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Modeling of non-stationary random field of undrained shear strength of soil for slope reliability analysis

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Abstract

The spatial variability of soil properties is often assumed to be modeled as stationary or weakly stationary random fields in slope reliability analyses. However, abundant site-specific data have revealed that the mean and standard deviation of soil properties, such as the undrained shear strength of soil, change with depth. Thus, the non-stationary characteristics of soil properties need to be properly accounted for. The aim of this paper is to propose a non-stationary random field (RF) model for the characterization of the spatial variability and the depth-dependent nature of the undrained shear strength of soil. With the proposed model, the uncertainties of the trend and fluctuating components can be modeled individually. As an example, a clay slope under undrained conditions is investigated to illustrate the proposed model. A subset simulation is carried out to evaluate the slope reliability incorporating the non-stationary characteristics of soil properties. The advantages of the proposed model, relative to the existing non-stationary RF models and the commonly-used stationary RF model in the literature, are demonstrated through a series of sensitivity studies.

Keywords: Slope reliability; Undrained shear strength; Spatial variability; Non-stationary random field; Trend component

1. Introduction

It is widely recognized that soil properties vary spatially even within homogeneous layers due to depositional and post-depositional processes (e.g., DeGroot and Baecher, 1993; Phoon and Kulhawy, 1999a, 1999b). The inherent spatial variability of soil properties is one of the major sources of uncertainties in geotechnical engineering that significantly affect slope stability (e.g., El-Ramly et al., 2002; Griffiths and Fenton, 2004). The soil properties in a statistically homogeneous soil layer are often assumed to be stationary or weakly stationary in slope reliability analyses (e.g., Griffiths and Fenton, 2004; Huang et al., 2010, 2017; Wang et al., 2011; Jha and Ching, 2013; Jiang et al., 2017a). Under this assumption, the mean and variance of soil properties are treated as constant within the region of the random field. An autocorrelation function governs the degree of correlation between the residuals of any two points regardless of their absolute coordinates within the random field. It is noted, however, that numerous site-specific data collected from in situ tests, including field vane shear tests and cone penetration tests, have confirmed that there are obvious non-stationary characteristics within the soil profile due to the in situ overburden stress (e.g., Soulie et al., 1990; Jaksa et al., 1997; Kulatilake and Um,

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2003; Löfroth, 2008; Haldar and Sivakumar Babu, 2009; Ching et al., 2010). Thus, the rationale behind the above assumption shall be clarified in particular for over-consolidated soils or layered soils where the mean and even variance of the soil properties, such as the undrained shear strength and hydraulic conductivity, change with depth (e.g., Lumb, 1966; Asaoka and A-Grivas, 1982; Chenari and Farahbakhsh, 2015; Shen et al., 2016).

In addition, many researchers have realized the importance of the non-stationary characteristics of soil properties and have taken into account the depth-dependent nature of soil properties in the stability analyses and even in the reliability analyses of geotechnical systems. For instance, Wilson et al. (2011, 2013), Griffiths and Yu (2015) and Keawsawasvong and Ukritchon (2017) quantified the influence of the undrained shear strength of soil (s_u), that varies with depth, on the stability of the tunnel planar, the soil slope and the trapdoor, respectively. In the literature (e.g., Hicks and Samy, 2002; Wu et al., 2012; Li et al., 2014, 2015a; Griffiths et al., 2015), the effects of the non-stationary characteristics of s_u on the reliability of the slope stability, the deep excavation stability, the shallow foundation and the strip footing have been studied. Nevertheless, the amount of research on the modeling of non-stationary random fields, where both the mean and the coefficient of variation (COV) increase with depth, as reported in Lumb (1966), is still limited (e.g., Phoon et al., 2016).

On the other hand, it is well acknowledged that in situ soil properties typically vary vertically as well as horizontally. The vertical spatial variation of a soil property $X(z)$ can be customarily decomposed into a smoothly varying trend component [$t(z)$] and a fluctuating component [$w(z)$] (e.g., Jaksa et al., 1997; Phoon and Kulhawy, 1999a; Srivastava and Sivakumar Babu, 2009), as follows:

$$X(z) = t(z) + w(z) \tag{1}$$

It is noted that the trend component $t(z)$ is also uncertain due to the limited sample size or the bias of the testing devices, soil disturbance and the models and correlations used to interpret the measurements (e.g., El-Ramly et al., 2002). Ng et al. (2017) summarized the varying ranges in $t(z)$ associated with different clay sites. Cao et al. (2016) further presented the varying ranges in the mean and standard deviation of $t(z)$ as [0.23, 1.4] and [0.01, 1.26], respectively. Moreover, the uncertainties involved in the trend and fluctuating components of soil properties are generally different (e.g., Uzielli et al., 2007; Ching and Wang, 2016). Thus, for a proper characterization of the spatial variation in soil properties, it is of significance to model the uncertainties in the trend and fluctuating components individually.

The aim of this study is to propose a non-stationary random field (RF) model for the characterization of the non-stationary characteristics of the undrained shear strength of soil. To achieve this goal, the paper is organized as follows. In Section 2, the discretization of the stationary and the non-stationary random fields is presented. In particular, a non-stationary RF model for the undrained shear strength of soil, that can model the uncertainties in the trend and fluctuating components individually, is developed. In Section 3, a subset simulation is employed to estimate the probability of slope failure in high dimensions. In Section 4, an example of a saturated clay slope under undrained conditions is studied to illustrate the proposed model. A series of sensitivity studies is carried out using this slope to show the advantages of the proposed model with respect to the published non-stationary RF models and stationary RF model. Finally, some conclusions are drawn from this study.

2. Modeling of spatial variation of soil properties

2.1. Discretization of stationary random fields

Several techniques have been developed to discretize the statistically homogenous random fields of spatially varying soil properties, including the midpoint method (e.g., Baecher and Christian, 2003), the local average subdivision method (e.g., Vanmarcke, 2010) and the Karhunen-Loève expansion method (e.g., Ghanem and Spanos, 2003; Jiang et al., 2014). The midpoint method is employed in this study to discretize the stationary random fields since it is conceptually simple and can easily be implemented by geotechnical practitioners (Li et al., 2015b). With this method, one realization of a two-dimensional (2-D) stationary non-Gaussian random field $\mathbf{X}(x,z)$ can be obtained at the centroids of random field elements, namely,

$$\mathbf{X}(x,z) = F^{-1}[\Phi(\mathbf{L}\boldsymbol{\xi})], \quad (x,z) \in \Omega \tag{2}$$

where (x, z) is the coordinate in the 2-D domain, Ω, and $F^{-1}(.)$ is the inverse function of the marginal cumulative distribution of the non-Gaussian random field, $\Phi(.)$ is the standard normal cumulative distribution function, $\boldsymbol{\xi} = (\xi_1, \xi_2, \ldots, \xi_n)^{\mathrm{T}}$ is a vector of the independent standard normal random samples with a size of n, in which n is the number of random variables that is relevant to the number of random field elements (n_e), and $\mathbf{L}$ is the lower triangular matrix, which can be obtained by factoring a bounded, symmetric and positively defined autocorrelation coefficient matrix $\sum$ with a dimension of $n_e \times n_e$ using the standard Cholesky decomposition algorithm.

$$\mathbf{L}\mathbf{L}^{\mathrm{T}} = \sum \tag{3}$$

where $\sum$ is the autocorrelation coefficient matrix, the (i, j)-th element of which is the autocorrelation coefficient between soil properties $\mathbf{X}$ at the centroids of the i-th and j-th random field elements, and $i, j = 1, 2, \ldots, n_e$. Due to the limited site-specific data, the theoretical autocorrelation functions, such as the exponential and Gaussian autocorrelation functions, are usually utilized to characterize the spatial autocorrelation of the soil properties (e.g., Li et al., 2015b). For convenience, a 2-D separable exponential autocorrelation function is adopted in this study:

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