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Coupled infiltration model of unsaturated porous media for steady rainfall

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Abstract

Unsaturated soil slopes introduce complex hydro-mechanical coupled processes which greatly alter matric suction distribution of an unsaturated soil during rainfall. In order to investigate matric suction and volume change of unsaturated soils, a two-dimensional hydro-mechanical coupled infiltration model (YS-Slope) is developed by incorporating the hydraulic and mechanical characteristics of unsaturated soils, such as the soil-water characteristic curve, permeability function, shear strength, and porosity. Special attention is given to the porosity-dependent permeability function of unsaturated soils. In addition, in order to highlight effectiveness of YS-Slope and coupling effects of hydro-mechanical processes on the infiltration behavior of unsaturated soils, a series of infiltration analyses for a soil column under various soil properties is conducted and their results are compared with those of commercial software, GEO-SLOPE (2012). The results of the numerical analyses show good agreement with data from the analytical solution and laboratory tests, which indicates that the proposed model is appropriate for use in the simulatfion o the infiltration of rainwater into deformable soils. The transient seepage and rainwater flow in deformable soils are influenced by the volume change of the soil. The change in matric suction on a slope due to rainfall infiltration influences change in effective stress while the effective stress alters seepage processes according to hydraulic properties. The results indicate that hydro-mechanical coupled behavior of soils has a positive effect on the stability of unsaturated soil slops during rainfall.

Keywords: Infiltration model; Coupled analysis; Unsaturated soil; Numerical analysis; Seepage, Matric suction

1. Introduction

It is important to evaluate the potential for landslides so that human safety can be maintained in high-risk areas. The likelihood of a shallow landslide due to rainfall infiltration on slope face is strongly dependent on the hydraulic properties of unsaturated soils (Kim et al., 2014). The pore-water pressure on the unsaturated soil slopes influences the infiltration rate, the wetting band depth, and the soil strength. A number of studies have been done on analytical solutions describing the infiltration process under transient state in homogeneous and layered soils. Gardner (1958) proposed an analytical solution for unsaturated flows based on an exponential hydraulic parameter model. Srivastava and Yeh (1991) developed theoretical solutions with hydraulic constitutive relations describing the non-uniform initial conditions for homogeneous or continuous heterogeneous soils based on the Richards equation. However, these solutions may be very restricted for any practical applications (e.g., complex geometry condition and stress–strain relationship).

For the finite element (FE) analysis of unsaturated soils, several commercial software, such as GEO-SLOPE (2012); PLAXIS 2D (2012); Soil Vision (2009) are widely used to simulate the water infiltration process and to evaluate the slope stability with respect

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Nomenclature

α, n, m	Fitting parameters of SWCC
$\bar{\alpha}$	Pore-size distribution parameter.
$\mathbf{B}^{e,u}$	Strain-displacement matrix for element
$\mathbf{c}^e$	Fourth-order elastic modulus tensor
$\mathbf{D}$	Elastic modulus matrix
$\mathbf{d}^e$	Nodal displacement vector for element
$\boldsymbol{\varepsilon}$	Small strain tensor
$\boldsymbol{\varepsilon}^h$	Strain vector
$\mathbf{g}$	Gravitational acceleration
γ_w	Unit weight of water
h_{cap}	Mean capillary rise
k_s	Saturated permeability
k_w	Unsaturated permeability
k_{rw}	Relative permeability
κ	Intrinsic permeability
l^2	Pore geometry parameter
M	Total mass of mixture
n	Porosity
p_w	Pore-water pressure
p_a	Pore-air pressure
φ'	Internal friction angle associated with the net normal stress
φ^b	Angle indicating the rate of increase in shear strength relative to matric suction
ρ	Mass density of mixture
ρ^{wR}	Real mass density of liquid
S	Degree of saturation
S_r	Residual degree of saturation
S_c	Degree of saturation due to capillary forces
S_a^*	Bounded degree of saturation due to adhesion
S^w	Infiltration rate
s, $p_a - p_w$	Matric suction
$\boldsymbol{\sigma}$	Total stress
$\boldsymbol{\sigma}'$	Effective stress
$\sigma - p_a$	Net normal stress
$\mathbf{t}^\sigma$	Total traction
τ	Shear strength of unsaturated soil
θ	Volumetric water content
θ_s	Saturated volumetric water content
θ_r	Residual volumetric water content
$\boldsymbol{\theta}^e$	Nodal vector of pore-water pressure for element
V	Total volume of mixture
$\mathbf{v}$	Velocity of solid
$\mathbf{v}_w$	True velocity of liquid
$\tilde{\mathbf{v}}^w$	Superficial Darcy velocity of liquid
η_w	Dynamic water viscosity
χ	Effective stress parameter

to the factor of safety. However, difficulties associated with incorporating a soil deformation and a complex hydro-mechanical coupled process have hindered the study of the mechanism of rainfall-induced slope failures. Recently, some researchers have developed a coupled hydro-mechanical finite element method, where the volume change of unsaturated soils is included in the analysis. To observe the coupled solid-water-air phenomenon in detail, the coupled balance equations for three phase system consisting of a solid and two immiscible fluids (i.e., liquid and gas) are formulated by Khalili et al. (2004), Gray and Schrefler (2007), and Borja et al. (2012). In addition, a number of constitutive models for unsaturated soils have been developed based on a combination of experimental observations and theoretical formulations (Alonso et al., 1990; Kohgo et al., 1993; Cui and Delage, 1996; Loret and Khalili, 2002; Borja, 2004; Sheng et al., 2008; Nuth and Laloui, 2008; Zhang and Ikariya, 2011; Zhou et al., 2012; Song and Yosef, 2015). Based on past research work, it can be concluded that the focus of most of the investigations was on validating the models the authors proposed. Although hydraulic properties and shear strength might affect the stability of soil slopes during rainfall (Cho and Lee, 2001, Zhang et al., 2005, Kim et al., 2012; Borja et al., 2012), coupled analyses are yet to be extensively employed in practical engineering problems (Griffiths and Lu, 2005; Pande and Pietruszczak, 2015).

In this study, the two-dimensional hydro-mechanical coupled infiltration model (called YS-Slope) is developed by incorporating hydraulic and mechanical properties of unsaturated soils. This model is verified with analytical solutions and triaxial shearing-infiltration test results. A series of infiltration analyses for a soil column under various soil properties are performed and their results are compared with those of the commercial software, GEO-SLOPE (2012) to investigate the coupling effect of hydro-mechanical processes on the infiltration behavior of unsaturated soils.

2. Mathematical frameworks for unsaturated flow

2.1. Governing equations

The volume and mass of a mixture can be defined mathematically. Based on small strain theory and homogeneous condition, the volume of the mixture is $V = V_s + V_w + V_a$ and the corresponding total mass is $M = M_s + M_w + M_a$. Similarly, for the α phase (where α is solid, liquid, and gas), $M_\alpha = \rho^{\alpha R} V_\alpha$, where $\rho^{\alpha R}$ is the true mass density of the α phase. The volume fraction occupied by the α phase is given by $n^\alpha = V_\alpha / V$. Therefore, for the mixture of a solid, liquid and gas, the concept of volume fractions can be applied as (de Boer, 2006):

$$n^s + n^w + n^a = 1 \tag{1}$$

where $n = (V_w + V_a)/V = n^w + n^a$ is the porosity. The partial mass density of the α phase is given by $\rho^\alpha = n^\alpha \rho^{\alpha R}$. In this model, mass exchange among the three phases is ignored (i.e., chemical reactivity and phase changes are neglected). The solid and liquid phases are assumed to be incompressible, and the pore-air pressure is considered negligible (i.e., $p_a \approx 0$). The

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