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Stability analysis of unsaturated soil slope during rainfall infiltration using coupled liquid-gas-solid three-phase model

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Abstract

Generally, most soil slope failures are induced by rainfall infiltration, a process that involves interactions between the liquid phase, gas phase, and solid skeleton in an unsaturated soil slope. In this study, a loosely coupled liquid-gas-solid three-phase model, linking two numerical codes, TOUGH2/EOS3, which is used for water-air two-phase flow analysis, and FLAC^{3D}, which is used for mechanical analysis, was established. The model was validated through a documented water drainage experiment over a sandy column and a comparison of the results with measured data and simulated results from other researchers. The proposed model was used to investigate the features of water-air two-phase flow and stress fields in an unsaturated soil slope during rainfall infiltration. The slope stability analysis was then performed based on the simulated water-air two-phase seepage and stress fields on a given slip surface. The results show that the safety factor for the given slip surface decreases first, then increases, and later decreases until the rainfall stops. Subsequently, a sudden rise occurs. After that, the safety factor decreases continually and reaches its lowest value, and then increases slowly to a steady value. The lowest value does not occur when the rainfall stops, indicating a delayed effect of the safety factor. The variations of the safety factor for the given slip surface are therefore caused by a combination of pore-air pressure, matric suction, normal stress, and net normal stress.

Keywords: Coupled liquid-gas-solid three-phase model; Pore-air pressure; Unsaturated soil slope stability; Rainfall infiltration

1. Introduction

A landslide is usually induced by rainfall infiltration, which is one of the most important subjects in the field of geotechnical engineering. As rainwater infiltrates the soil slope, due to the advancing wetting front, the pore-air pressure in the unsaturated zone increases and the matric suction decreases, compromising slope stability (Sun et al., 2015). Meanwhile, the infiltration of rainwater causes a change in the effective stress, leading to variations of porosity; in turn, the variations of the porosity affect the seepage properties (Xu et al., 2009). Therefore, the interactions between the liquid phase, gas phase, and solid skeleton in an unsaturated soil slope should be considered in the analysis of unsaturated soil slope stability during rainfall infiltration.

In general, analysis of soil slope stability during a rainfall event is performed using the limit equilibrium methods and by considering only the changes in liquid-phase flow (Cho and Lee, 2001; Collins and Znidarcic, 2004). The changes in gas-phase flow are usually ignored due to the difficulties in obtaining the magnitude of pore-air pressure (Sako et al., 2011). The gas-phase flow induced by rainfall has a significant effect on the seepage process in the saturated-unsaturated soil and on the soil slope stability (Wang et al., 1998; Sun et al., 2007, 2009; Guo et al., 2008; Regmi et al., 2010; Kuang et al., 2013; Sun et al., 2015). An

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uncoupled model for slope stability analysis considering the gas phase flow has been developed based on the limit equilibrium method and according to the water-air two-phase seepage field calculated from a multi-phase flow model (Sun et al., 2009; Regmi et al., 2010). Although this uncoupled model is relatively easy to implement using existing available multiphase flow models, the dependence of hydraulic properties (such as the porosity and hydraulic conductivity) on deformation is not taken into account. A coupled model of slope stability analysis considering the gas-phase flow was established by solving a liquid-gas-solid three-phase mathematical model to obtain the water-air two-phase seepage and stress conditions (Hu et al., 2011). The coupled model can produce the most realistic results, but it is very difficult to establish a fully coupled three-phase model. Thus, a loosely coupled three-phase model is a good choice due to the ease of implementation and its satisfying accuracy. A loosely coupled methodology, called TOUGH2-FLAC^{3D}, proposed by Rutqvist et al. (2002), can be adopted to investigate the coupled multiphase fluid flow and soil skeleton deformation. TOUGH2 (Pruess et al., 1999) was used for multiphase fluid flow simulation, while FLAC^{3D} (ICGI, 2002) was used for mechanical simulation.

In this study, the loosely coupled method based on TOUGH2-FLAC^{3D} was used to investigate the features of water-air two-phase flow and stress fields in an unsaturated soil slope induced by rainfall infiltration. Then, a method for calculation of the safety factor for a given slip surface was developed using the simulated water-air two-phase seepage and stress fields.

2. Coupled liquid-gas-solid three-phase model

TOUGH2, a computer code for non-isothermal multiphase multi-component flow in three-dimensional porous and fractured media, is used for multiphase fluid flow simulation, in which the deformation of the soil is not taken into account. The TOUGH2 simulator was chosen in this study because its source code is available for further modification. The TOUGH2/EOS3 model was adopted for the study. EOS3 is a module of the TOUGH2 simulator for the two-phase flow for water and air, in which two fluid phases, the liquid phase (subscript l) and gas phase (subscript g), are considered. The liquid phase consists of water (superscript w) and dissolved air (superscript a). The gas phase consists of air (superscript a) and water vapor (superscript w). Thus, there are two components, water and air. FLAC^{3D}, a three-dimensional explicit finite-difference computer program for solving geomechanical problems, is used to simulate the mechanical system, in which the airflow induced by rainfall is not included. In FLAC^{3D}, an embedded programming language, the FISH language, enables the users to define new variables and functions. FLAC^{3D} can communicate with TOUGH2 via this feature.

When rainwater infiltrates the soil slope, the liquid saturation, the distributions of pore-water pressure and pore-air pressure, and matric suction change, leading to changes in the soil density, the effective stresses, and the strains of soils. The changes in the strains affect the porosity of soils, causing changes in the intrinsic permeability and the capillary pressure, and further influencing the seepage processes. Therefore, in the coupled liquid-gas-solid three-phase model, the porosity, intrinsic permeability, and capillary pressure in TOUGH2 should be updated every time step. Then, the pore pressures should be updated in FLAC^{3D} to calculate the new porosity in the next time step.

2.1. Modifications to mechanics

In the multiphase fluid flow process, information about liquid saturation and pore pressures (pore-water and pore-air pressures) can be provided by TOUGH2, which is used to calculate the average pore pressure through Eq. (1) (Rutqvist et al., 2002):

$$p = S_{\mathrm{l}} p_{\mathrm{l}} + (1 - S_{\mathrm{l}}) p_{\mathrm{g}} \tag{1}$$

where p is the average pore pressure, S_{l} is the liquid saturation, and p_{l} and p_{g} are the pore-water pressure and pore-air pressure, respectively (the pore pressures refer to the atmosphere pressure).

By substituting the pore pressure into Eq. (1), FLAC^{3D} can be used to calculate the effective stress, the strain, the displacement, and the stress. The change in porosity due to the deformation of the soil can be expressed as (Coussy, 1995; Bary, 2002)

$$\mathrm{d}\phi = (1 - \phi_0)\varepsilon_{\mathrm{v}} - (1 - \phi_0)\varepsilon_{\mathrm{s}} \tag{2}$$

where ϕ is the porosity, $\mathrm{d}\phi$ is the change in porosity, ϕ_0 is the porosity at zero stress (the initial state), ε_{v} is the volumetric strain increment, and ε_{s} is the shear strain increment.

2.2. Modifications to fluid flow

Deformation due to the mechanical response is translated to the increase or decrease in porosity. The intrinsic permeability is corrected according to the Kozeny-Carman equation (Chapuis and Aubertin, 2003):

$$K = K_0 \left(\frac{\phi}{\phi_0}\right)^3 \left(\frac{1 - \phi_0}{1 - \phi}\right)^2 \tag{3}$$

where K is the corrected intrinsic permeability, and K_0 is the intrinsic permeability at zero stress.

The capillary pressure is modified with the current intrinsic permeability and porosity, according to the function proposed by Leverett (1941):

$$p_{\mathrm{cL}} = p_{\mathrm{c}} \frac{\sqrt{K_0/\phi_0}}{\sqrt{K/\phi}} \tag{4}$$

where p_{cL} is Leverett's corrected capillary pressure, and p_{c} is the calculated capillary pressure depending on the liquid saturation.