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Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration

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ABSTRACT

Even though soil is a mixture of solids with voids that are filled by air and water, most previous studies on rainfall infiltration and its influence on slope stability were based on a single-phase water flow model by assuming that the pore air pressure was atmospheric. The purpose of this study is to examine the effect of interactions between air and water flow due to heavy rainfall on the mechanical stability of an unsaturated soil slope. Water-air two-phase flow analyses were conducted to investigate the contribution of pore-air pressure on infiltration by rainfall. In order to study the infiltration behavior with respect to soil type, flow analyses were performed with two types of soil under similar settings. Results obtained from the two-phase infiltration analysis were then used as input to the stability analysis by the strength reduction method. Infiltration and stability analyses based on a single-phase water flow model were also carried out, which helped clarify the effects of air flow induced by rainfall infiltration on an unsaturated soil slope. The results showed an increase in pore air pressure during infiltration because rainwater displaced the air in the unsaturated zone; hence, remarkable delaying effects on water flow were induced. Such water-air interactions in the pore space of soil significantly affected the stability and behavior of the soil slope.

1. Introduction

Slope failures due to rainfall are very frequent worldwide, and the damage caused by such failures is substantial. 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 of soil due to a rise in moisture content (Ng and Shi, 1998; Cho and Lee, 2001).

The role of water infiltration in soil and the subsequent pore pressure response at depth are critical for understanding the transient conditions that lead to slope failure (Lu and Godt, 2013). Since soil is a mixture of solids with voids that are filled by fluids such as air and water, in order to exactly interpret the infiltration of rainfall through the slope surface, a fully coupled formulation of the water and air flow and the stress-strain behavior of soil should be considered.

However, assumptions for the sake of simplicity have been introduced. The most widely used infiltration analysis method is to solve the Richards (1931), which considers single-phase flow of water by ignoring the stress-strain behavior and air flow in soil (e.g., Ng and Shi, 1998; Rahardjo et al., 2001).

When rainfall infiltration occurs through pore space in an unsaturated region, the flow of air also occurs, or the air is compressed by the interaction at the water-air interface. It is well known, based on experiments and analyses, that the flow of air through the pore space in unsaturated soil affects the infiltration of water (Touma and Vauclin, 1986; Sun et al., 2015). However, because of the difficulties of measuring pore-air pressure and analyzing air flow, the air flow induced by rainfall is ignored in general slope stability analyses by setting the pore air pressure to zero (Sun et al., 2015). In order to study the mechanical behavior due to rainfall infiltration of the slope, coupled hydro-mechanical analyses have been conducted. However, most of the solutions considered the air pressure in soil to be equal to the atmospheric pressure based on the assumption that the air flow is free relative to the flow of water (e.g., Alonso et al., 1995; Cho and Lee, 2001; Smith, 2003; Borja and White, 2010; Borja et al., 2012; Hamdhan and Schweiger, 2011; Wang et al., 2015).

Only a few studies have been conducted regarding the effect of air flow due to rainfall infiltration on the stability of soil slopes. Hu et al. (2011) applied a coupled three phase (solid-water-air) model to simulate the coupled deformation, water flow, and gas transport processes in a homogeneous soil slope and to assess the evolution of the safety factor of the slope using the Morgenstern-Price Method under a long, heavy rainfall. They showed that air transport in a homogeneous soil slope that was subjected to a heavy rainfall has a significant effect on slowing the propagation of the wetting front and decreasing slope stability.

Zhang et al. (2009) and Sun et al. (2015) investigated the characteristics of airflow response to rainfall in a soil slope using a water-air tp (two-phase) flow model. Slope stability analyses on the given slip surface using the limit equilibrium method were then performed based

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on the simulated water-air tp seepage conditions, taking into consideration the contribution from pore air pressure. The results by Zhang et al. (2009) showed that pore air pressure generated in the unsaturated zone reduces the safety factor, and as the distance between the slip surface and the underground water level increased, the influence of pore air pressure on soil slope stability also increased. Sun et al. (2015) showed that capillary pressure is beneficial, while pore air pressure is unfavorable to slope stability for a given slip surface.

Hu et al. (2011) adopted a linear elastic model for simplicity to describe the mechanical behavior of the soils. Therefore, the effects of nonlinear deformation and the shear strength of unsaturated soils on the process of rain infiltration and the evolution of slope stability were not considered. Zhang et al. (2009) and Sun et al. (2015) used a fixed given slip surface to analyze the slope stability. In other words, they did not reflect the continuous transition of the critical failure surface with the progression of the wetting front.

In this study, water-air tp flow analyses were conducted to investigate the effect of air flow due to rainfall infiltration on the stability of unsaturated soil slopes. In order to study the infiltration behavior with respect to soil type, flow analysis was performed for two types of soil under similar conditions. The result obtained from the tp infiltration analysis was then used as input for the stability analysis that accounted for mechanical equilibrium of the system, taking into consideration the contribution from pore air pressure. For the purpose of comparison, infiltration and stability analyses based on a water sp. (single-phase) flow model were also carried out, which helped clarify the effects of air flow induced by rainfall infiltration on unsaturated soil slopes.

2. Two-phase flow analysis

In this study, two-dimensional finite difference code FLAC Ver. 7.0 (Itasca, 2011) was used to analyze rainfall infiltration of unsaturated soil slopes. The tp flow option in FLAC allows numerical modeling of the flow of two immiscible fluids through porous media.

2.1. Unsaturated flow

In tp flow, the void space is completely filled by the two fluids. One of the fluids (the wetting fluid) wets the porous medium more than the other (the non-wetting fluid). In soil-water systems, water is the wetting fluid, and air is the non-wetting fluid. Wetting and non-wetting fluid transport are described by Darcy's law:

$$q_i^w = -k_{ij}^w k_r^w \frac{\partial}{\partial x_j}(P_w - \rho_w g_k x_k) \tag{1}$$

$$q_i^a = -k_{ij}^w \frac{\mu_w}{\mu_a} k_r^a \frac{\partial}{\partial x_j}(P_a - \rho_a g_k x_k) \tag{2}$$

where k_{ij}^w is saturated mobility coefficient, k_r is the relative permeability of the fluid (which is a function of water saturation S_w), μ is dynamic viscosity, ρ_w is water density, ρ_a is air density, P_w is the pore water pressure, P_a is the pore air pressure, and g is gravitational acceleration. Water is identified by the subscript w, and air is identified by the subscript a.

Air and water have different viscosities. This difference leads to a difference in each phase's ability to flow through soil. The viscosity ratio (μ_w/μ_a) is used within FLAC-tp (Eq. (2)) rather than the individual viscosities of the fluids within the media. The viscosity ratio dictates that an increase in this value represents an increased flow rate for the air phase relative to the water phase. It has been shown experimentally that the viscosity of air is much less than the viscosity of water (Fredlund and Rahardjo, 1995). This fact dictates that the air within soil flows much more freely than water.

The permeability used in FLAC is actually the mobility coefficient. The relationship between hydraulic conductivity (k_s), commonly used when Darcy's law is expressed in terms of head, and permeability (k) is:

$$k = \frac{k_s}{g\rho_w} \tag{3}$$

Relative permeability, expressed as a percentage of maximum permeability, is a function of saturation, and the relationship is usually empirically determined. Following van Genuchten (1980) and Mualem (1976), a closed-form expression of relative permeability of water is used:

$$k_r^w = S_e^b \left[1 - \left(1 - S_e^{1/a}\right)^a\right]^2. \tag{4}$$

The following equation for the relative permeability of air by Lenhard and Parker (1987) is used:

$$k_r^a = (1 - S_e)^{1/2} \left[1 - S_e^{1/a}\right]^{2a}, \tag{5}$$

where a and b are constants and S_e is the effective saturation.

The air coefficient of permeability decreases as the water degree of saturation increases until the suction reaches the air-entry value of the soil. Air flow takes the form of air diffusion through the soil-water when soil suction is below the air-entry value of the soil. At this point, the air coefficient of permeability tends to an extremely small value, i.e., diffusivity of air through the water in the soil (Fredlund et al., 2012). Therefore, small value of the air coefficient of permeability is specified at under low suctions by Eq. (5) to describe the air flow at low suction.

The effective saturation is defined by van Genuchten (1980) as:

$$S_e = \frac{S_w - S_r}{1 - S_r} = \frac{1}{\left[1 + (\psi/P_o)^{\frac{1}{1-a}}\right]^a}, \tag{6}$$

where S_r is the residual saturation, ψ(Pa) is the matric suction, and P_o(Pa) is a parameter that depends approximately on the air-entry value.

The matric suction is calculated from Eq. (6) as:

$$\psi = P_a - P_w = P_o\left[S_e^{-1/a} - 1\right]^{1-a}. \tag{7}$$

Combining the fluid balance laws with the fluid constitutive laws for water and air gives following expressions:

$$n\left[\frac{S_w}{K_w}\frac{\partial P_w}{\partial t} + \frac{\partial S_w}{\partial t}\right] = -\left[\frac{\partial q_i^w}{\partial x_i} + S_w \frac{\partial \varepsilon}{\partial t}\right] \text{ and} \tag{8}$$

$$n\left[\frac{S_a}{K_a}\frac{\partial P_a}{\partial t} + \frac{\partial S_a}{\partial t}\right] = -\left[\frac{\partial q_i^a}{\partial x_i} + S_a \frac{\partial \varepsilon}{\partial t}\right], \tag{9}$$

where ε is volumetric strain, n is porosity, K is fluid bulk modulus, $S_a(=1 - S_w)$ is air saturation, and t is time.

In a fluid-only calculation, the term $\frac{\partial \varepsilon}{\partial t}$ is omitted. Equations for two-phase flow are solved using discretization and the explicit finite-difference method.

2.2. Balance of momentum

The balance equation is

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g_i = \rho \frac{d\dot{u}}{dt}, \tag{10}$$

where σ is the total stress, ρ is bulk density, and $\dot{u}$ is velocity. For water-