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Research Paper

Uncertainty of rainfall-induced landslides considering spatial variability of parameters

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ABSTRACT

A cross-correlation analysis is conducted to determine the impacts of the heterogeneity of hydraulic conductivity K_s, soil cohesion c' and soil friction angle ($\tan\varphi'$) on the uncertainty of slope stability in time and space during rainfall. We find the relative importance of $\tan\varphi'$ and c' depends on the effective stress. While the sensitivity of the stability to the variability of K_s is small, the large coefficient of variation of K_s may exacerbate the variability of pore-water pressure. Therefore, characterizing the heterogeneity of hydraulic properties and pore-water distribution in the field is critical to the stability analysis.

1. Introduction

Properties of geologic formation generally exhibit a high degree of spatial variabilities at a multiplicity of scales. 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. Slope stability analysis considering spatial variability of soil properties thus has become popular in recent years (e.g., [3,5,7–10,14–18,21,29,30,32,36]). The soil properties, which are considered significant to the slope stability and commonly discussed in literatures, are the shear strength parameters (the effective cohesion c' and the effective soil friction angle ϕ') and the saturated hydraulic conductivity K_s.

Previous studies show that the spatial variability of the shear strength parameters has various effects on the slope stability under different circumstances. For infinite slopes, studies [3,16] showed that analyses without properly accounting for spatial variability can lead to unconservative estimates of the probability of slope failure. Li et al. [22] emphasized that the probability of slope failure will be overestimated if a linear increasing trend underlying the shear strength parameter is ignored or simplified as a constant. For two-dimensional slopes, Ji et al. [18] found that ignoring spatial variability of the shear strength parameters significantly overestimated the failure probability. Cho [9] stressed the importance of spatial variability of soil properties with regard to the outcome of a probability assessment. Griffiths et al. [15] and Jiang et al. [20] pointed out that ignoring spatial variability of shear strength parameters could lead to non-conservative estimates (underestimation) of the probability of slope failure, when the coefficients of variation of the shear strength parameters are large, and the factor of safety evaluated at mean parameters is close to 1.

The effect of spatial variability of the saturated hydraulic conductivity K_s on the slope stability is complex. Santoso et al. [29] pointed out that considering spatial variability of K_s, their analysis can lead to a shallow slope failure, which does not exist in the analysis using a homogeneous slope. As mentioned by Cho [7], in the early stage of infiltration, the wetting front's advancement decreases the factor of safety at the slope's upper portion, and hence, the critical failure surface likely exists in the upper portion of the slope. As infiltration progresses, the critical failure surface moves downwards, and the likelihood of failure at the base of the slope continuously decreases. Besides, at early time, a large

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vertical correlation scale or a small coefficient of variation of K_s lead to a small probability of failure at the impermeable slope base. On the contrary, a large vertical correlation scale or a large coefficient of variation of K_s may yield a large probability of the failure at the base at late time.

Previous studies have focus on the effects of mean, variance, and correlation structure (i.e., the averaged thickness, width, and length of the heterogeneity) of parameters on the probability of slope failure. That is, these works reveal influences of the uncertainty or spatial variability of properties over the entire slope, without resorting to the detailed spatial distributions of properties. On the other hand, the temporal evolution of the role of uncertainties of different properties (such as K_s and c', ϕ') at different locations in the slope stability and the spatial relationship between the stability of a potential slip surface and heterogeneity at various parts of a slope remain relatively unexplored. Rainfall infiltration processes in slopes are generally complex because of the presence of saturated and unsaturated zones and the time-varying water table, in addition to the heterogeneous nature of geologic media. The effect of heterogeneity of different properties on the slope stability would evolve with time during rainfall infiltration processes, and deserves further investigation. In addition, the effects of spatial variabilities of hydraulic properties (e.g., K_s) and mechanical properties (e.g., c', ϕ') on slope stability are generally investigated separately, and their relative importance to uncertainties of slope stability and their interaction are poorly understood. Furthermore, all these previous studies have relied on Monte Carlo (MC) simulation, which is often dependent on generated realizations of parameter values. Using such an approach, it is also difficult to examine the direct relationship between these properties and slope stability.

The objective of this study is to provide a better understanding of the temporal and spatial evolution of uncertainty of slope stability during rainfall, considering uncertainty or spatial variability of parameters. In order to achieve this objective, we first investigate the temporal and spatial evolution of cross correlations between the factor of safety at a potential slip surface and the saturated hydraulic conductivity and the shear strength parameters during a rainfall infiltration process in homogeneous and heterogeneous infinite slopes. Subsequently, the contributions to the standard deviation of FS_i at a potential slip surface from the variation of each parameter are presented, using the typical ranges of the variation of parameters reported in literature. Finally, seepage and stability analyses of two typical heterogeneous slopes are used to illustrate how the heterogeneities of soil properties influence the slope stability, and to demonstrate the importance of the cross-correlation analysis of heterogeneous slope on the stability analysis of heterogeneous slope under rainfall infiltration.

2. Methodology

2.1. Basic equations

The factor of safety along ith potential slip surface (i.e., FS_i) of an infinite slope can be evaluated using the limit equilibrium model (LEM) with a unified effective stress under both saturated and unsaturated conditions [23]. If we let the pore air pressure u_a be atmospheric pressure (i.e., $u_a = 0$), FS_i can be expressed as (e.g., [1,7,16,22]):

$$FS_i = \frac{((H - z_i)\gamma_i \cos^2\beta - \sigma_i^s)\tan\phi_i' + c_i'}{(H - z_i)\gamma_i \sin\beta\cos\beta} = \left(\frac{1}{\tan\beta} + \frac{-\sigma_i^s}{(H - z_i)\gamma_i \sin\beta\cos\beta}\right)\tan\phi_i' + \frac{c_i'}{(H - z_i)\gamma_i \sin\beta\cos\beta}\ (0 \leqslant z_i < H,\ i = 1, \ldots, n) \quad (1)$$

where β is the slope inclination; γ_i is the averaged total unit weight above ith potential slip surface; H denotes the vertical distance of soils from the slope base to the land surface; c_i' and ϕ_i' are the effective cohesion and the effective soil friction angle at ith potential slip surface, and z_i is the elevation (positive upward) of ith potential slip surface relative to the slope base (see Fig. 1); σ_i^s represents the effective negative pore water pressure under unsaturated conditions or effective positive pore water pressure under saturated conditions at ith potential slip surface [23].

The factor of safety for the entire slope (denoted as FS) is:

$$FS = \min\{FS_i\} = \min\left\{\left(\frac{1}{\tan\beta} + \frac{-\sigma_i^s}{(H - z_i)\gamma_i \sin\beta\cos\beta}\right)\tan\phi_i' + \frac{c_i'}{(H - z_i)\gamma_i \sin\beta\cos\beta}\right\}\ (0 \leqslant z_i < H,\ i = 1, \cdots, n) \quad (2)$$

According to [23], σ_i^s can be expressed as:

$$\sigma_i^s = -\frac{\theta_i - \theta_r}{\theta_s - \theta_r}(u_a - u_{w_i}) = -S_{e_i}(u_a - u_{w_i}) \quad (3)$$

where u_{wi}, S_{e_i} and θ_i are the pore water pressure, the effective water saturation and the volumetric moisture content at ith potential slip surface, respectively; θ_s and θ_r denote the saturated and residual volumetric moisture contents, respectively. $\sigma_i^s = S_{e_i}u_{w_i} < 0$ for unsaturated conditions ($u_{w_i} < 0$), $\sigma_i^s = u_{w_i} \geqslant 0$ for saturated conditions ($u_{w_i} \geqslant 0$). Via this unified effective stress theory, Eq. (1) can account for both the reduction in matric suction and the development of positive pore water pressure in a continuous form [7,23].

In this paper, the variation in unit weight resulting from changes in moisture content during infiltration is considered by integration of the moisture content profile above the potential slip surface. That is, the total unit weight γ_i can be expressed as follows:

$$\gamma_i = \frac{1}{H - z_i}\int_{z_i}^{H}(\gamma_d + \theta(z)\gamma_w)dz \quad (0 \leqslant z_i < H) \quad (4)$$

where γ_d is the dry unit weight of the soil; γ_w is the unit weight of water.

The rainfall infiltration process in the infinite slope is assumed described by a one-dimensional governing vertical flow equation:

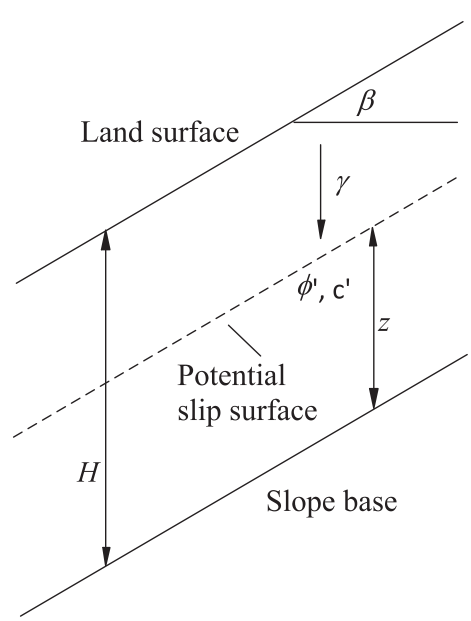

Fig. 1. An infinite slope model.