Environ Geol (2008) 55:1269–1277
DOI 10.1007/s00254-007-1075-1

ORIGINAL ARTICLE

Numerical modeling of rainstorm-induced shallow landslides in saturated and unsaturated soils

Tung-Lin Tsai · Hung-En Chen · Jinn-Chuang Yang

Received: 5 July 2007 / Accepted: 7 October 2007 / Published online: 31 October 2007

Abstract For the assessment of shallow landslides triggered by rainfall, the physically based model coupling the infinite slope stability analysis with the hydrological modeling in nearly saturated soil has commonly been used due to its simplicity. However, in that model the rainfall infiltration in unsaturated soil could not be reliably simulated because a linear diffusion-type Richards' equation rather than the complete Richards' equation was used. In addition, the effect of matric suction on the shear strength of soil was not actually considered. Therefore, except the shallow landslide in saturated soil due to groundwater table rise, the shallow landslide induced by the loss in unsaturated shear strength due to the dissipation of matric suction could not be reliably assessed. In this study, a physically based model capable of assessing shallow landslides in variably saturated soils is developed by adopting the complete Richards' equation with the effect of slope angle in the rainfall infiltration modeling and using the extended Mohr–Coulomb failure criterion to describe the unsaturated shear strength in the soil failure modeling. The influence of rainfall intensity and duration on shallow landslide is investigated using the developed model. The result shows that the rainfall intensity and duration seem to have similar influence on shallow landslides respectively triggered by the increase of positive pore water pressure in saturated soil and induced by the dissipation of matric suction in unsaturated soil. The rainfall duration threshold decreases with the increase in rainfall intensity, but remains constant for large rainfall intensity.

Keywords Shallow landslide · Saturated and unsaturated soils · Rainstorm

List of symbols

C	the change in volumetric water content per unit change in pressure head
C_0	the minimum value of C
c'	effective cohesion
D_0	K_s/C_0
d_Z	water depth
d_{LZ}	slope depth
FS	factor of safety
I_Z	rainfall intensity
K_{s}	saturated hydraulic conductivity
K_{L}	hydraulic conductivity in lateral direction (x and y)
K_{z}	hydraulic conductivities in slope–normal direction (z)
S	the degree of saturation
M	fitting parameter
N	fitting parameter
T	rainfall duration
u_{a}	pore air pressure
u_{w}	pore water pressure
Z	the coordinates
σ	total normal stress
ψ	groundwater pressure head
θ	soil volumetric water content
θ_{s}	saturated moisture content
θ_{r}	residual moisture content
α	slope angle
ϕ'	effective friction angle

T.-L. Tsai (✉)
Department of Civil and Water Resources Engineering,
National Chiayi University, 300 Sefu Road,
Chiayi City 60004, Taiwan
e-mail: tltsai@mail.ncyu.edu.tw

H.-E. Chen · J.-C. Yang
Department of Civil Engineering,
National Chiao Tung University, Hsinchu City, Taiwan

ϕ^{b} the friction ϕ angle with respect to the matric suction
ζ fitting parameter
γ the unit weight of soil
γ_{w} the unit weight of water

Introduction

Landslide often poses a serious threat to both lives and property in many places around the world. Although slope failures may happen due to human-induced factors such as the loading of the slope or the cutting away of the toe for construction purposes, many occur simply due to rainfall, especially in regions with residual soil subjected to rainstorm. Up to now, the assessment of rainstorm-induced shallow landslide has still been a research topic of wide concern for soil scientists. The empirical rainfall threshold concept and the physically based model are two commonly used approaches. The empirical rainfall threshold concept can be very simply applied to the assessment of rainfall-induced landslide, but it seems to provide a minimal amount of insight into the actually physical processes that trigger landslide. Therefore, to investigate in more detail landslide occurrence, the physically based model needs to be used.

With assumptions of steady or quasi-steady water table, and groundwater flows parallel to hillslope, various physically based models coupling the infinite slope stability analysis with the hydrological modeling (Montgomery and Dietrich 1994; Wu and Sidle 1995; Borga et al. 1998) were developed to assess shallow landslide induced by land use and hydrological conditions. Iverson (2000) further developed a flexible modeling framework of shallow landslide with approximation of Richards' equation (1931) valid for hydrological modeling in nearly saturated soil. This led to the use of a linear diffusion-type Richards' equation for simulating rainfall infiltration. The extension version of Iverson's model was proposed to take variable rainfall intensity into account for hillslope with finite depth (Baum et al. 2002). Without the assumption of constant infiltration capacity, the Iverson's model was modified by amending the boundary condition at the top of the hillslope to consider more general infiltration process (Tsai and Yang 2006). Due to its simplicity the physically based model with the hydrological modeling in nearly saturated soil (Iverson 2000; Baum et al. 2002; Tsai and Ynag 2006) was commonly used for the assessment of shallow landslides triggered by rainfall (Crosta and Frattini 2003; Keim and Skaugset 2003; Frattini et al. 2004; Lan et al. 2005; D'Odorico et al. 2005; Tsai 2007).

It had been observed that the soil failure could be caused by the loss in unsaturated shear strength when the matric suction is dissipated, except the increase of positive pore water pressure in saturated soil due to groundwater table rise. The physically based model with the hydrological modeling in nearly saturated soil could not reliably assess the shallow landslide caused by the dissipation of matric suction because a linear diffusion-type Richards' equation rather than the complete Richards' equation was used to model rainfall infiltration, and the matric suction effect on shear strength of soil was not actually considered to examine the soil failure. In this study, to reliably assess shallow landslide, a physically based model has been developed not only by using the complete Richards' equation with the effect of slope angle, but also by adopting the extended Mohr–Coulomb failure criterion (Fredlund et al. 1978) to describe the unsaturated shear strength.

In the following sections, the methodology of model development including the hydrological modeling and the soil failure modeling is first described. After the developed model is verified, its applicability is demonstrated. The effect of rainfall intensity and duration on shallow landslides in saturated and unsaturated soils is then investigated using the developed model.

Methodology of model development

Hydrological modeling

The unsteady and variably saturated Darcian flow of groundwater in response to rainfall infiltration of a hillslope can be governed by the Richards' equation with a local rectangular Cartesian coordinate system (Bear 1972; Hurley and Pantelis 1985) shown in Fig. 1 as follows:

$$\frac{\partial\psi}{\partial t}\frac{d\theta}{d\psi}=\frac{\partial}{\partial x}\left[K_{L}(\psi)\left(\frac{\partial\psi}{\partial x}-\sin\alpha\right)\right]+\frac{\partial}{\partial y}\left[K_{L}(\psi)\left(\frac{\partial\psi}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[K_{z}(\psi)\left(\frac{\partial\psi}{\partial z}-\cos\alpha\right)\right] \tag{1}$$

in which ψ is the groundwater pressure head; θ is the moisture content; α is the slope angle; t is time. The coordinate x points down the ground surface; y points tangent to the topographic contour that passes through the origin; z points into the slope, normal to the x–y plane. K_{L} and K_{z}, a function of soil properties and ψ, are hydraulic conductivities in the lateral direction (x and y) and slope–normal direction (z), respectively.

For the case of shallow soil and a rainfall time shorter than the time necessary for transmission of lateral pore water pressure, (1) can be represented in the vertical direction (Iverson 2000) as follows:

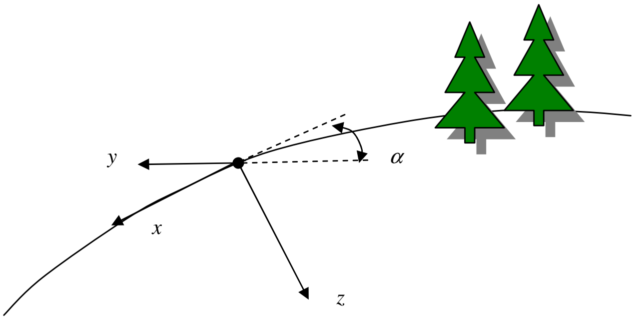

Fig. 1 Three-dimensional groundwater flow in hillslope

$$C(\psi)\frac{\partial\psi}{\partial t} = \cos^2\alpha\frac{\partial}{\partial Z}\left[K_z(\psi)\left(\frac{\partial\psi}{\partial Z} - 1\right)\right] \quad (2)$$

where $C(\psi) = d\theta/d\psi$ is the change in moisture content per unit change in groundwater pressure head. The elevation Z shown in Fig. 2 is vertically measured downward from a horizontal reference plane that passes through the origin on the ground surface. With the assumption of nearly saturated soil, (2) can be linearized as follows (Iverson 2000):

$$\frac{\partial\psi}{\partial t} = D_0\cos^2\alpha\frac{\partial^2\psi}{\partial Z^2} \quad (3)$$

$D_0 = K_s/C_0$ in which C_0 is the minimum value of $C(\psi)$ and K_s is the saturated hydraulic conductivity. The linear diffusion-type Richards' equation given by (3) was used for simulating rainfall infiltration in the physically based model with the hydrological modeling in nearly saturated soil (Iverson 2000; Baum et al. 2002; Tsai and Yang 2006). However, to actually analyze rainfall infiltration in variably saturated soil the complete Richards' equation shown in (2) is used in this study.

The appropriate initial and boundary conditions are needed for solving (2). For initially steady state with water table of d_Z in vertical direction shown in Fig. 2, the initial condition in terms of the groundwater pressure head can be expressed as

$$\psi(Z, 0) = (Z - d_Z)\cos^2\alpha \quad (4)$$

For a slope with depth of d_{LZ} measured in vertical direction, the boundary conditions in terms of groundwater pressure head at impervious and pervious bases can be respectively written as

$$\frac{\partial\psi}{\partial Z}(d_{IZ}, t) = \cos^2\alpha \quad (5)$$

and

$$\psi(d_{LZ}, t) = (d_{LZ} - d_Z)\cos^2\alpha \quad (6)$$

The ground surface of hillslope subjected to the rainfall with intensity of I_z yields

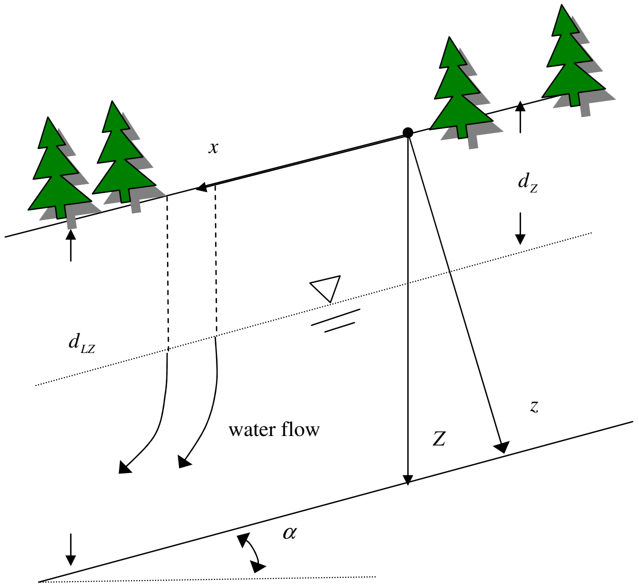

Fig. 2 Schematic illustration of the infinite slope stability analysis integrated with hydrological modeling

$$\frac{\partial\psi}{\partial Z}(0,t) = -I_Z/(K_Z)_{Z=0} + \cos^2\alpha \quad \text{if } \psi(0,t) \le 0 \ \text{ and } t < T \quad (7)$$

$$\psi(0,t) = 0 \quad \text{if } \psi(0,t) > 0 \quad \text{and } t < T \quad (8)$$

$$\frac{\partial\psi}{\partial Z}(0,t) = \cos^2\alpha \quad \text{if } t > T \quad (9)$$

where T is the rainfall duration. $(K_Z)_{Z=0}$ denotes the hydraulic conductivity at the ground surface of hillslope. In the physically based model with the hydrological modeling in nearly saturated soil (Iverson 2000; Baum et al. 2002), the ponding condition shown in (8) was neglected, and the infiltration capacity of soil was assumed to equal the saturated hydraulic conductivity, which is independent of the degree of saturation. This led to the use of the beta line to correct the overestimated groundwater pressure heads near the ground surface of the hillslope.

Equations (2) and (4–9) need to be numerically solved with an iterative procedure as shown in Fig. 3 due to the nonlinearity. The groundwater pressure head at the ground surface of the hillslope, i.e., $\psi(0,t)$, is first obtained by assuming that the infiltration rate equals the rainfall intensity shown in (7). If $\psi(0,t)$ is less than or equals zero, that is, the ponding does not happen, the calculated results are accepted. The computation moves forward to the next time step. If the calculated $\psi(0,t)$ is greater than zero, that is, the ponding occurs, with neglecting the water depth of overland flow (Hsu et al. 2002; Wallach et al. 1997; Tsai and Yang 2006) $\psi(0,t) = 0$ is used as a boundary condition to recalculate once more for the same time step.

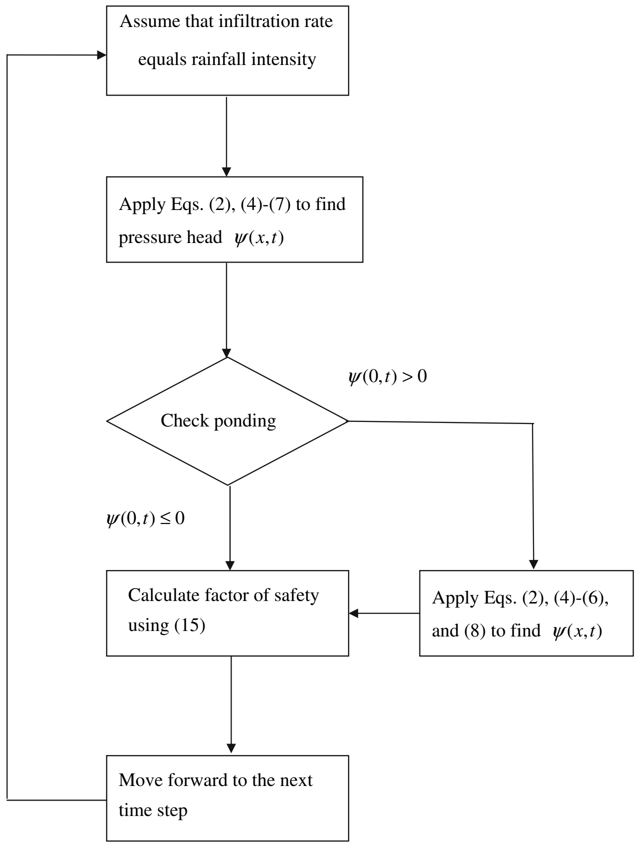

Fig. 3 Flow chart of hydrological modeling

In addition, for solving the Richards' equation shown in (2) a two-step finite-difference Crank–Nicolson procedure (Hills et al. 1989; Hsu et al. 2002) is used in conjunction with the function of the water retention curve proposed by van Genuchten (1980) as follows:

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + [\xi|\psi|]^N} \right)^M \tag{10}$$

$$\frac{K_Z(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/2} \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{M}} \right]^M \right\}^2 \tag{11}$$

where S is the degree of saturation. θ_s denotes the saturated moisture content and θ_r represents the residual moisture content. ζ, N, and M are fitting parameters, with M related to N by

$$M = 1 - \frac{1}{N} \tag{12}$$

Soil failure modeling

The infinite slope stability analysis is a preferred tool to evaluate shallow landslide due to its simplicity and practicability (Montgomery and Dietrich 1994; Wu and Sidle 1995; Borga et al. 1998; Iverson 2000; Morrissey et al. 2001; Crosta and Frattini 2003; Collins and Znidarcic 2004). This concept is generally valid for the case of landslide with a small depth compared to its length and width. This assumption is also compatible with that used to previously develop hydrological modeling of hillslope.

The shear strength of unsaturated soil can be represented by the extended Mohr–Coulomb failure criterion (Fredlund et al. 1978) as follows:

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \tag{13}$$

where c' is the effective cohesion. ϕ' and ϕ^b are respectively the effective friction angle and the friction angle with respect to the matric suction, i.e., $u_a - u_w$. σ is the total normal stress. u_a and u_w denote pore air pressure and pore water pressure, respectively. Clearly, when the soil is saturated u_a and u_w become equal, and (13) reverts to the classical shear strength of saturated soil as follows:

$$\tau = c' + (\sigma - u_w) \tan \phi' \tag{14}$$

Equation (14) rather than (13) was used for describing the shear strength of soil in the physically based model with the hydrological modeling in nearly saturated soil (Iverson 2000; Baum et al. 2002; Tsai and Yang 2006). This does not actually take into account the martic suction effect on unsaturated shear strength. In this study, (13) is used to describe the shear strength of variably saturated soil. For the sake of simplicity it is assumed that ϕ' and ϕ^b remain constant in spite of the degree of saturation (Escario and Saez 1986).

A hillslope failure at a certain depth Z occurs when the acting stress equals the resisting stress due to friction and cohesion. Using the infinite slope stability analysis together with the shear strength of unsaturated soil given by (13), and assuming that the pore air pressure is atmospheric, the factor of safety can be written as

$$\mathrm{FS} = \frac{\tan \phi'}{\tan \alpha} + \frac{c' - \gamma_w \psi_c \tan \phi^b - \gamma_w \psi_p \tan \phi'}{\gamma Z \sin \alpha \cos \alpha} \tag{15}$$

where γ_w and γ represent the unit weights of water and soil, respectively. In (15), when the groundwater pressure head is negative, that is, the soil is unsaturated, ψ_c is equal to ψ, which can be obtained from (2), whereas ψ_p is zero. On the contrary, ψ_p is identical to ψ, and ψ_c is zero, while the groundwater pressure head is positive, that is, the soil is saturated. It reveals from (15) that the slope failure could occur not only in saturated soil due to the increase in positive groundwater pressure head, but also in unsaturated soil due to the decrease in negative groundwater pressure head, that is, the dissipation of matric suction. In addition, if the soil remains unsaturated, the factor of safety never reaches unity in a gentle slope, i.e., $\phi' > \alpha$.

By setting FS = 1 in (15), the stability envelope (Collins and Znidarcic 2004) can be represented as

$$Z = \frac{c' - \gamma_w \psi_c \tan \phi^b - \gamma_w \psi_p \tan \phi'}{\gamma \cos^2 \alpha \cdot (\tan \alpha - \tan \phi')} \tag{16}$$

The stability envelope given by (16) can be used to calculate the minimal groundwater pressure head for the occurrence of soil failure at depth Z under the hillslope characteristics, i.e., γ, ϕ', ϕ^b, α, and c'. The soil failure at depth Z occurs when the groundwater pressure head computed by the developed model due to rainfall infiltration is equal to or greater than that calculated by the stability envelope shown in (16).

The governing equations and boundary conditions used herein for the hydrological modeling and the soil failure modeling seem similar to those used for assessing rainfall-triggered shallow landslides in saturated and unsaturated soils by Collins and Znidarcic (2004), Anderson and Howes (1985), and Tarantino and Bosco (2000), but the effect of slope angle is reliably taken into account in this study.

Demonstration of model applicability

Before the applicability of the physically based model developed herein is demonstrated, the verification is conducted by modeling rainfall infiltration into an initially dry soil (Hills et al. 1989). Figure 4a shows that the mass error reaches maximum at about 0.05 h after the simulation, and then decreases with the increase in simulation time. The mass error is defined as the ratio of the difference between true mass added and calculated mass added to true mass added. In addition, the moisture content distribution simulated by the developed model is close to that from Hills et al. (1989) as shown in Fig. 4b. In the demonstration of the applicability of the developed model, the soil parameters are adopted as follows: $\phi' = 27.5°$, $\phi^b = 23.5°$ $c' = 3$ Kpa, $\gamma = 20{,}000$ N/m^3, $\gamma_w = 9{,}800$ N/m^3, $K_s = 8.68 \times 10^{-6}$ m/s, $N = 2.0$, $\theta_s = 0.47$, $\theta_r = 0.17$, and $\xi = 0.01$.

Modeling shallow landslide in saturated soil

The hillslope with an impervious base has a slope angle of 23° and depth of 2.72 m. The initial groundwater table is 1.63 m below the ground surface of the hillslope. The simulated groundwater pressure heads with respect to time from the rainstorm with rainfall intensity of 45 mm/h lasting for 6 h are displayed in Fig. 5a. Figure 5a shows that the groundwater pressure heads increase with respect to time during the period of rainfall, and the ponding occurs between 3 and 6 h after the rainfall. The groundwater pressure heads are redistributed after the end of the rainfall, and the steady state seems to be reached at 40 h after the end of the rainfall. The resulting groundwater pressure head curve intersects the stability envelope, that is, the landslide is induced at 20.5 h after the end of the rainfall at the impervious base of hillslope as shown in point A of Fig. 5a in which the soil is saturated. The above-mentioned shows that the developed model can assess shallow landslides induced by the increase in the positive pore water pressure in saturated soil due to groundwater table rise.

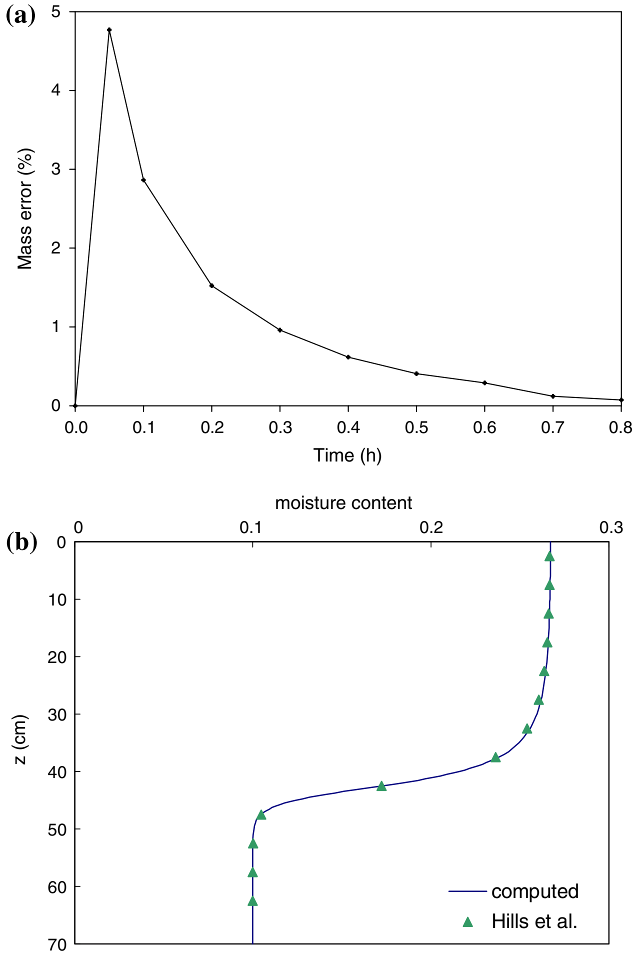

Fig. 4 Rainfall infiltration into an initially dry soil (**a**) mass error; (**b**) moisture content

Modeling shallow landslide in unsaturated soil

The hillslope with a pervious base has a slope angle of 37° and depth of 2.13 m, and is subjected to the rainstorm with rainfall intensity of 45 mm/h and rainfall duration of 8 h. With the initial groundwater table at the depth of 3.76 m below the ground surface of hillslope, the simulated groundwater pressure heads with respect to time are shown in Fig. 5b. Figure 5b indicates that the wetting front

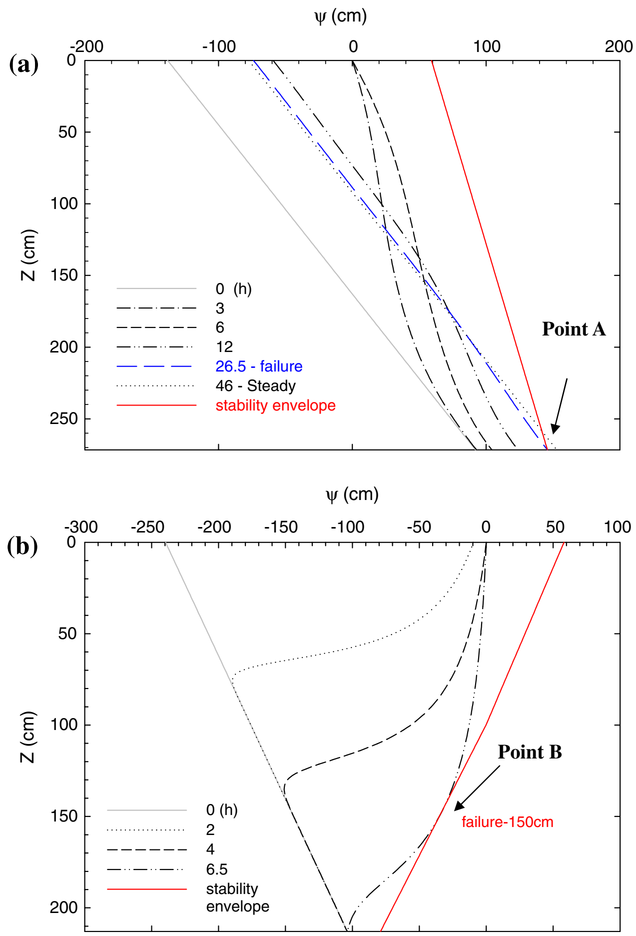

Fig. 5 Simulated results of hydrological modeling and soil failure modeling for shallow landslides in saturated and unsaturated soils

propagates downward, and the matric suction decreases with respect to time during the period of rainfall. The soil failure is triggered at 6.6 h after the rainfall at the depth of 1.5 m below the ground surface of the hillslope as shown in point B of Fig. 5b, in which the groundwater pressure head is negative, that is, the soil is unsaturated. The result shows that the developed model can assess the shallow landslide in unsaturated soil due to the dissipation of matric suction, except the increase of positive pore water pressure in saturated soil as in the previous demonstration.

Effect of rainfall intensity and duration on shallow landslides

Shallow landslides in saturated soil

With the same hillslope condition as for modeling shallow landslides in saturated soil in the previous section, the simulated groundwater pressure heads with respect to time from two rainstorms with the same rainfall intensity of 22.5 mm/h, but respectively lasting for 6 and 12 h, are depicted in Fig. 6a and b. Figure 6c and d display the resulting groundwater pressure heads with respect to time from two rainstorms, respectively, with rainfall intensity of 90 mm/h and rainfall duration of 3 h, and with rainfall intensity of 45 mm/h and rainfall duration of 6 h. It shows from Fig. 6a–d that the rainfall intensity and duration strongly influence the infiltration behavior of soil. The times to ponding and steady state are significantly related to the rainfall intensity and duration.

Figure 6a and b shows that under the same rainfall intensity it is easier for the rainstorm with great rainfall duration to induce the soil failure than for that with short rainfall duration due to the large amount of rainfall infiltration, i.e., the great rise in the groundwater table, as shown in Fig. 7. Owing to the same reason Fig. 6a and d indicates that under the same rainfall duration the rainstorm with great rainfall intensity is more likely to trigger the landslide. Figure 6b–d shows that the two rainstorms with rainfall intensities of 22.5 and 45 mm/h, respectively, lasting for 12 and 6 h can trigger the landslide, whereas the soil failure is not induced by the rainstorm with rainfall intensity of 90 mm/h and rainfall duration of 3 h. This reveals that with the same rainfall amount the rainstorm having great rainfall intensity could not more easily trigger the landslide as compared with the rainstorm having low rainfall intensity. The outcome is due to the fact that the great rainfall intensity is more likely to cause the ponding that significantly influences the rainfall infiltration rate, i.e., the rise of the groundwater table as shown in Fig. 7. It must be mentioned from Fig. 6b and d that the two rainstorms with the same rainfall amount all induce shallow landslides, but the times to failure seem to be different owing to the variations in rainfall duration and intensity. It could be concluded from the above-mentioned that the shallow landslide is significantly related to rainfall intensity and duration.

To further examine the influence of rainfall intensity and duration on shallow landslides triggered by the increase of positive pore water pressure, the rainfall threshold for landslide occurrence is shown in Fig. 8. In Fig. 8, the rainfall threshold curve can divide the graph into two parts. The landslide is not induced if the rainstorm lies to the left side of the threshold curve. On the other hand, the rainstorm lying to the right side of the threshold curve can trigger the landslide. For example, the rainstorm with rainfall intensity of 22.5 mm/h and rainfall duration of 6 h cannot induce landslide, because it lies to the left side of the rainfall threshold curve, whereas the rainstorm with the rainfall intensity of 45 mm/h and identical rainfall duration can cause soil failure. Figure 8 shows that the rainfall duration threshold decreases with the increase in rainfall

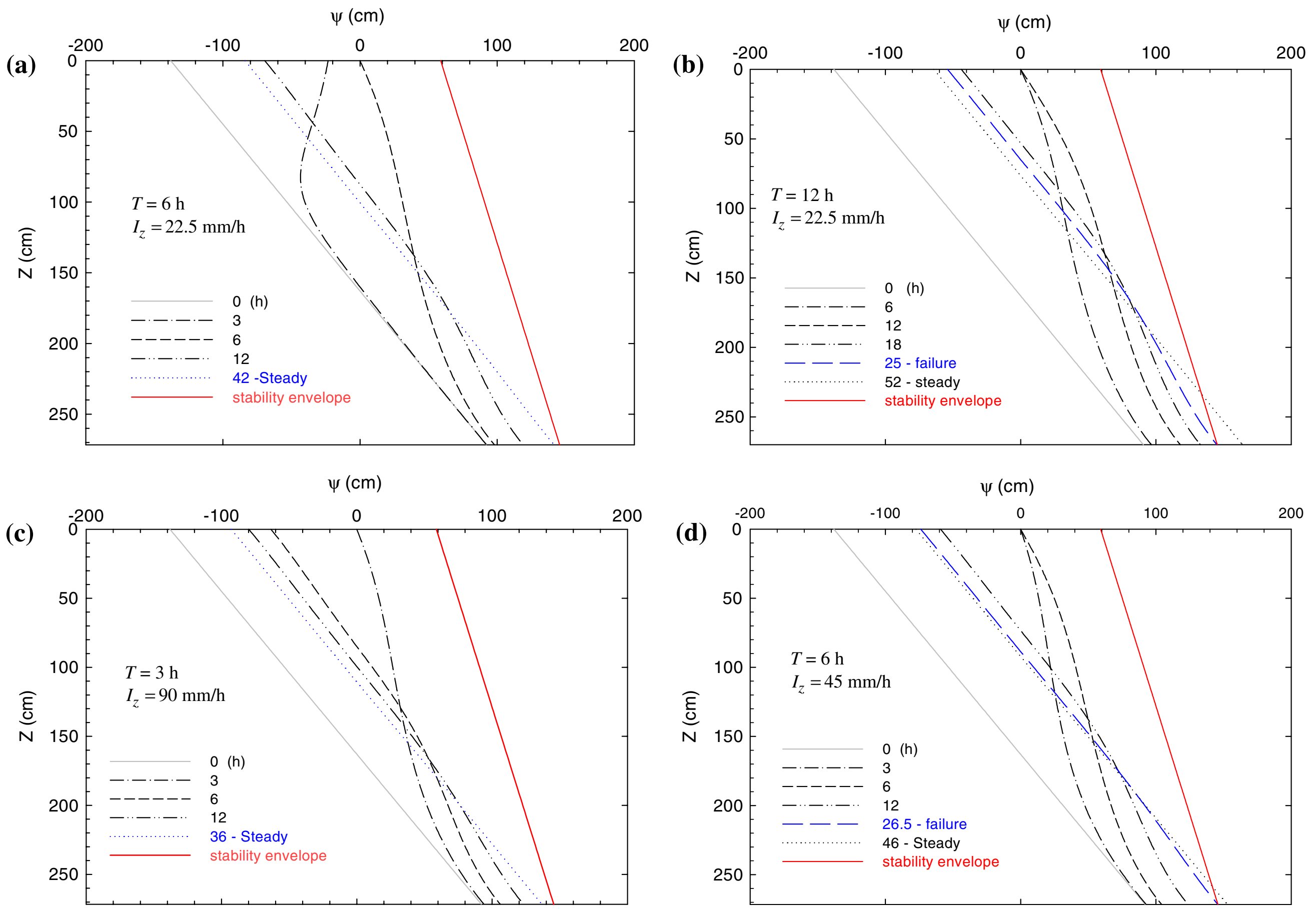

Fig. 6 Simulated results of hydrological modeling and soil failure modeling for shallow landslide in saturated soil from different rainfall intensities and durations

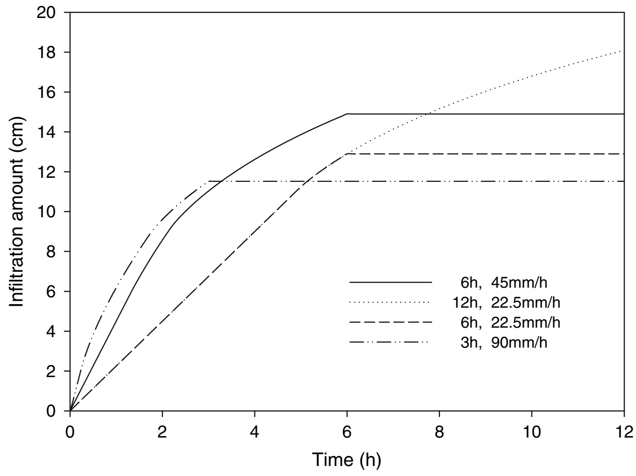

Fig. 7 Infiltration amounts from different rainfall intensities and durations

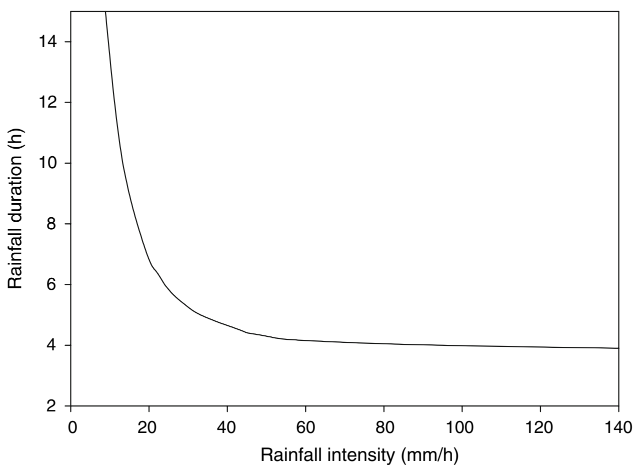

Fig. 8 Simulated results of hydrological modeling and soil failure modeling for shallow landslide in unsaturated soil

intensity, but it seems to remain unchanged for large rainfall intensity. In this example, the rainfall duration threshold is about 7 h for the rainfall intensity of 20 mm/h and decreases to 4.5 h for the rainfall intensity of 40 mm/h. However, the rainfall duration threshold remains 4 h, while the rainfall intensity is greater than 60 mm/h.

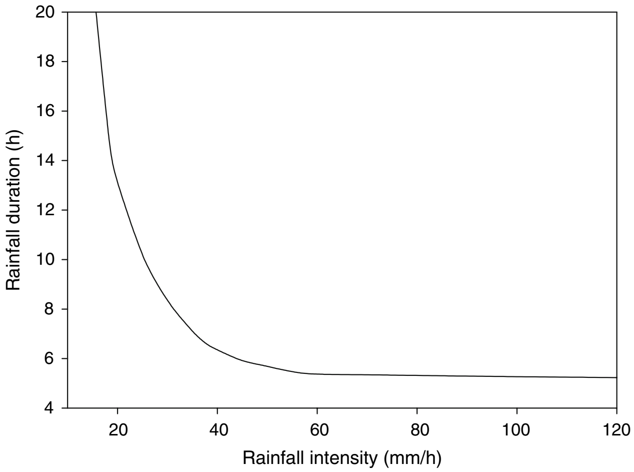

Fig. 9 Rainfall threshold for landslide occurrence in unsaturated soil

Shallow landslide in unsaturated soil

To investigate the influence of rainfall intensity and duration on shallow landslide triggered by the dissipation of matric suction, the rainfall threshold for landslide occurrence is shown in Fig. 9 with the same hillslope condition as for modeling shallow landslides in unsaturated soil in the previous section. Figure 9 indicates that the rainstorm with a rainfall intensity of 90 mm/h and rainfall duration of 4 h, for which the resulting groundwater pressure heads with respect to time are depicted in Fig. 10a, does not cause the landslide. However, the soil failures are induced by the two rainstorms with rainfall intensities of 22.5 and 45 mm/h, respectively, lasting for 16 and 8 h, for which the resulting groundwater pressure heads with respect to time are shown in Fig. 10b and c. Fig. 9 reveals that the rainfall threshold curve for shallow landslides triggered by the dissipation of matric suction seems similar to that induced by the increase of positive pore water pressure as shown in Fig. 8. For the soil failure in unsaturated soil the rainfall duration threshold diminishes with the increase of rainfall intensity, but seems to be constant for large rainfall intensity. It must be mentioned from Fig. 10b and c that due to the differences in rainfall intensity and duration, not only the depths of failure, but also the times to failure for the two rainstorms, regardless of having the same rainfall amount, seem to be inconsistent.

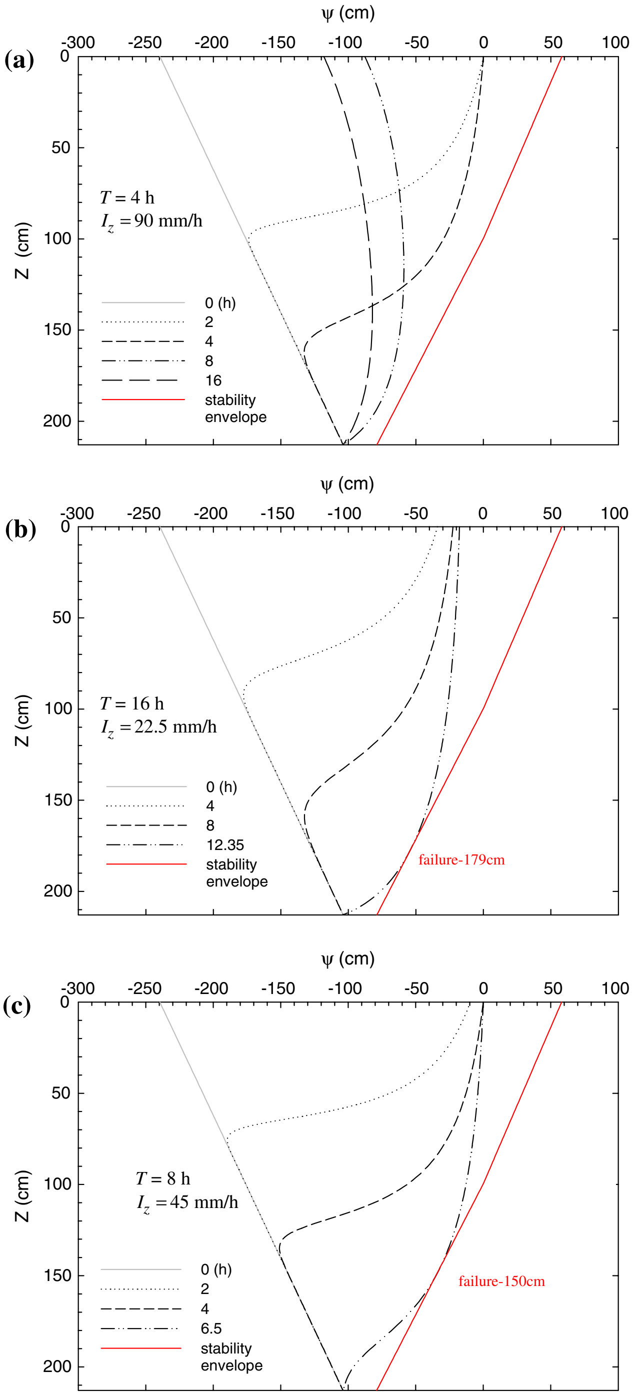

Fig. 10 Simulated results of hydrological modeling and soil failure modeling for shallow landslides in unsaturated soil from different rainfall intensities and durations

Conclusions

Shallow landslides triggered by rainfall threaten both lives and property in many places around the world. Due to its simplicity, the physically based model coupling the infinite slope stability analysis with the hydrological modeling in nearly saturated soil commonly has been used for practical applications by many soil scientists. However, except the shallow landslide in saturated soil due to groundwater table rise, that model could not actually assess the shallow landslide caused by the decrease in shear strength of unsaturated soil because a linear diffusion-type Richards' equation had replaced the complete Richards' equation to model rainfall infiltration, and the influence of martic suction on unsaturated shear strength was not actually considered to analyze soil failure. In this study, to reliably assess shallow landslides in variably saturated soil, the physically based model was developed not only by using the complete Richards' equation with the effect of slope angle in the hydrological modeling, but also by adopting the extended Mohr–Coulomb failure criterion to describe the shear strength of variably saturated soil in the slope failure modeling. The demonstration of the model's applicability shows that the developed model can assess the soil failure triggered by the increase of positive pore water pressure in saturated soil due to a rise in the groundwater table. In addition, the assessment of the shallow landslide induced by the loss in unsaturated shear strength due to the dissipation of matric suction can also be conducted using the developed model.

The influence of rainfall intensity and duration on shallow landslides is examined using the developed model. The result reveals that the effects of rainfall intensity and duration on shallow landslides in saturated and unsaturated soils seem to be similar. The rainfall duration threshold decreases with the increase in rainfall intensity, but it remains unchanged for large rainfall intensity. Under the same rainfall intensity the rainstorm with great rainfall duration more easily causes the soil failure than that with short rainfall duration. As compared with the rainstorm having low rainfall intensity, the rainstorm with great rainfall intensity is more likely to trigger the landslide under the same rainfall duration, whereas it could not be easier to induce the landslide under the same rainfall amount. For the two rainstorms with the same rainfall amount, the depths of failure and the times to failure seem to be different due to the variations in rainfall intensity and duration.

References

Anderson MG, Howes S (1985) Development of application of a combined soil water-slope stability model. Q J Eng Geol London 18:225–236

Baum RL, Savage WZ, Godt JW (2002) TRIGRS—a Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis, Virginia, US Geological Survey Open file report 02–424

Bear J (1972) Dynamics of fluids in porous media. Dover, Mineola

Borga M, Fontana GD, De Ros D, Marchi L (1998) Shallow landslide hazard assessment using a physically based model and digital elevation data. Environm Geol 35:81–88

Collins BD, Znidarcic D (2004) Stability analyses of rainfall induced landslides. J Geotech Geoenviron Eng 130(4):362–372

Crosta GB, Frattini P (2003) Distributed modeling of shallow landslides triggered by intense rainfall. Nat Haz Earth Syst Sci 3:81–93

D'Odorico P, Fagherazzi S, Rigon R (2005) Potential for landsliding: dependence on hyetograph characteristics. J Geophys Res Earth Surf 110(F1)

Escario V, Saez J (1986) The shear strength of partly saturated soils. Geotechnique 36:453–456

Frattini P, Crosta GB, Fusi N, Negro PD (2004) Shallow landslides in pyroclastic soil: a distributed modeling approach for hazard assessment. Eng Geol 73:277–295

Fredlund DG, Morgenstern NR, Widger RA (1978) The shear strength of unsaturated soils. Can Geotech J 15:313–321

Hills RG, Hudson DB, Wierenga DB (1989) Modeling one-dimensional infiltration into very dry soils 1. Model development and evaluation. Water Resour Res 25:1259–1269

Hsu SH, Ni CF, Hung PF (2002) Assessment of three infiltration formulas based on model fitting on Richards' equation. J Hydrol Eng 7(5):373–379

Hurley DG, Pantelis G (1985) Unsaturated and saturated flow through a thin porous layer on a hillslope. Water Resour Res 21:821–824

Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour Res 36:1897–1910

Keim RF, Skaugset AE (2003) Modelling effects of forest canopies on slope stability. Hydrol Process 17:1457–1467

Lan HX, Lee CF, Zhou CH, Martin CD (2005) Dynamic characteristics analysis of shallow landslides in response to rainfall event using GIS. Environ Geol 47:254–267

Montgomery DR, Dietrich WE (1994) A physically based model for the topographic control on shallow landslide. Water Resour Res 30:83–92

Morrissey MM, Wieczorek GF, Morgan BA (2001) A comparative analysis of hazard models for predicting debris flows in Madison County, Virginia. US Geological Survey Open file report 01–67

Richards LA (1931) Capillary conduction of liquids in porous mediums. Physics 1:318–333

Tarantino A, Bosco G (2000) Role of soil suction in understanding the triggering mechanisms of flow slides associated with rainfall. In: Wieczorek GF, Naeser ND (eds) Debris-flow hazards mitigation: mechanics, prediction, and assessment, pp 81–88

Tsai TL (2007) The influence of rainstorm pattern on shallow landslide. Environ Geol (in press)

Tsai TL, Yang JC (2006) Modeling of rainfall-triggered shallow landslide. Environ Geol 50(4):525–534

Van Genuchten (1980) A closed-form equation for predicting hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898

Wallach R, Grigorin G, Rivlin J (1997) The errors in surface runoff prediction by neglecting the relationship between infiltration rate and overland flow depth. J Hydrol 200:243–259

Wu W, Slide RC (1995) A distributed slope stability model for steep forested basins. Water Resour Res 31:2097–2110