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Research Paper

Effect of spatial variability of shear strength on reliability of infinite slopes using analytical approach

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ABSTRACT

This paper develops an analytical approach for reliability analysis of infinite slope stability in presence of spatially variable shear strength parameters. The analytical approach considers spatial autocorrelation of each parameter and cross-correlations between different parameters. It is robust, computational efficient and provides insight to the importance of spatial correlation scale on slope reliability analysis. This paper also explores the difference in continuous and discrete random fields and emphasizes the importance of fine discretization in relation to correlation scale. Finally, it shows that conditioning the stability analysis with information about trends and spatial data leads to reliability assessments with less uncertainty.

1. Introduction

In slope stability analysis, the criterion that defines the stability is the factor of safety (FS). It is defined as the ratio of the shear strength or resisting force of the slope to the stress or disturbing force. When FS is less than unity, slope failure is assumed to occur. The shear strength of a slope depends on its soil properties. Soil properties such as shear strength parameters and hydraulic conductivity generally exhibit a high degree of spatial variability at various scales (e.g., [1–4]), and it is practically impossible to characterize them in detail within a slope. This reality forces us to cope with uncertain in our evaluations of slope stability. As a consequence, reliability-based analysis is deemed more appropriate than the traditional deterministic approach (e.g., [5,6]).

The spatial variability of shear strength parameters has been shown to play a significant role in reliability analysis of slope stability. For example, Lacasse and Nadim [7] discussed spatial variability and measurement methods in characterizing soil properties in slope stability analysis. They stressed the importance of these uncertainties for geotechnical design. Cho [8] conducted a probabilistic stability evaluation of layered slopes considering spatial variabilities of shear strength parameters and unit weight, and he emphasized the effects of the spatial correlation of soil properties on slope reliability. Griffiths et al. [9] and Jiang et al. [10] indicated that ignoring spatial variability of shear strength parameters could lead to non-conservative estimates (underestimation) of the slope reliability when the coefficients of variation of the shear strength parameters are large. This is particularly important when the factor of safety evaluated using mean values of parameters is close to 1.

It has been well recognized that an infinite slope conceptual model, as a simple model for assessing the factor of safety of shallow landslides or large "length-to-depth ratio" slopes, can yield important insights into slope reliability analyses. For instance,

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Griffiths et al. [11] used the infinite slope model to demonstrate effects of spatially variable parameters such as soil strength, slope geometry and pore pressures on the reliability analysis of slope stability. More recently, using this conceptual model, Li et al. [12] illustrated that the linearly increasing mean trend of shear strength parameters has a considerable effect on the reliability analysis of slope stability and critical slip depths. Similarly, Zhang et al. [13] developed a spreadsheet template based on this model for predicting the time-dependent probability of rainfall-induced slope failures. This template enables past performance information to be incorporated, and the uncertainty of different parameters to be considered. Using the infinite slope model, Cho [14] investigated the effect of variation and correlation scale of permeability upon the probability of slope failure and depths of critical slip surfaces during the process of rainfall infiltration. Likewise, with this model, Ali et al. [15] systematically studied the nature of triggering mechanisms and the associated risk of rainfall-induced landslides in the presence of spatially variable hydraulic conductivity.

All these previous studies have relied on Monte Carlo (MC) simulation. That is, the reliability of slope stability analysis is determined based on statistical analysis of factor of safety values derived from a physical model with a large number of generated realizations of parameter values. While MC simulation is a straight-forward approach, it requires a significant amount of computational resources, specifically for multidimensional problems. More importantly, the number of realizations required to obtain a stable estimation is always subjected to questions.

To overcome aforementioned issues associated with MC simulation, this paper develops an analytical approach for reliability analysis of infinite slope stability in presence of spatially variable shear strength parameters. The analytical approach considers spatial autocorrelation of each parameter and cross-correlations between different parameters. Moreover, it allows one to directly relate the spatial statistics of each parameter heterogeneity (mean, variance and correlation scale) through a physical model to the probability of failure, without conducting time-consuming MC simulation.

This article is organized as follows. First, the general procedure of the analytical approach is developed for homogeneous slopes and heterogeneous slopes with either normally or log normally distributed parameters. Subsequently, three illustrative examples of slope reliability analysis (i.e., Infinite undrained clay slope, Infinite clay slope with linearly increasing mean trend and Infinite c'-$\tan\phi'$ slope) are investigated to validate the approach. Lastly, implications of the results of these examples for future studies are discussed.

2. Analytical approach of slope reliability

The infinite slope model is a widely accepted model for slope stability analysis in practice (e.g., [11–18]). In particular, shallow landslides with large length-to-depth ratios of the landslide mass, and planar failure surfaces, which are developed parallel to the slope surface, are usually modeled as infinite slopes (Fig. 1(a)), for example, slope failures in the layer of weathered residual soil that overlays the bedrock [14]. Field studies also confirmed that characters of most shallow landslides are consistent with the infinite slope model [12].

Without considering deformation (or neglecting stress-strain relationship), the factor of safety at depth z (FS_z) of an infinite slope (Fig. 1(b)) is often evaluated using the limit equilibrium method (LEM), which can be expressed as follows (e.g., [11,12,14,15]):

$$FS_z = \frac{\tau_f}{\tau_m} = \frac{(z\gamma\cos^2\beta - \sigma^s)\tan\phi' + c'}{z\gamma\sin\beta\cos\beta} = \frac{\tan\phi'}{\tan\beta} + \frac{-\sigma^s\tan\phi' + c'}{z\gamma\sin\beta\cos\beta} \quad (z \leqslant H) \tag{1}$$

where τ_f and τ_m are the shear strength of soil and the shear stress at a given depth z (positive downward), respectively; β is the slope inclination; γ is the total unit weight; H denotes the vertical distance of soils from the slope base to the land surface; σ^s represents the effect of the negative pore water pressure for unsaturated conditions and the positive pore water pressure when saturated at any point of depth z [16]; ϕ' and c' are the effective soil friction angle and the effective cohesion at depth z.

In the following analysis, we will assume that σ^s is zero at all depths within the slope. That is, we assume that there is no presence of water or fluid pressures in the slope. Therefore, Eq. (1) is simplified as:

$$FS_z = \frac{\tan\phi'}{\tan\beta} + \frac{c'}{z\gamma\sin\beta\cos\beta} \quad (z \leqslant H) \tag{2}$$

Because of unknown spatial distribution of the parameter values in Eq. (2), any depth of the slope is a possible "weakest" part within the slope. Hence, a procedure is required to locate the critical slip surface corresponding to the minimum factor of safety. Precisely, the factor of safety (FS) for the entire slope is:

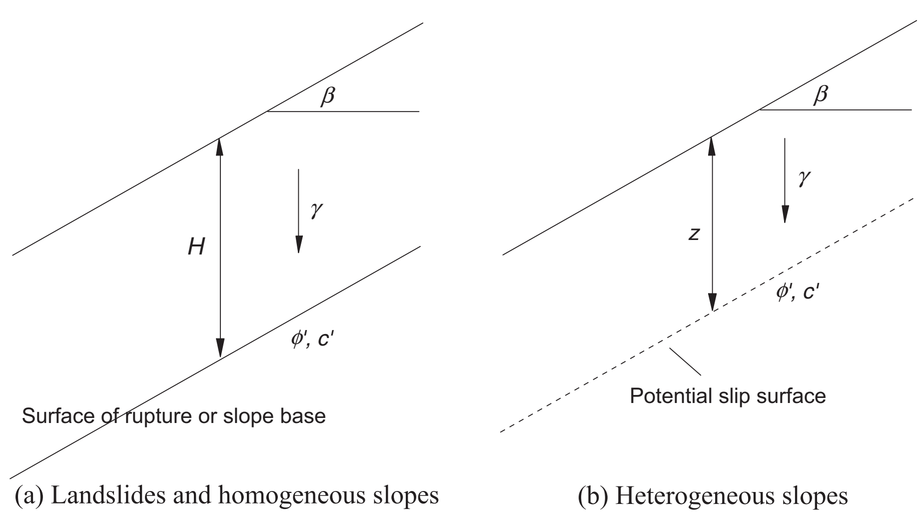

Fig. 1. Infinite slope model.