soil element; $\ln\mathrm{S}_i$ represents the normalized soil property sampled within the ith soil element; and, $\mu_{\ln s}$ and $\sigma_{\ln s}$ represent the mean and standard deviation of the normalized soil property $\ln s = \ln(s)$, respectively:

$$\sigma_{\ln s} = \sqrt{\ln[1 + (\sigma_s/\mu_s)^2]} \tag{2}$$

$$\mu_{\ln s} = \ln\mu_s - \frac{1}{2}\sigma_{\ln s}^2 \tag{3}$$

where μ_s and σ_s represent the mean and standard deviation of the unnormalized soil property s. Due to the spatial averaging effect, the statistics of the soil property that is averaged over the soil element