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ORIGINAL ARTICLE

Numerical analysis of 1D coupled infiltration and deformation in layered unsaturated porous medium

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Abstract Unsaturated layered soils are common in nature and engineering practices, including highway embankments and waste landfills. Based on the principle of effective stresses and considering the deformation in unsaturated porous medium and changes in permeability with the stress state during rainfall, a one-dimensional model for simulating coupled seepage and deformation in layered unsaturated porous medium is established. A finite element program was written in FlexPDE to analyze the hydro-mechanical coupled process of rainfall infiltration into a two-layer unsaturated porous medium. The factor of safety as a function of the wetting front depth is discussed based on a simple infinite slope analysis. The numerical results demonstrate that the coupling of seepage and deformation plays a significant role in the movement of wetting front, the distribution of pore-water pressure, and the slope stability. The coupling of seepage and deformation should be taken into account when analyzing the rainfall infiltration into the layered unsaturated porous medium, especially for a combination of a short-duration heavy rain and high initial suctions.

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Introduction

Much of the earth's surface is classified as arid or semi-arid regions. The soils above the groundwater table in these regions remain unsaturated due to water evaporation and transpiration (Fredlund and Rahardjo 1993). An unsaturated soil is a multiphase system including the solid, liquid, gas, and contractile skin, which exhibits more complex properties than a saturated soil does (Fredlund and Morgenstern 1976). During rainfall infiltration into an unsaturated soil, seepage and deformation interact. Pore-water pressure changes during the infiltration process will lead to changes in stress state, which is closely related to the mechanical behavior of the soils (e.g., Zhao and Zhang 2014). The stress changes also affect the infiltration velocity and the pore-water pressure distribution in the unsaturated porous medium. Hence, seepage and stress-induced deformation problems are important in engineering practices and should be formulated by using a coupled approach (Cho and Lee 2001; Zhang et al. 2011).

Coupled seepage and deformation due to rainfall require governing equations which formulate the equilibrium of the soil skeleton and the fluid flow in the unsaturated porous media. Several formulations for coupled problems in unsaturated soils have been reported (Lloret et al. 1987; Alonso et al. 1989; Thomas and He 1995; Kim 2000; Wang et al. 2009; Ravichandran 2009). Lloret et al. (1987) presented a constitutive model for the analysis of coupled flow and deformation in partially saturated soils. Thomas and He (1995) presented a theoretical expression for coupled heat–moisture transfer in deformable unsaturated soils and a numerical solution was obtained using a finite element method. Kim (2000) performed a finite element analysis of coupled water-table fluctuation and land deformation in unsaturated soils due to surface loading. Wang et al. (2009) proposed a parallel finite element scheme for coupled THM problems in porous media. Ravichandran (2009) presented fully coupled governing equations to study the response of a partially saturated soil embankment under earthquake loading considering both relative accelerations and relative velocities of the pore fluids.

Many of the aforementioned studies are based on the assumption that the porous medium is homogeneous. However, the natural soil fabric is hydraulically and mechanically anisotropic due to long-term geologic processes and the infiltration in a layered porous medium differs from that in a homogeneous soil layer. Rainfall infiltration into layered porous media hence becomes a concern in recent years. A general two-layer soil can be divided into two categories: a lower permeability upper layer or a higher permeability upper layer (Corradini et al. 2011). Many shallow slope failures occur in weathered residual soils overlying bedrock; shallow failure surfaces are often located near the interface between the upper soil layer and the underlying bedrock (Biavati et al. 2006; Muntohar and Liao 2010; Zhang et al. 2011; Chen and Zhang 2014). Zhan et al. (2013) utilized Laplace Transform to obtain an analytical solution to water infiltration into an infinite soil slope. Although analytical methods to water infiltration in unsaturated porous media provide an opportunity for verifying numerical methods (Wu and Zhang 2009; Wu et al. 2012a, b, 2013), numerical solutions are still welcomed in engineering practices because of constraints facing analytical solutions (Rahardjo et al. 2010).

In this paper, the stress–strain behavior of the unsaturated porous media is represented with an elastic constitutive model based on the effective stress theory (e.g., Lu et al. 2010), and the soil–water characteristic curves are described by the van Genuchten (1980) model. The governing equations of coupled seepage and deformation are written in a partial differential equation solver, FlexPDE (PDE Solutions Inc. 2004) to obtain the numerical solutions for two-layer unsaturated porous media under different conditions of rainfall and initial pore-water pressure head. This helps understand the mechanisms of rainfall infiltration into layered unsaturated porous media and shallow slope failures in partially saturated soils.

Theory

To analyze the coupled problems effectively, several assumptions are made as follows:

(i) The soil in each layer is homogeneous and behaves as an elastic material;
(ii) the soil skeleton is deformable, but the pore water is not compressible;
(iii) the volume change of the soil is due to the change in effective stress only, the total stress change is not considered;
(iv) the pore air is assumed to be connected to the atmosphere so the air pressure is zero.

Effective stress in unsaturated soils

When a saturated soil medium is assumed to be elastic, its constitutive relations can be formulated with an effective stress variable ($\sigma' = \sigma - u_{\mathrm{w}}$) according to the generalized Hooke's law (Terzaghi 1996). For an unsaturated soil medium, Lu et al. (2010) proposed an effective stress for all saturations by modifying the saturation contribution:

$$\sigma' = (\sigma - u_{\mathrm{a}}) - \sigma^{\mathrm{s}} \tag{1}$$

where σ' is the effective stress; σ is the total stress; u_{a} is the pore-air pressure; σ^{s} is defined in a general form of

$$\sigma^{\mathrm{s}} = -(u_{\mathrm{a}} - u_{\mathrm{w}}) \quad (u_{\mathrm{a}} - u_{\mathrm{w}}) \le 0 \tag{2a}$$

$$\sigma^{\mathrm{s}} = f(u_{\mathrm{a}} - u_{\mathrm{w}}) \quad (u_{\mathrm{a}} - u_{\mathrm{w}}) \ge 0 \tag{2b}$$

where u_{w} is the pore-water pressure; f is a scaling function describing the link between suction stress and matric suction (Lu et al. 2010), which is approximately $(-S_{\mathrm{e}})$. If the van Genuchten model (1980) is used to describe the soil–water characteristic curve (SWCC), it can be expressed as:

$$S_{\mathrm{e}} = \frac{1}{[1 + (\alpha|h_{\mathrm{m}}|)^{n}]^{m}} \tag{3}$$

where h_{m} is the pore-water pressure head, $h_{\mathrm{m}} = u_{\mathrm{w}}/\gamma_{\mathrm{w}}$, γ_{w} is the unit weight of water; α, n and m are fitting parameters, $m = 1 - 1/n$.

Based on assumptions (iii) and (iv), and combined with Eq. (2b), taking partial derivative with respect to time in Eq. (1), we obtain

$$\frac{\partial \sigma'}{\partial t} = -\frac{\partial (S_{\mathrm{e}} u_{\mathrm{w}})}{\partial t} \tag{4}$$

Substituting the effective stress tensor σ'_{ij} into the elastic constitutive relation of the soil structure gives

$$\varepsilon_{\mathrm{ij}} = \left(\frac{1+\mu}{E}\right)\sigma'_{\mathrm{ij}} - \frac{\mu}{E}\sigma'_{\mathrm{kk}}\delta_{\mathrm{ij}} \tag{5}$$

where $\varepsilon_{\mathrm{ij}}$ is the strain tensor; μ is the Poisson's ratio; E is the elastic modulus; σ'_{kk} is the sum of the effective stresses in all directions; δ_{ij} is the Kronecker delta.

In a 1D problem, the strains in both y and z directions (ε_y,ε_z) are zero. Substituting $\varepsilon_y = 0$ and $\varepsilon_z = 0$ into Eq. (5) yields

$$\varepsilon_x = \frac{1-\mu-2\mu^2}{E(1-\mu)}\sigma'_x \tag{6}$$

where ε_x is the strain in the x direction, $\varepsilon_x = \partial u/\partial x$, u is the displacement in the x direction; σ'_x is the effective stress in the x direction.

Taking partial derivative with respect to time on both sides of Eq. (6), we obtain

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{1}{C}\frac{\partial \sigma'_x}{\partial t} = -\frac{1}{C}\frac{\partial (S_e u_w)}{\partial t} \tag{7}$$

where ε_v is the volumetric strain, $\varepsilon_v = \varepsilon_x$ for a 1D condition; C is a constant, $C = E(1-\mu)/(1-\mu-2\mu^2)$.

Soil–water characteristic curves

The soil–water characteristic curve can be written as follows (van Genuchten 1980):

$$\theta = \theta_r + S_e(\theta_s - \theta_r) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha|h_m|)^n]^m} \tag{8}$$

where θ is the volumetric water content; θ_s is the saturated volumetric water content; θ_r is the residual volumetric water content.

The hydraulic conductivity is expressed as follows (Mualem 1978):

$$k = k_s S_e^{1/2}[1 - (1 - S_e^{1/m})^m]^2 \tag{9}$$

where k is the unsaturated permeability coefficient; k_s is the coefficient of permeability at full saturation.

In most cases, k_s is considered as a constant. But in fact, it has close links with porosity or stresses, and can be related to the volumetric strain as follows (Tortike 1991):

$$k_s = k_{s0}\frac{(1+\varepsilon_v/n_0)^3}{1+\varepsilon_v} \tag{10}$$

where k_{s0} is the initial saturated permeability coefficient; n_0 is the initial porosity of the soil.

Governing equation for 1D seepage considering deformations in porous unsaturated media

Based on the mass conservation and Darcy's law, the 1D Richard's equation can be expressed as

$$\frac{\partial}{\partial x}\left[k\frac{\partial}{\partial x}(h_m + x)\right] = \frac{\partial \theta}{\partial t} \tag{11}$$

The volumetric water content for an elastic material is given by the following expression (Dakshanamurthy et al. 1984):

$$\theta = \beta\varepsilon_v + \omega(u_a - u_w) \tag{12}$$

where $\beta = E/H(1-2\mu)$, H is the modulus for the soil structure with respect to matric suction, remaining constant for an elastic material; $\omega = 1/R - 3\beta/H$, R is the modulus relating changes in volumetric water content with changes in matric suction, $1/R = \partial\theta/\partial s$, s is the matric suction, $s = u_a - u_w$.

Based on the van Genuchten model (1980) in Eq. (8), we obtain

$$\frac{1}{R} = \frac{\partial \theta}{\partial h_m}\frac{\partial h_m}{\partial s} = (\theta_s - \theta_r)m\alpha n S_e^{1+\frac{1}{m}}(\alpha|h_m|)^{n-1}\left(-\frac{1}{\gamma_w}\right) \tag{13}$$

$$\frac{\partial \varepsilon_x}{\partial t} = -\frac{1}{C}\frac{\partial (S_e u_w)}{\partial t} = -\frac{\gamma_w}{C}\left[S_e + h_m\frac{\partial S_m}{\partial h_m}\right]\frac{\partial h_m}{\partial t} \tag{14}$$

Substituting Eqs. (12) and (14) into Eq. (11), the differential equation for unsaturated infiltration considering the deformation of the unsaturated porous media is given as

$$\begin{aligned}\frac{\partial}{\partial x}\left[k_x\left(1+\frac{\partial h_m}{\partial x}\right)\right] = -\gamma_w\left\{\frac{\beta}{C}\left[S_e + h_m\frac{\partial S_e}{\partial h_m}\right] + \omega \right.\\ \left. + h_m\frac{\partial (1/R)}{\partial h_m}\right\}\frac{\partial h_m}{\partial t}\end{aligned} \tag{15}$$

If the deformation of the unsaturated porous media is ignored, the seepage governing equation without the coupling effects can be expressed as

$$\frac{\partial}{\partial x}\left[k_x\left(1+\frac{\partial h_m}{\partial x}\right)\right] = \frac{\partial \theta}{\partial h_m}\frac{\partial h_m}{\partial t} \tag{16}$$

1D equation for equilibrium

The force equilibrium equation for an unsaturated soil is

$$\sigma_{ij,j} + b_i = 0 \tag{17}$$

where σ_{ij} is total stress tensor; b_i is the body force vector, $b_i = \gamma_w n_0 S_r + \gamma_s(1-n_0)$; γ_s is the unit weight of solid particles; S_r is the degree of saturation, $S_r = \theta/\theta_s$.

Based on assumption iv, substituting Eqs. (1) and (6) into Eq. (17) yields

$$\frac{\partial (C\varepsilon_v + S_e u_w)}{\partial x} + [\gamma_w n_0 S_r + \gamma_s(1-n_0)] = 0 \tag{18}$$

Initial and boundary conditions

The initial pore-water pressure head and displacement can be described as follows:

$$h_m(x,0) = h_i(x) \tag{19a}$$

$$u(x,0) = u_i(x) \tag{19b}$$

where h_i is the initial pore-water pressure head; and u_i is the initial displacement. They are related to the position, x.

The boundary conditions consist of the bottom boundary of the subsoil and the top boundary of the upper soil. The bottom boundary is an impermeable boundary with fixed displacement in the vertical direction. The ground surface is subjected to rainfall infiltration and controlled by Neuman boundary conditions, and the flux is assumed equal to the rainfall intensity.

Analysis of slope stability due to infiltration

When rain water infiltrates an unsaturated residual soil slope, the shear strength of unsaturated soils gradually decreases with the advancement of wetting front, and may lead to shallow failures (Van Asch et al. 1999; Rahardjo et al. 2010). Figure 1 shows a typical two-layer profile with an upper layer of thickness L_1. α is the angle of the slope. The slip surface at depth z is assumed to be parallel to the ground surface. On the basis of the modified Mohr–Coulomb failure criterion, a simplified infinite slope analysis (Cho 2009) can be used to compute the safety factor F_s of the slope:

$$F_s = \frac{\tau_f}{\tau_m} = \frac{c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b}{W\sin\alpha}\frac{1}{\cos\alpha} \tag{20}$$

where τ_f is the shear stress; τ_m is the shear strength; c' is the effective cohesion; $(\sigma_n - u_a)$ is the net normal stress; ϕ' is the effective angle of friction; ϕ^b is the internal friction angel associated with the matric suction, assumed to be a constant; W is the is the weight of a slice with unit width. The shear strength of an unsaturated soil can be expressed as $\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$. As rainfall infiltration proceeds, the sheer strength of soil will decrease sharply. When the soil is fully saturated, the shear strength is $\tau_f = c' + (\sigma_n - u_w)\tan\phi'$.

Assume that the pore-air pressure is atmospheric ($u_a = 0$). Equation (20) can be reduced to:

$$F_s = \frac{\tan\phi_1'}{\tan\alpha} + \frac{2c_1'}{\gamma_1 z\sin 2\alpha} - \frac{2u_w\tan\phi_1^b}{\gamma_1 z\sin 2\alpha}; \quad z \le L_1 \tag{21a}$$

$$F_s = \frac{\tan\phi_2'}{\tan\alpha} + \frac{2c_2'}{\{\gamma_1 L_1 + \gamma_2(z - L_1)\}\sin 2\alpha} - \frac{2u_w\tan\phi_2^b}{\{\gamma_1 L_1 + \gamma_2(z - L_1)\}\tan\alpha}; \quad z > L_1 \tag{21b}$$

The calculated factors of safety with the wetting depth corresponding to different initial suctions are shown in Fig. 2. The angle of the slope α is 35°, other parameters used in the analysis are shown in Table 1 and Fig. 2. In all cases, the factor of safety decreases most rapidly near the ground surface. The factor of safety is minimal when the wetting front reaches the interface, and then increases when the wetting front enters the lower layer because of the different mechanical parameters of the lower layer (Cho 2009).

For two-layer slopes with an underlying less permeable layer, a perched water table will be formed when the infiltrated moisture reaches the interface. This causes a rapid rise in the pore-water pressure head, and a reduction in the shear strength of partially saturated soils, ultimately

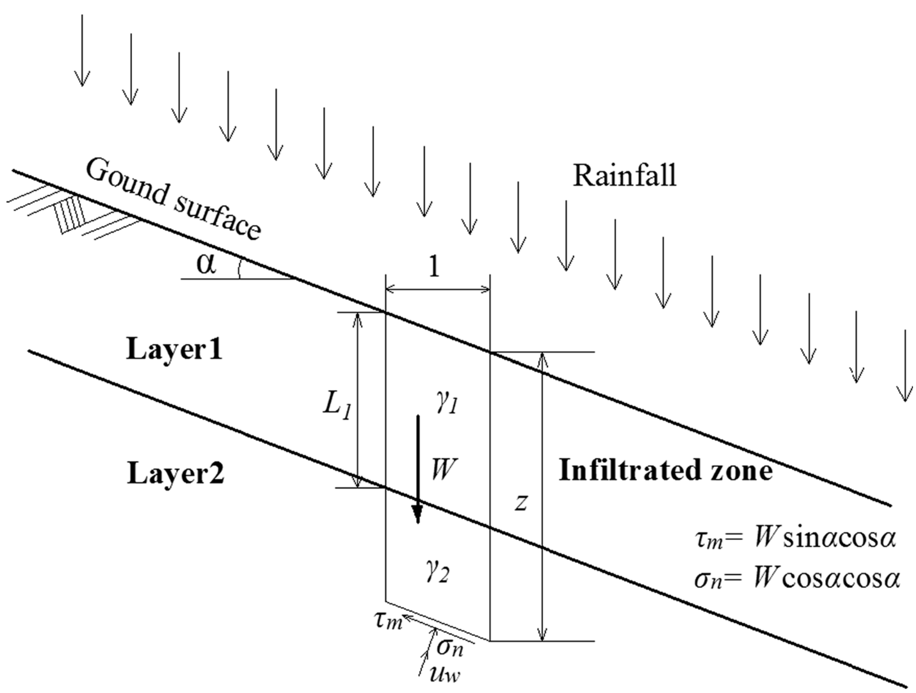

Fig. 1 Infinite slope analysis in a two-layer unsaturated soil profile (Cho 2009)

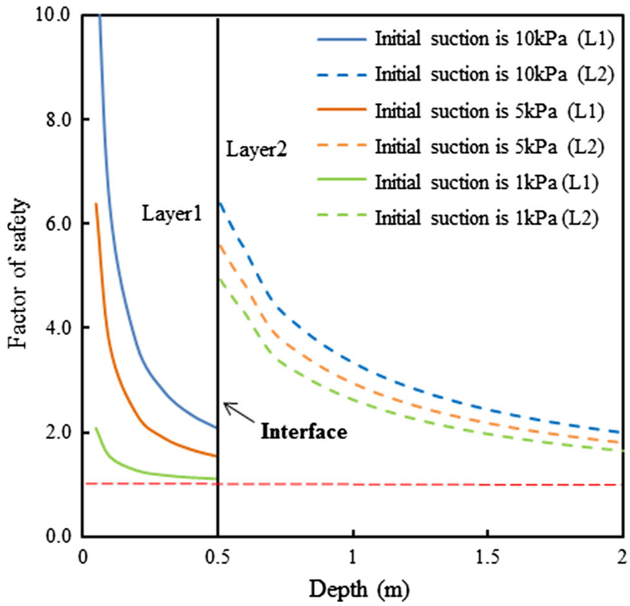

Fig. 2 Variation of the factor of safety with the depth of wetting front

resulting in a rapid decrease of safety factor. When ponding occurs and the matric suction at the interface completely disappears, the factor of safety can be described as

$$F_s = \frac{\tan \phi_1'}{\tan \alpha} + \frac{2c_1'}{\gamma_1 L_1 \sin 2\alpha} - \frac{2u_w \tan \phi_1'}{\gamma_1 L_1 \sin 2\alpha} \quad (22)$$

Numerical simulation of coupled infiltration in two-layer unsaturated porous medium

Infiltration model

Figure 3 shows a simplified model (Cho 2009) for evaluating how water infiltrates into a two-layer unsaturated porous medium considering the coupled seepage and deformation under various rainfall durations with the same rainfall amount. In the analysis, the initial pore-water pressure head was −2 m throughout the whole profile and the thickness of the upper layer was 0.5 m. Saturated hydraulic conductivities for the two kinds of soil are significantly different. The hydraulic parameters of the soil layers (Ma et al. 2010) are shown in Table 2. Figure 4 shows the soil–water characteristic curve and the hydraulic conductivity for each layer.

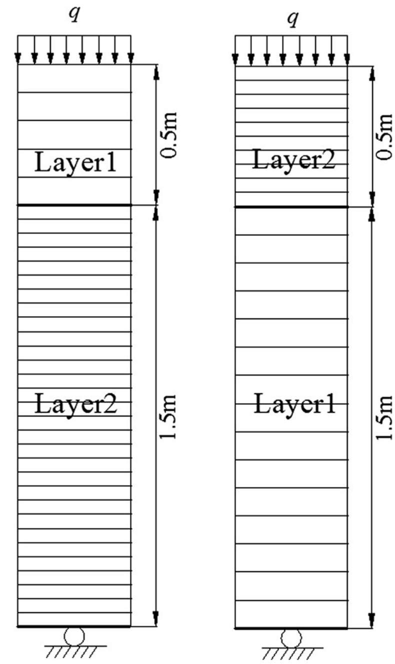

Fig. 3 Conceptual models for two-layer soil

The two-layer soil profile is characterized by an upper layer with saturated hydraulic conductivity k_{1s} and an underlying layer with saturated hydraulic conductivity k_{2s}. For shallow two-layer slope failures, the bedrock below the slip surface usually has a lower permeability, namely $k_{1s} > k_{2s}$. A computational program was written in a partial differential equation solver, FlexPDE (PDE Solutions Inc. 2004), to obtain pore-water pressures and volumetric water contents over time during rainfall infiltration. In order to verify the accuracy of FlexPDE in solving partial differential equations, the numerical solutions to the uncoupled condition from SEEP/W and FlexPDE are compared. Figure 5 shows the pore-water pressure profiles under the condition of $k_{1s} > k_{2s}$, $q = 3$ mm/h, $t = 40$ h. The calculated results from FlexPDE are in good agreement with those from SEEP/W, and the relative error is less than 3.4 %. It clearly shows that FlxPDE effectively solves the governing equations for coupled seepage and deformation in layered unsaturated porous media.

Effect of soil layer

Figures 6 and 7 show the changes in pore-water pressure and volumetric water content over time in the two-layer

Table 1 Physical and mechanical properties of the soils

	μ	E (MPa)	H (MPa)	γ_s (kN/m^3)	c' (kPa)	Φ' (kPa)	Φ^b (kPa)
Layer 1	0.35	10	10	13.7	0	35	25
Layer 2	0.4	10	10	15	5	25	20

Table 2 Hydraulic parameters for the soils (Ma et al. 2010)

	k_{s0} (m/s)	θ_s	θ_r	a (m^{-1})	n	m
Layer 1	3.21E−06	0.51	0.08	1.05	1.547	0.353
Layer 2	8.42E−07	0.5	0.14	0.86	1.611	0.379

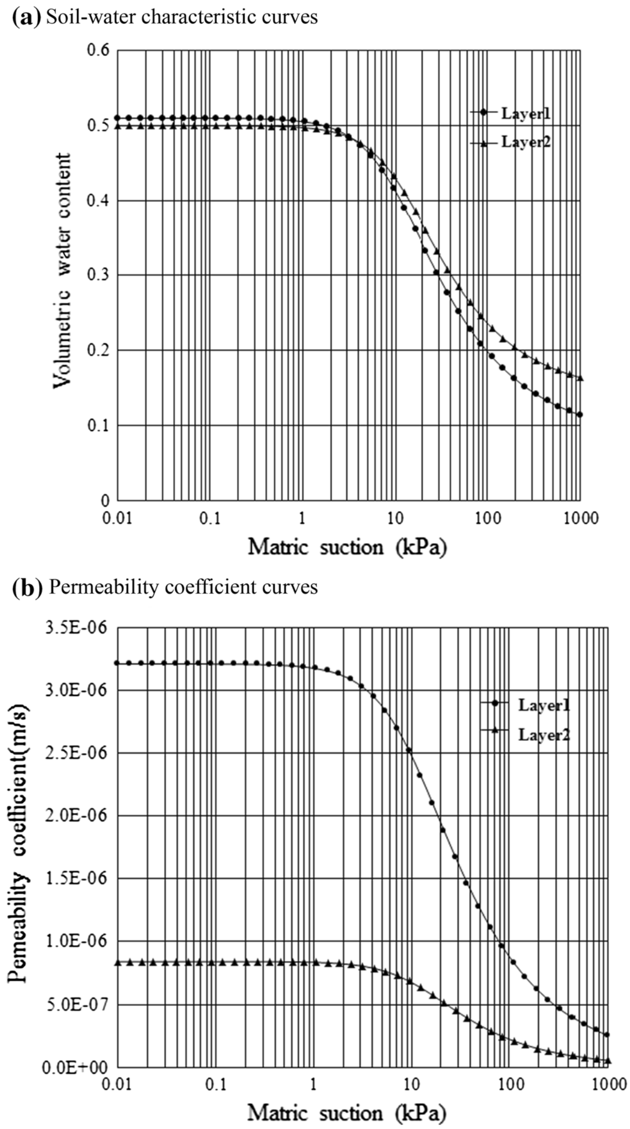

Fig. 4 Hydraulic properties of the soils

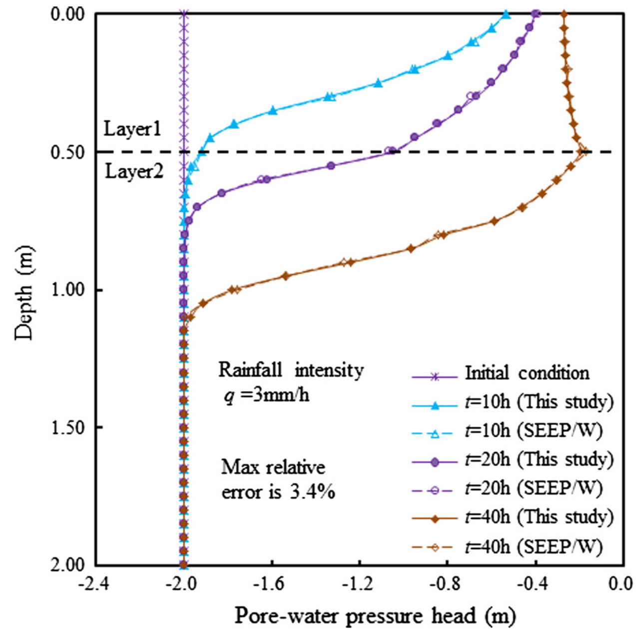

Fig. 5 Comparison of the pore-water pressure heads from Flex PDE and SEEP/W under the uncoupled condition

soil profile for the cases of $k_{1s} > k_{2s}$ and $k_{1s} < k_{2s}$ when the rainfall of 3 mm/h lasts 40 h. As shown in Figs. 6 and 7, the soil layering has a significant influence on pore-water pressure and moisture distributions. The wetting front for the case of $k_{1s} > k_{2s}$ advances faster than that for the $k_{1s} < k_{2s}$ case before reaching the interface of the soil layers. But the opposite will happen when it passes through the interface. The pore-water pressure and the volumetric water content profiles present similar distributions along depth. The moisture under the uncoupled condition responds faster than that considering the soil deformation. The differences in pore-water pressure head at the interface between the coupled and uncoupled conditions increase at the beginning of rainfall infiltration and then decrease with time. When rainfall lasts 20 h, the coupling difference at the interface is 0.91 m for the $k_{1s} > k_{2s}$ case, and 0.66 m for the $k_{1s} < k_{2s}$ case. It is clear that soil layering affects the moisture distribution and the coupling of seepage and deformation to a certain degree.

Effect of rainfall duration

Rainfall duration has a significant effect on slope stability. Many procedures have been developed to define intensity-duration rainfall thresholds for the occurrence of landslides (Cannon et al. 2011; Segoni et al. 2014). In order to analyze the effect of rainfall duration on the pore-water pressure head profile and the slope stability, the case of $k_{1s} > k_{2s}$ is examined, which is common in a weathered soil region. Three durations with the same rainfall amount are considered: $q = 3$ mm/h, $t = 40$ h; $q = 6$ mm/h, $t = 20$ h; and $q = 12$ mm/h, $t = 10$ h. As shown in Figs. 8 and 9, the changes in the pore-water pressure at the shallow depths under the shortest duration rainfall is more obvious than those under a less intense rain with a longer duration. The settlement at the ground surface decreases with the rainfall duration which is a result of the assumption that the deformation is due to the wetting or drying of the soil only. When the rainfall amount is constant, the longer the rainfall duration is, the more deeply the wetting

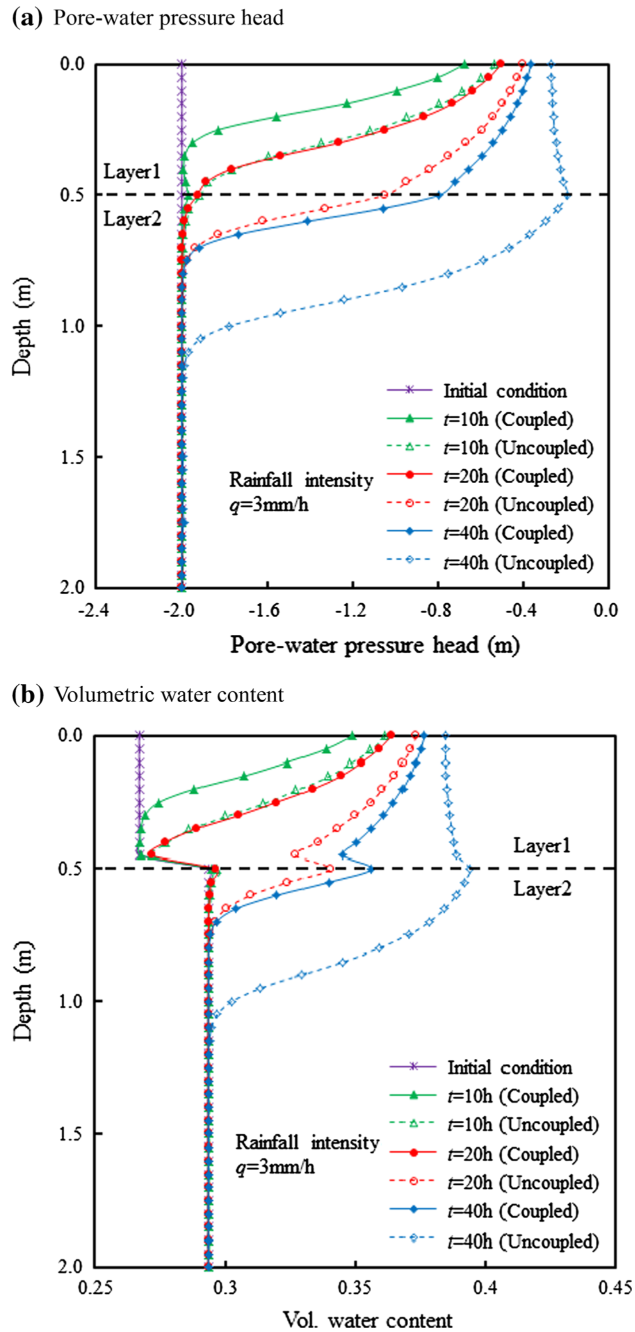

Fig. 6 Hydrological responses for the case of $k_{1s} > k_{2s}$

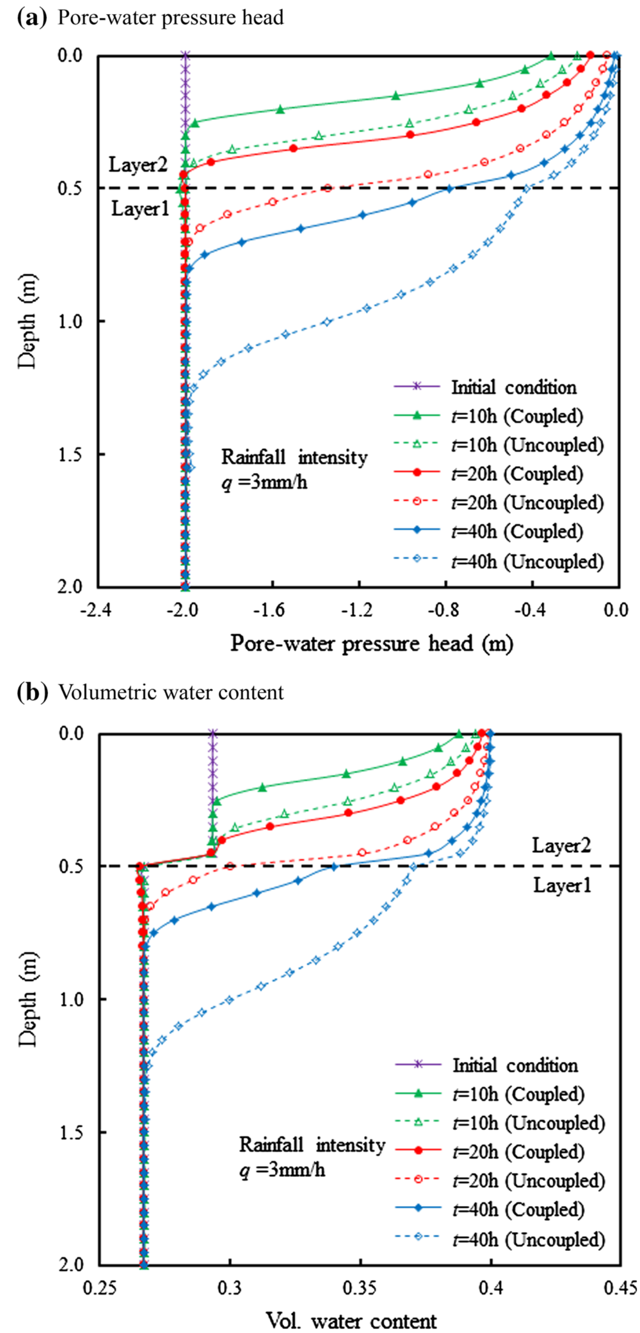

Fig. 7 Hydrological responses for the case of $k_{1s} < k_{2s}$

front advances. The rapid matric suction dissipation at the interface at $t = 10$ h leads to a sharp decrease in the factor of safety (see Figs. 10, 11). The relationship between the factor of safety and pore-water pressure head can be determined by the derived equations in Eqs. (21a) and (22). A great difference in wetting front depth and pore-water pressure head response exists between the coupled and uncoupled conditions. When the amount of rainfall is 99.3 mm at $t = 100$ h and no deformation is taken into account, perched water will be formed at the interface owing to the low permeability of the subsoil and large rainfall intensity. The corresponding factor of safety is 0.99, which means failure will occur at this moment. While for those under the coupled condition, no ponding will happen and the factor of safety hardly changes.

Effect of initial pore-water pressure head

Different initial pore-water pressure heads ($h_m = -1$, -2, -4 m) are employed to illustrate their effects on the pore-

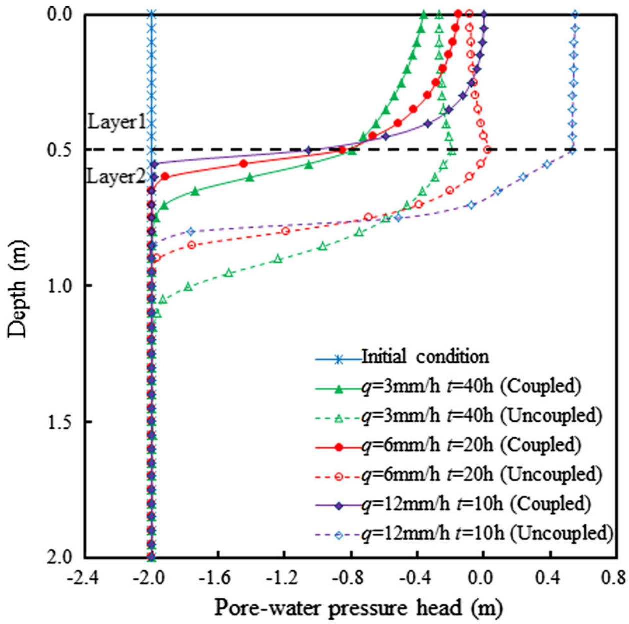

Fig. 8 Pore-water pressure head profiles for different rainfall durations

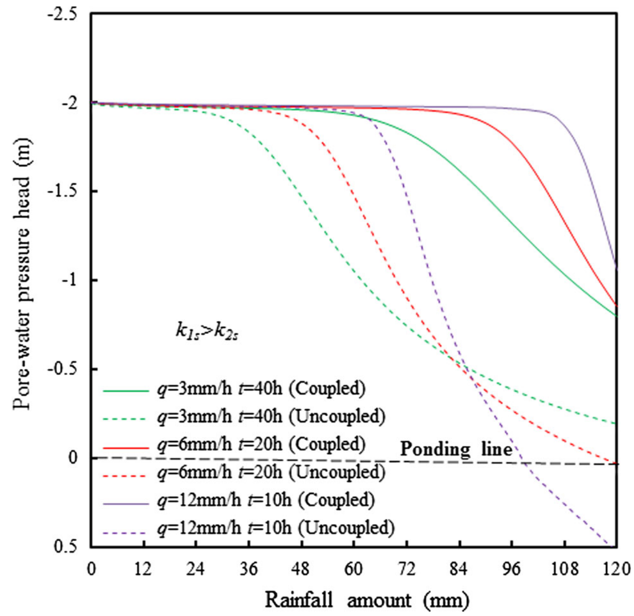

Fig. 10 Pore-water pressure head responses at the interface for different rainfall durations

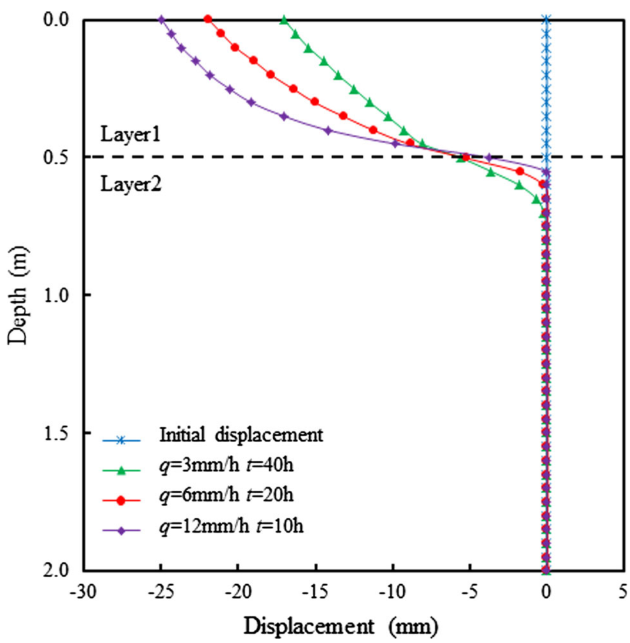

Fig. 9 Displacement profiles for different rainfall durations

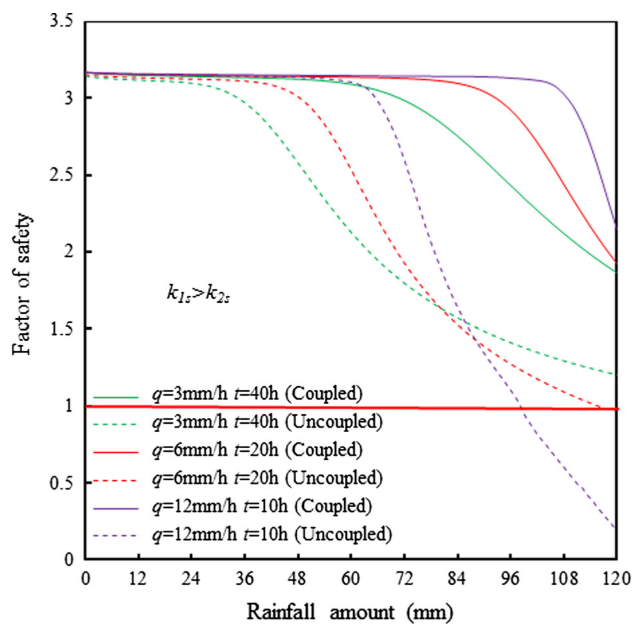

Fig. 11 Factors of safety at the interface for different rainfall durations

water pressure head and volumetric water content profiles under both coupled and uncoupled conditions. As shown in Figs. 12 and 13, the initial matric suction has a strong influence on the depth of the wetting front and the soil displacement. The greater h_m is, the deeper the wetting front advances, and the greater the settlement at the ground surface is. When the rainfall of 3 mm/h lasts 40 h and the coupling effect is considered, the difference in the wetting front depth between the initial conditions of $h_m = -1$ m and $h_m = -4$ m reaches 1.1 m. The pore-water pressure head under the coupled and uncoupled conditions shows a great difference, especially at high initial matric suctions. The pore-water pressure change considering the coupling effect always lags behind that under the uncoupled condition. The coupling hysteresis impacts the hydrological response at the interface and

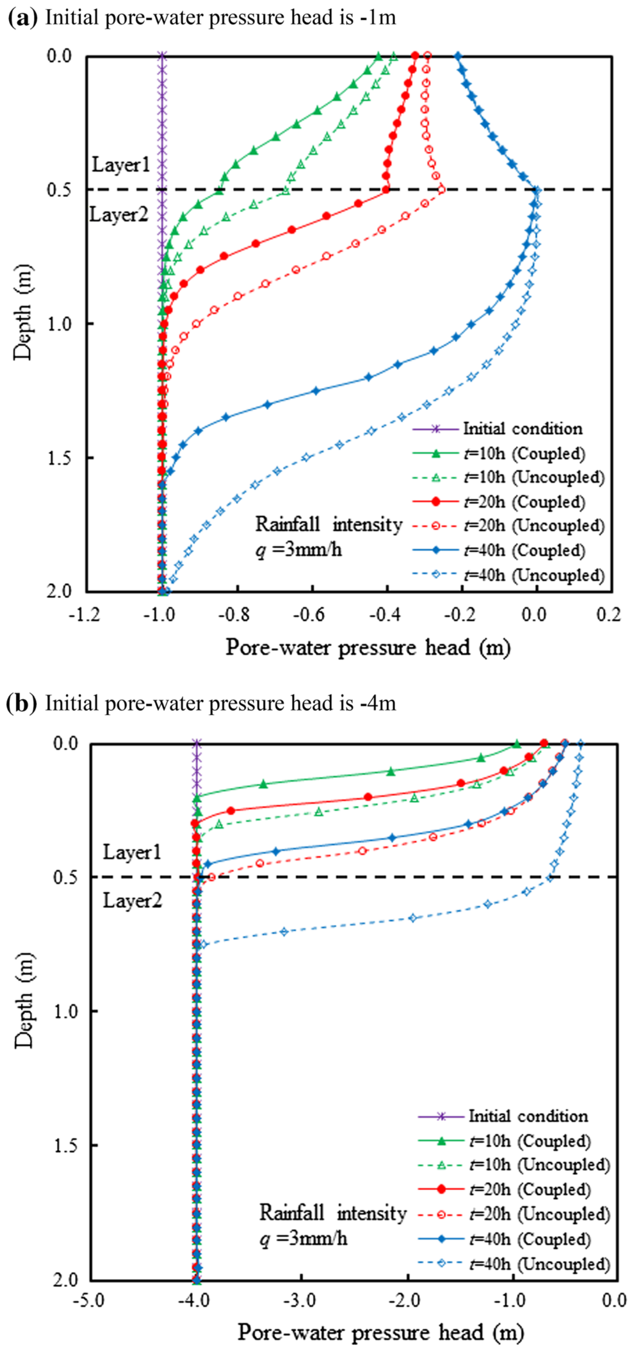

Fig. 12 Pore-water pressure head profiles for different initial conditions

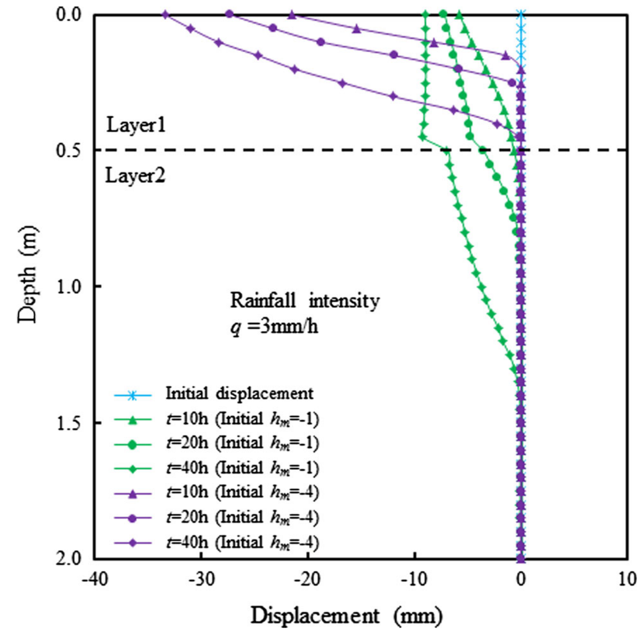

Fig. 13 Displacement profiles for different initial conditions

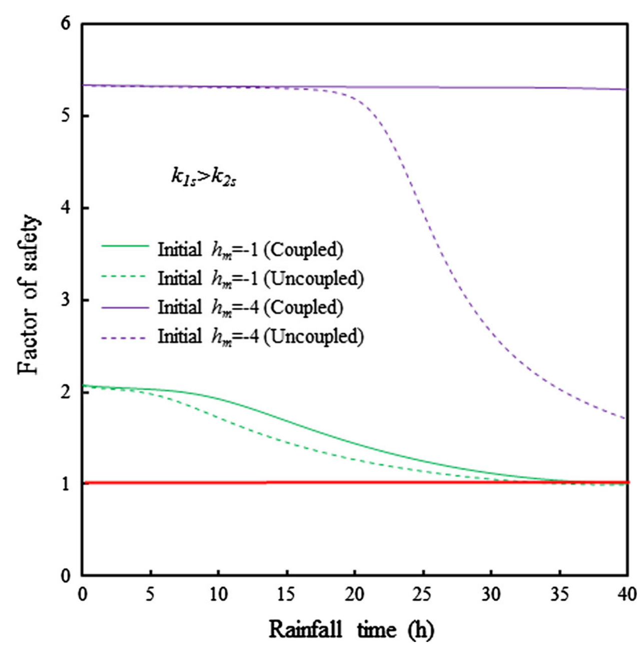

Fig. 14 Factors of safety at the interface in relation to time for different initial conditions

lead to a difference in the factor of safety shown in Fig. 14.

Effect of saturated permeability coefficient

The saturated permeability coefficient, an important parameter in analyzing coupled seepage and deformation in unsaturated porous media, can be expressed as an explicit function of the volumetric strain as shown in Eq. (10). Figure 15 shows the pore-water pressure head profiles considering the deformation and not considering the deformation. There is a small difference between them at the early stage of water infiltration and the difference gradually decreases over time. At $t = 40$ h, the distributions of pore-water pressure head become very close.

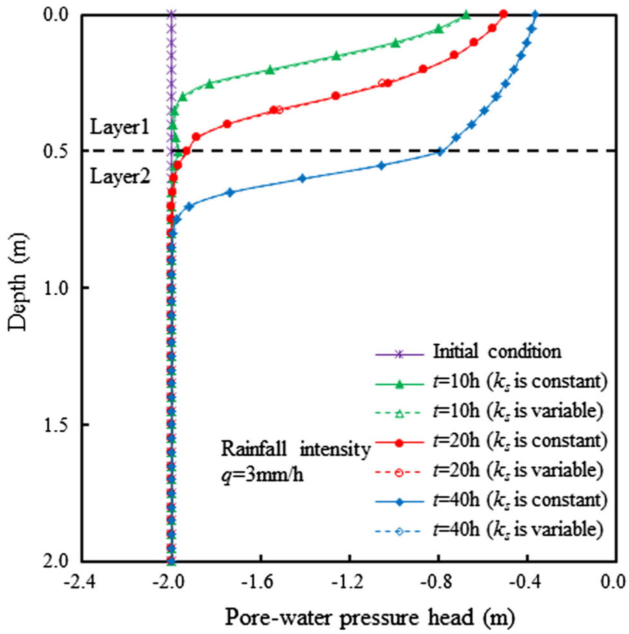

Fig. 15 Pore-water pressure head profiles when k_s is constant or variable

Summary and conclusions

A numerical solution to 1D coupled water flow and deformation in two-layer unsaturated porous media is obtained using a finite element method. The van Genuchten model is adopted to represent the soil–water characteristic curves and the coefficient of permeability. A conceptual model of two-layer unsaturated porous medium is established in FlexPDE to analyze the rainfall infiltration process under different conditions. A simplified analysis of an infinite slope is used to compute the factor of safety as a function of the depth of wetting front and special attention is paid to the hydrological response at the interface between two layers of unsaturated porous media in this study.

The results demonstrate that the moisture distributions due to rainfall infiltration are affected by many factors including soil layering, rainfall duration and initial pore-water pressure head. Large differences exist between the coupled and uncoupled conditions. The pore-water pressure responses considering the soil deformation lag behind those without considering the coupling effect, which leads to delayed effects on the decrease of factor of safety. The coupling effects become marked when the initial matric suctions in the two-layer soil are high or the rain is intense but its duration is short. The initial saturated permeability coefficient has a reduced impact on the rainfall infiltration for a long-duration rain event.

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