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Research Paper

Risk assessment of slope failure considering the variability in soil properties

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ABSTRACT

To assess the risk of slope failure, this study employs a rigorous method that is referred to as the random finite difference method (RFDM). The RFDM is capable of considering the spatial variability of soil properties subject to different auto-correlation structures. Comparisons with the collected data are made with respect to two idealized slopes, and a parametric analysis is presented. The results demonstrate that the spatial auto-correlation structures significantly affect the slope failure risk. Depending on the rotated angle, the rotated anisotropy auto-correlation structure shows a dual effect on the reliability of the slope compared to a transverse anisotropy case.

1. Introduction

Soil properties typically exhibit considerable spatial variability in strength due to geotechnical uncertainties, even within homogeneous soil layers. The stability of a slope can be affected or dominated by the presence of soil variability. Numerous failure modes exist for a variable soil slope because the slip surface tends to seek out the weakest path (e.g., [1–3]). From an engineering perspective, slope designers consider not only the slope stability but also the consequence of damage caused by slope failure. To quantify the risk of slope failure, a common method is to consider the product of the probabilities of failure and consequence (e.g., [4–9]). Thus, the impact of material variability on slope risk may be more profound because the failure consequences associated with different slope failure modes generally differ. Slope stability was quantified by a factor of safety in traditional deterministic methods, which provide minimal information about the consequence of slope failure in variable soils. Conversely, probabilistic approaches provide an appropriate tool to address the soil variability in slope reliability analysis and risk assessment.

At the early stage, the majority of probabilistic studies aim to describe the slope stability using the probability of failure or a reliability index (e.g., [1,10–12]). However, these studies did not quantify the consequence associated with a slope failure in a variable soil. In recent years, few studies focused on the risk response of a soil slope using several probabilistic analysis methods. According to the differences among the assumptions and algorithms, probabilistic analysis methods can be divided into two categories: analytical methods and numerical methods. In the context of analytical methods, Huang et al. [7] evaluated the consequence of slope failure for multiple failure modes using a limit analysis method, which combines lower and upper bound theorems with random fields generated by the Karhunen-Loeve expansion method. Jiang et al. [13,14] developed an efficient analytical approach for risk assessment by limit equilibrium analysis. Scholars such as Zhang and Huang [15] and Li and Chu [16] have explored the risk of slope failure using the proposed representative slip surfaces method. In predicting the probability of slope failure and risk, analytical methods are generally effective but have limitations. These methods usually require the location and shape of potential slip surfaces, which limit their application for slope risk assessment associated with multiple potential failure mechanisms. As noted by Jiang et al. [13], their method is suitable for the risk analysis of a slope with a circular slip surface. A study of the risk of rainfall-induced slope failure was conducted considering the effects of spatially variable hydraulic conductivity [17].

Alternatively, a rigorous numerical based method that is referred to as the "random finite element method (RFEM)" provides a rational approach for the probabilistic analysis of slope stability (e.g., [1]). Hicks et al. [18] analyzed the influence of the soil variability on the probability of failure and the slip mass of a three-dimensional slope by the RFEM. Li et al. [19,20] introduced the subset simulation to the RFEM, which provides an effective method for calculating the slope risk at small probability levels. Subsequently, Xiao et al. [21,22] proposed an improved method—the auxiliary random finite element method (ARFEM)—to study the influence of the horizontal variability of soil properties on the risk of three-dimensional slope failure. Using the RFEM, Liu et al. [23] investigated the effect of the stratigraphic

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boundary uncertainty on the risk of a layered slope in variable soils. These studies have demonstrated how the spatial variability of soil strength significantly affects the slope failure risk.

In these probabilistic analysis methods, random fields are commonly employed to describe the spatial variability of soil properties. However, determining the values of the statistical parameters (i.e., auto-correlation function, auto-correlation distance, or scale of fluctuation) that describe the auto-correlation structure of the spatial variability is difficult due to the limited field observations. Therefore, theoretical auto-correlation functions and experimental auto-correlation distances are often employed in the reliability analysis of a slope. Li et al. [24] explored the influence of five theoretical auto-correlation functions on the slope reliability and determined that the slope reliability is not sensitive to the type of auto-correlation function. Conversely, numerous results demonstrate that the influence of the auto-correlation distance on the slope reliability and risk of failure is significant [13,18,19,26].

In general, two patterns of auto-correlation structures—isotropic and anisotropic—are assumed. Their anisotropy indicates that the auto-correlation distances in all horizontal directions are equivalent and the largest distances, whereas the auto-correlation distances in the vertical direction are the smallest distances. This situation was termed transverse anisotropy by Zhu and Zhang [27]. Due to various depositional processes, Zhu and Zhang [27] divided the soil spatial variability into six patterns: isotropy, transverse anisotropy, rotated anisotropy, general anisotropy, general rotated anisotropy, and a combination of two anisotropy patterns. However, few studies have discussed other patterns in the reliability analysis of slope, particularly for risk assessment of slope failure.

To address this problem, risk assessment of slope failure has been analyzed when soil parameters are subjected to different auto-correlation structures. An effective probabilistic method, which is referred to as the random finite difference method (RFDM), is employed in this paper; it combines random fields with the finite difference code FLAC^{3D} [3]. Chenari and Alaie [28] employed the RFDM to study the probability of failure of undrained slopes. The RFDM is extended to assess the risk of slope failure in this paper. In the RFDM, random fields of soil shear strength are generated for different auto-correlation structures via the matrix decomposition method. Next, the factor of safety is calculated by the finite difference code FLAC^{3D}, and the critical slip surface and the corresponding slip mass are determined by a self-compiling program. The probabilities of failure and risk assessment are finally obtained using Monte Carlo simulation (MCS). Additionally, two slopes are introduced to check the validity of the RFDM for the risk assessment of slope failure and to explore the influence of four typical auto-correlation structures (i.e., isotropy, transverse anisotropy, rotated anisotropy and combination anisotropy).

2. Random finite difference method (RFDM)

2.1. Generation of random fields

Random fields adequately describe spatial variability. In a random field, an important measure of the variability is the auto-correlation distance. The auto-correlation distance may not be constant for different directions in a soil mass, which produces various auto-correlation structures. Typical soil profiles, as shown in Fig. 1, correspond to the six previously mentioned patterns. Note that two lines with arrows are used to indicate the auto-correlation between two principal directions in each profile, and the length indicates the degree of auto-correlation. In the profiles, the long line represents the strongest auto-correlation, and the short line represents the weakest auto-correlation.

In Fig. 1a, the lengths in the two principal directions and the lengths in the other directions are identical, i.e., an isotropic structure. In Fig. 1b, the two principal directions are orthogonal and parallel to the Cartesian coordinate axes. This structure is defined as transverse anisotropy. The strongest auto-correlation is exhibited in the horizontal direction, whereas the auto-correlation in the vertical direction is the weakest direction. In Fig. 1c, the two principal directions are rotated by the angle β on the pattern of transverse anisotropy caused by geologic or man-made processes; this structure is defined as rotated anisotropy. In Fig. 1d, the two principal directions are not orthogonal but form the angle η, and one of the two principal directions remains parallel to an axis. Fig. 1e shows a rotated case of general anisotropy. Fig. 1f displays a combination case that involves two auto-correlation structures in a soil profile.

As stated by Zhu and Zhang [27], the existence of the joints is an important factor that causes general anisotropy and general rotated anisotropy structures. This phenomenon is more common in rock and is less likely to appear in soil. Therefore, this paper focuses on the influence of the other four auto-correlation structures on the risk of slope failure because soil slopes are considered. Note that a multilayered soil slope is selected to simulate the combination case, in which the properties in different soil layers are characterized by transverse anisotropy or rotated anisotropy with different rotated angles.

Prior to the generation of random fields for different auto-correlation structures, their expressions must be established. Currently, the exponential auto-correlation function is commonly employed to describe the auto-correlation structure (e.g., [19,20,24,27,29,30]). Two expressions are employed to describe the exponential auto-correlation structure for two-dimensional conditions: single exponential auto-correlation functions and squared exponential auto-correlation functions. Considering the analyzed structures (i.e., isotropy, transverse anisotropy and rotated anisotropy) as an example, the expressions of the two exponential auto-correlation functions $\rho(\tau_x, \tau_z)$ and auto-correlation distance θ_ϕ (ϕ is the directional angle) are given as

Single exponential auto-correlation function (e.g., [19,20,24,29]):

Isotropy:

$$\rho(\tau_x, \tau_z) = \exp\left[-\frac{|\tau_x|}{\theta}-\frac{|\tau_z|}{\theta}\right] \tag{1a}$$

$$\theta_\phi = \frac{\theta}{|\cos\phi| + |\sin\phi|} \tag{1b}$$

Transverse anisotropy:

$$\rho(\tau_x, \tau_z) = \exp\left[-\frac{|\tau_x|}{\theta_1}-\frac{|\tau_z|}{\theta_2}\right] \tag{2a}$$

$$\theta_\varphi = \frac{\theta_1\theta_2}{\theta_2|\cos\varphi| + \theta_1|\sin\varphi|} \tag{2b}$$

Rotated anisotropy:

$$\rho(\tau_x, \tau_z) = \exp\left[-\frac{|\tau_x\cos\beta + \tau_z\sin\beta|}{\theta_1}-\frac{|-\tau_x\sin\beta + \tau_z\cos\beta|}{\theta_2}\right] \tag{3a}$$

$$\theta_\varphi = \frac{\theta_1\theta_2}{\theta_2|\cos\varphi\cos\beta + \sin\varphi\sin\beta| + \theta_1|-\cos\varphi\sin\beta + \sin\varphi\cos\beta|} \tag{3b}$$

Squared exponential auto-correlation function (e.g., [27,30]):

Isotropy:

$$\rho(\tau_x, \tau_z) = \exp\left[-\frac{\sqrt{\tau_x^2 + \tau_z^2}}{\theta}\right] \tag{4a}$$

$$\theta_\phi = \theta \tag{4b}$$

Transverse anisotropy:

$$\rho(\tau_x, \tau_z) = \exp\left[-\sqrt{\left(\frac{\tau_x}{\theta_1}\right)^2 + \left(\frac{\tau_z}{\theta_2}\right)^2}\right] \tag{5a}$$