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Probabilistic stability analysis of rainfall-induced landslides considering spatial variability of permeability

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ABSTRACT

Many regions around the world are vulnerable to rainfall-induced landslides. A variety of methods have been proposed for revealing the mechanism of landslide initiation. Current analysis methods, however, do not consider the effects of non-homogeneous soil profiles and variable hydraulic responses on rainfall-induced slope failures. In Korea, where the depth of weathering is very shallow, many slope failures occur in the layer of weathered residual soil that overlays the bedrock. These failures are characterized by shallow failure surfaces located near the interface between the weathered soil and the underlying bedrock. In this study, probabilistic stability analyses were conducted for a weathered residual soil slope with shallow impermeable bedrock to study the failure mechanism of rainfall-related landslides. A series of seepage and stability analyses of an infinite slope based on one-dimensional random fields were performed to study the effects of uncertainty due to the spatial heterogeneity of hydraulic conductivity on the failure of unsaturated slopes due to rainfall infiltration. The results showed that a probabilistic framework can be used to efficiently consider various failure patterns caused by spatial variability of hydraulic conductivity in rainfall infiltration assessment for a shallow infinite slope.

1. Introduction

Landslides are attributed to a number of factors, such as geologic features, topography, vegetation, weather, or combinations of these factors. In Korea, disastrous shallow landslides occur mostly due to concentrated heavy rainfall in weathered granite residual soil slopes.

According to previous studies, rainfall can cause the development of a perched water table, a rise in the main groundwater level, surface erosion, and an increase in unit weight with a rise in moisture content (Ng and Shi, 1998). An understanding of the mechanism behind these slope failures is requisite for the development of a reasonable procedure for analyzing soil slope stability pertaining to transient seepage due to rainfall (Cho and Lee, 2001).

The one-dimensional infinite slope model is frequently used to study shallow landslides in which a slope length is significantly greater than its soil layer thickness (e.g. Cho and Lee, 2002; Lu and Godt, 2008; Ray et al., 2010; Santoso et al., 2011; Li et al., 2013). Shallow landslides are common when soil thickness ranges from 1 to 3 m (Ray et al., 2010).

The role of water infiltration into shallow soils and the subsequent pore pressure response at depth is critical to understanding the transient conditions that lead to shallow slope failure. A strong correlation exists between the timing of intense precipitation and dynamic variation in pore water pressure (Lu and Godt, 2013).

The infiltration of water into a soil slope depends not only on rainfall intensity and duration but also on the hydraulic properties of the near-ground surface soil, such as its saturated hydraulic conductivity, hydraulic conductivity function, and water retention capacity. Rainfall must be sustained over a considerable time, and the rainfall intensity must approach the soil's saturated coefficient of permeability at the ground surface in order to eliminate matric suction from the soil profile (Zhang et al., 2004; Fredlund et al., 2012).

Generally, methods used for stability analysis of rainfall-induced landslides are deterministic, with soil properties characterized as constants for a given soil layer and each specified layer assumed to be homogeneous (Gui et al., 2000). However, predicting rainfall infiltration through soil slopes inevitably involves uncertainties. Furthermore, soils are highly variable and heterogeneous. Geomorphological processes, such as sedimentation or weathering, can lead to soil regions characterized by a degree of spatial heterogeneity that takes the form of random variations in material properties (Lacasse and Nadim, 1996).

Since the first use of RFEM (Random Finite Element Method) in steady seepage by Griffiths and Fenton (1993) and Fenton and Griffiths (1993), several studies on seepage flow have considered the spatial fluctuations of a parameter by using random field theory (Gui et al., 2000; Srivastava et al., 2010; Cho, 2012).

Griffiths et al. (2011) performed random field analyses based on infinite slope assumptions, which clearly demonstrated the important “seeking out” effect of failure mechanisms in spatially random materials. They showed that there is a significant probability that the critical mechanism will occur above the base of the soil column where the factor of safety is lower.

Several researchers have investigated the influence of spatial variability and uncertainty associated with hydraulic conductivity

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on soil slope stability. Gui et al. (2000) investigated the effects of stochastic hydraulic conductivity on the slope stability of an embankment dam through a probabilistic seepage analysis using a combination of random field simulation, seepage analysis, and slope stability analysis.

Srivastava et al. (2010) used commercially available finite difference numerical code for modeling the permeability parameter as a spatially-correlated lognormally-distributed random variable and studied its influence on both the steady state seepage flow and slope stability analysis.

Santoso et al. (2011) presented a probabilistic framework to assess the stability of an unsaturated infinite slope under rainfall. They showed that shallow failures widely observed in Singapore are attributed to positive pore water pressures developed in layers near the ground surface. They also demonstrated numerically that probabilistic analysis accounting for spatial variability in the saturated hydraulic conductivity can reproduce the shallow failure mechanism. However, they did not consider a failure mechanism associated with shallow weathering depth. The failure mechanism is characterized by shallow failure surfaces located near the interface between the weathered soil and underlying bedrock due to a rise of groundwater that exerts seepage force and adds weight to the slope.

In this study, a probabilistic stability analysis of rainfall-induced landslides was performed. The traditional limit equilibrium analysis of infinite slope for an unsaturated slope under rainfall was extended to develop a probabilistic approach that accounts for the uncertainties and spatial variation of the hydraulic conductivity in a soil profile.

To study shallow failure modes the approach by Santoso et al. (2011) was extended. A unified effective stress concept under both saturated and unsaturated conditions has been adopted, which enables account for both the reduction in matric suction and the development of positive pore water pressure by the rise of water table above bedrock in a continuous form. The variation in unit weight that results from changes in moisture content during infiltration was also considered.

A series of seepage and stability analyses of an infinite slope were performed using one-dimensional random fields in order to study the effects of uncertainty due to spatial heterogeneity of hydraulic conductivity upon the rainfall-induced failure of an unsaturated slope with shallow impermeable bedrock.

2. Seepage analysis

2.1. Governing equation

The differential equation governing flow was derived assuming that flow follows Darcy's law regardless of the soil's degree of saturation (Richards, 1931). Combining Darcy's law with the mass conservation law gives the governing equation for the one-dimensional flow of water through an unsaturated soil as follows (Papagiannkis and Fredlund, 1984):

$$\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = m_w \gamma_w \frac{\partial h}{\partial t} \tag{1}$$

where h is the total head, m_w is the slope of the soil water characteristic curve, γ_w is the unit weight of water, t is time, and k_z is the hydraulic conductivity in the vertical direction, depending on pore water pressure.

The transient nonlinear differential equation (Eq. (1)) was solved using an iterative finite element scheme until the computed solution did not change by more than a specific value in successive iterations. A detailed description of the solution algorithm can be found in the literature (Fredlund and Rahardjo, 1995; Cho and Lee, 2001).

When solving time dependent problem with spatially random soil permeability, time step is very critical to get reliable results (e.g., Huang et al., 2010). Over the period of one time increment, the process is considered to be linear and the incremental stepping forward in time approximates the nonlinear process (Geo-Slope, 2012). In this study, therefore, small time steps were used to accurately follow the wetting process in the heterogeneous soil, which increased the number of time steps. A time-adaptive scheme that ensures a reasonable number of time steps will be needed to enhance the computational efficiency.

For the vertical seepage analysis, this study employed a one-dimensional soil column model using a two-dimensional finite element analysis routine developed based on the theory of saturated–unsaturated flow.

2.2. Hydraulic characteristics

The generalized Darcy's Law was used to describe the velocities of pore water. However, the hydraulic conductivity that is constant in the saturated soils depends on the degree of saturation or the matric suction in unsaturated soils. A number of empirical and semi-empirical functions have been proposed to represent the hydraulic conductivity function. In this study, soil hydraulic functions are described by a set of closed form equations (van Genuchten, 1980)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha\Psi)^n]^m} \tag{2–1}$$

where $m = 1 - 1/n$, $n > 1$and

$$k = k_s S_e^{1/2}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{2–2}$$

in which Ψ is the matric suction, S_e is the effective water saturation, θ is the volumetric water content, θ_r and θ_s denote the residual and saturated volumetric water contents, respectively, m, n, and α are retention parameters, k is the hydraulic conductivity function, and k_s is the saturated hydraulic conductivity.

3. Slope stability analysis

3.1. Infinite slope analysis

Rainfall-induced landslides are usually characterized by shallow failure surfaces that develop parallel to the slope surface. A slope that tends to fail in shear along planar surfaces parallel to the ground surface and which has competent subsoil may be analyzed as an infinite slope (Cho and Lee, 2002). Under these conditions, the limit equilibrium method can be applied to calculate the factor of safety.

Based on the Mohr–Coulomb failure criterion, the factor of safety of the infinite slope shown in Fig. 1 can be readily expressed as:

$$F_s = \frac{\tau_f}{\tau_m} = \frac{c' + \sigma' \tan\phi'}{W \sin\beta \cos\beta} \tag{3}$$

where τ_f is the shear strength of soil, τ_m is the shear stress at any point along the potential failure surface, β is the slope angle, W is the weight of the soil slice, c' is the effective cohesion, σ' is the effective normal stress, and ϕ' is the effective friction angle.

Many attempts have been made to extend the concept of effective stress to unsaturated soils (e.g. Bishop, 1959). Recently, Lu and Likos (2006) and Lu and Godt (2008) have suggested a unified effective stress under both saturated and unsaturated conditions as:

$$\sigma' = (\sigma_n - u_a) - \sigma^s \tag{4}$$

where u_a is the pore air pressure, σ_n is the total stress due to the self weight of the soil, and σ^s is suction stress expressed in terms