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Effects of the spatial variability of permeability on rainfall-induced landslides

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ABSTRACT

The saturated hydraulic conductivity (K_s) of soil is characterized by strong spatial variability and often decreases with depth. The main objective of this paper is to investigate how the trend function of the mean of saturated hydraulic conductivity (μ_{K_s}) and its spatial variability affect the distribution of critical failure surfaces and the probability of slope failure during a period of rainfall. A random field method is used to simulate the spatial variability structure in the numerical analysis of a slope, and a numerical procedure for a probabilistic slope stability analysis based on Monte Carlo simulations is presented, in which K_s is modeled as a non-stationary log-normal random field. For a hypothetical weathered soil slope subjected to rainfall, a deterministic analysis and a sequence of probabilistic analyses are conducted using an infinite unsaturated slope model. The results show that these shallow failures are attributed to the reduction of matric suction and the development of positive pore pressure. The probability of slope failure increases with an increase in the variation of the trend component (Δk), but the rate of increase levels off at the later stage of rainfall. Ignoring the trend component of μ_{K_s} would lead to less conservative estimates of the failure probability. The coefficient of variability has a more significant influence on the distribution of the critical failure surfaces and the probability of failure than does the correlation length of K_s.

1. Introduction

Rainfall is one of the most significant triggering factors for natural landslides. It has been widely recognized that as rainwater infiltrates into the soil, the unit weight of the soil will increase with the increase of moisture content, and the contribution of matric suction to soil shear strength will decrease or dissipate (Lim et al., 1996; Ng and Shi, 1998; Rahardjo et al., 2007; Zhang et al., 2010). If many fractures are present in the slope or if the rainwater flows from a higher permeable layer to a lower permeable layer, a perched water table will develop, and the pore–water pressure will become positive, which accelerates the failure process of the slope (Wieczorek, 1987; Rahardjo et al., 1995; Santoso et al., 2011). Generally, the methods used for the analysis of rainfall-induced landslides are deterministic, such as conventional numerical simulations and physically-based hydrologic models (Ng and Shi, 1998; Iverson, 2000; Cho, 2009; Han et al., 2014). However, these methods do not incorporate the uncertainty and spatial variability of soil parameters, particularly the saturated hydraulic conductivity, which exhibits strong variability and defines percolation gradients inside soil mantle (Russo and Bresler, 1981; Vieira and Fernandes, 2004). Probabilistic methods were introduced to overcome these limitations. Zhang et al. (2014) and Dou et al. (2014) presented a probabilistic method for investigating the probability of rainfall-induced slope failure using a mechanics-based model by modeling the saturated hydraulic coefficient as a random variable. More importantly, with the development of random field theory, several studies have explored the effects of the spatial variability of permeability on the stability of rainfall-induced landslides.

Santoso et al. (2011) presented a probabilistic framework to assess the stability of unsaturated slope under rainfall by modeling the saturated hydraulic conductivity as a lognormal stationary random field. Zhu et al. (2013) explored a stationary random field model using the Fast Fourier Transformation (FFT) method to investigate the effects of the spatial variability of soil on saturated-unsaturated flow and slope stability. Cho (2014) discussed various failure patterns of weathered residual soil slope caused by the spatial variability of hydraulic conductivity in the rainfall infiltration based on the one-dimensional random field of an infinite slope model. These studies demonstrate the effects of the spatial variability of the saturated hydraulic conductivity on the slope stability, and provide an innovative idea and method for further research. However, the studies described above used stationary random fields of the saturated hydraulic conductivity, which assumes that the values of the saturated hydraulic conductivity at every location within the soil profile follow the same distribution with the same statistical parameters (e.g., constant mean and variance). However, extensive testing data indicate that the saturated hydraulic conductivity is depth-dependent, and the spatial variation consists of two pieces: a

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smooth trend component and a fluctuating component. The trend component of the saturated hydraulic conductivity generally decreases with soil depth, which results in a decrease of the mean and variance with depth (Ehrenberg and Nadeau, 2005; Wan et al., 2010). Therefore, the corresponding random field should be non-stationary, and rainfall-induced landslides may not be predicted accurately if this characteristic is ignored.

In this paper, the soil properties other than the saturated hydraulic conductivity are treated as deterministic parameters to highlight the significance of the variation in the hydraulic conductivity on seepage through an unsaturated soil slope and the resulting impact on the failure probability and failure modes of rainfall-induced landslides. The research presented in this paper is an extension of Cho (2014), in which a series of seepage and stability analyses of an infinite slope are performed using a one-dimensional non-stationary random field of the saturated hydraulic conductivity to study the effects of the trend component and its variability on the failure of unsaturated slopes due to rainfall infiltration. The objectives of our studies are: (1) establishing a non-stationary random field of the saturated hydraulic conductivity whose expectation decreases with depth in the unsaturated soil slope, based on the local average subdivision method using the FISH code in FLAC; (2) adopting the module of two phase flow to conduct a series of infiltration analyze in FLAC and combining the infinite slope stability model to investigate how the variability of the saturated hydraulic conductivity (e.g., coefficient of variability, correlation length and trend component) affects the distributions of the critical failure surfaces and the corresponding safety factors.

2. Realization of the non-stationary random field

In general, the spatial variation of soil parameters can be decomposed into a smoothly varying trend function and a fluctuating component as follows:

$$\xi(z) = t(z) + \omega(z) \tag{1}$$

where ξ is the in situ soil property, z is the depth, $t(z)$ is a smooth trend function, and $\omega(z)$ is a fluctuating component that represents the inherent soil variability.

The trend functions of soil parameters are relevant to chemical weathering, physical disintegration, substance construction, and geological process (Phoon and Kulhawy, 1999; Zhang et al., 2009; Rahardjo et al., 2012). Compared with other physical parameters of soil, the saturated hydraulic conductivity exhibits strong variability and can be modeled as a lognormal random field (Benson et al., 1999; Duncan, 2000). In this paper, the trend function was assumed to be linear with soil depth. In other words, we assume that the saturated hydraulic conductivity decreases linearly with depth and therefore can be modeled as a lognormal non-stationary random field.

In this study, the local average method was used to simulate the random field in one-dimensional space (Fenton and Vanmarcke, 1990). The essence of the method is to use numerical characteristics of K_s (e.g., expectation, variance and autocorrelation function) to describe its spatial variability and to use a variance reduction function to transition from the "point of variability" to "spatial variability" (Fenton and Griffiths, 2008; Vanmarcke, 2010). Therefore, the key to realizing the lognormal non-stationary random field is to determine the expectation of K_s (μ_{K_s}), the coefficient of variation [$CoV(K_s)$] or a standard deviation σ_{K_s} and the correlation function. Clearly, ln K_s obeys a normal distribution with a mean of $\mu_{\ln K_s}$ and a variance of $\sigma_{\ln K_s}$.where

$$\sigma^2_{\ln K_s} = \ln\left(1+\sigma^2_{K_s}/\mu^2_{K_s}\right) = \ln\left[1+CoV^2(K_s)\right] \tag{2}$$

$$\mu_{\ln K_s} = \ln\left(\mu_{K_s}\right) - \frac{1}{2}\sigma^2_{\ln K_s} \tag{3}$$

and an exponential correlation function is used:

$$\rho(\tau) = \exp\left(-\frac{|\tau|}{l_v}\right) \tag{4}$$

in which τ is the vertical distance between two observations, and l_v is the correlation length.

The variance reduction function that determines the spatial average characteristic of K_s can be expressed as:

$$\Gamma^2(T) = \frac{\sigma^2_{T\ \ln K_s}}{\sigma^2_{\ln K_s}} = \frac{2}{T}\int_0^T\left(1-\frac{\tau}{T}\right)\rho(\tau)d\tau \tag{5}$$

where T is the averaging domain, $\sigma^2_{\ln K_s}$ is the variance of a point property, $\sigma^2_{T\ \ln K_s}$ is the variance of ln K_s after being locally averaged. Therefore, the lognormal non-stationary random field of K_s is given by:

$$K_s(z_i) = \exp\left\{\mu_{\ln K_s}(z_i) + \sigma_{\ln K_s}(z_i)\cdot\Gamma(T)\cdot X(z_i)\right\} \tag{6}$$

where $X(z)$ is a normal stationary random field for K_s. Thus, a non-stationary random field $K_s(z_i)$ will be produced from $X(z)$ when μ_{K_s} varies with z.

A one-dimensional rainfall infiltration model is then developed in FLAC. The random values of K_s are generated and assigned to each element of the numerical model using the FISH code. This results in a non-stationary random field of the saturated hydraulic conductivity that decreases linearly with depth.

3. Analysis of rainfall infiltration

The module of Two Phase Flow was adopted to simulate the process of rainfall infiltration in FLAC (Itasca, 2006). The initial pressure of the gas phase was set to zero to ignore the effects of the gas phase on rainfall infiltration.

In Two Phase Flow, the flow of water and gas through the soil is governed by Darcy's law, which can be written as:

$$q^w = K^w(\theta)\nabla H^w \tag{7}$$

$$q^g = K^g(\theta)\nabla H^g \tag{8}$$

where q is the flow flux, ∇H is the hydraulic gradient, $K(\theta)$ is the unsaturated permeability, and the liquid phase and gas phase are identified by the superscripts w and g, respectively.

Considering mass conservation, the governing equation for the one-dimensional flow can be obtained as

$$\frac{\partial}{\partial z}\left(K^w\frac{\partial H^w}{\partial z}\right) = \frac{\partial(nS^w)}{\partial t} \tag{9}$$

$$\frac{\partial}{\partial z}\left(K^g\frac{\partial H^g}{\partial z}\right) = \frac{\partial(nS^g)}{\partial t} \tag{10}$$

where S^w and S^g are the saturations of the liquid phase and gas phase, respectively, and n is the porosity.

The two fluids completely fill the pore space, so

$$S^w + S^g = 1 \tag{11}$$

and the pressure difference ($H^g - H^w$) is the capillary pressure, which is a function of saturation.

$$(H^g - H^w)\gamma_w = \psi(S_w) \tag{12}$$

where $\psi(S_w)$ is the capillary pressure, which is also called matric suction.