Environ Earth Sci (2011) 63:65–75
DOI 10.1007/s12665-010-0669-1

ORIGINAL ARTICLE

Examination of influences of rainfall patterns on shallow landslides due to dissipation of matric suction

Tung-Lin Tsai · Jyun-Kai Wang

Received: 19 July 2009 / Accepted: 6 July 2010 / Published online: 24 July 2010

Abstract The influences of rainfall patterns on shallow landslides due to the dissipation of matric suction are examined in this study. Four representative rainfall patterns including the uniform, advanced, intermediated, and delayed rainfalls are adopted. The results show that not only the occurrence of shallow landslides but also the failure depth and the time of failure are affected by the rainfall pattern. The different rainfall patterns seem to have the same minimum landslide-triggering rainfall amount. There is a rainfall duration threshold for landslide occurrence for a rainfall event with larger than the minimum landslide-triggering rainfall amount. For each rainfall pattern, the rainfall duration threshold for landslide occurrence decreases to constant with the increase of rainfall amount. The uniform rainfall has the least rainfall duration threshold for landslide occurrence, followed by the advanced rainfall, and then the intermediated rainfall. For each rainfall pattern, the failure depths and the times of failure from the same amount of rainfall with different durations could be largely different. In addition, the differences of the failure depths and the times of failure between various rainfall patterns with the same amount and duration of rainfall could be also significant. The failure depth and the time of failure, as compared with the occurrence of shallow landslides, are more sensitive to the rainfall condition. In other words, in comparison with the evaluation of the occurrence of shallow landslides, it needs more accurate rainfall prediction to achieve reliable estimations of the failure depth and the time of failure.

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

Keywords Shallow landslides · Matric suction · Rainfall pattern

List of symbols

C	The change in volumetric water content per unit change in pressure head
c'	Effective cohesion
d_Z	Water depth
d_{LZ}	Slope depth
FS	Factor of safety
G_s	The specific gravity of soil solid
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
S_r	The residual degree of saturation
S_e	The effective 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 volumetric water content
θ_r	Residual volumetric water content
α	Slope angle
ϕ'	Effective friction angle
ζ	Fitting parameter
χ	The parameter for shear strength of unsaturated soil

$\overline{\gamma}$ The depth-averaged 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. Slope failures may happen owing to human-induced factors such as the loading of the slope or the cutting away of the toe for construction purposes, but many occur simply due to rainfall, especially in region with residual soil subjected to rainstorm. The empirical rainfall threshold concept and the physical-based model are two commonly used approaches to the assessment of landslide.

With assumptions of steady or quasi-steady groundwater table, and groundwater flows parallel to hillslope, various physical-based models coupling the infinite slope stability analysis with hydrological modeling (Montgomery and Dietrich 1994; Wu and Sidle 1995; Borga et al. 1998) were developed to assess shallow landslides induced by land use and hydrological conditions. Iverson (2000) further developed a flexible modeling framework of shallow landslide with the approximation of the Richards' equation (1931) valid for hydrological modeling in nearly saturated soil. This led to the use of the linear diffusion-type Richards' equation for modeling 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 top of hillslope to consider more general infiltration process (Tsai and Yang 2006). Due to efficiency, the physical-based model with the hydrological modeling in nearly saturated soil (Iverson 2000; Baum et al. 2002; Tsai and Yang 2006) was commonly used for the assessment of shallow landslides triggered by rainfall (Crosta and Frattini 2003; Keim and Skauqset 2003; Frattini et al. 2004; Lan et al. 2005; D'Odorico et al. 2005; Tsai 2008).

It had been observed that the soil failures could be caused not only by the increase of positive pore water pressure in saturated soil due to the groundwater table rise, but also by the loss in unsaturated shear strength due to the dissipation of matric suction. The physical-based model with the hydrological modeling in nearly saturated soil could not assess the shallow landslides caused by the dissipation of matric suction since the linear diffusion-type Richards' equation rather than the complete Richards' equation was used for modeling rainfall infiltration, and the effect of matric suction on the unsaturated shear strength was not reliably considered to examine the soil failures. Therefore, many physical-based shallow landslide models using the complete Richards' equation and the extended Mohr–Coulomb failure criterion (Fredlund et al. 1978) valid for describing the shear strength of unsaturated soil were developed (Anderson and Howes 1985; Tarantino and Bosco 2000; Collins and Znidarcic 2004; Tsai et al. 2008). However, in those physical-based shallow landslide models, the unit weight of soil was assumed constant rather than varying with the degree of saturation. In addition, the shear strength of unsaturated soil also remained unchanged in spite of the degree of saturation, i.e., the nonlinearity in the shear strength of unsaturated soil was not taken into account (Gan et al. 1988; Escario et al. 1989; Vanapalli et al. 1996). Tsai and Chen (2010) further developed the physical-based shallow landslide model considering the effect of degree of saturation on the unit weight and the shear strength of unsaturated soil.

Besides the physical-based model, the empirical rainfall threshold concept is commonly applied for the assessment of the occurrence of landslides. Based on historical records of landslides and the corresponding rainfall data, the rainfall threshold for landslide occurrence can be simply related either to the critical cumulative rainfall amount (Campbell 1975) or to the rainfall intensity (Brand et al. 1984), but the most commonly used was developed by simultaneously considering the rainfall intensity and the rainfall duration (Caine 1980). To take the climatic effect into account, the rainfall intensity-duration threshold for landslide occurrence was further refined by normalizing the rainfall intensity with the mean annual rainfall amount (Cannon and Ellen 1985; Jibson 1989; Wieczorek et al. 2000). Another frequently used rainfall threshold correlates the amount of rainfall until landslide initiation with the maximum rainfall intensity (Govi et al. 1985). In addition, the influence of the antecedent rainfall on the rainfall threshold for landslide occurrence was also considered (Glade 2000).

The empirical rainfall threshold for landslide occurrence was probably associated with the rainfall amount, the rainfall duration, the mean rainfall intensity, the maximum hourly rainfall intensity, or the antecedent rainfall, but it did not take the rainfall pattern into account. Tsai (2008) applied the modified Iverson's model (Tsai and Yang 2006) to investigate the influences of rainfall patterns on shallow landslides in saturated soils due to the groundwater table rise. However, as previous mentioned, the soil failure could be also induced by the decrease in unsaturated shear strength owing to the dissipation of matric suction besides the increase of pore water pressure in saturated soil due to the groundwater table rise. The objective of this study was to further examine the effects of rainfall patterns on shallow landslides in unsaturated soils due to the dissipation of matric suction. This examination is conducted using the physical-based shallow landslide model developed by Tsai and Chen (2010) in which the complete Richards' equation is applied to hillslope hydrological modeling, and the effects of degree of saturation on the unit weight and the shear strength of unsaturated soil are taken into account for the infinite slope stability analysis. In the following sections, the hydrological modeling and the soil failure modeling used herein are first described. The influences of rainfall patterns on shallow landslides induced by the decrease in matric suction are then investigated.

Framework of shallow landslide modeling

Hydrological modeling

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

$$\frac{\partial\psi}{\partial t}\frac{d\theta}{d\psi} = \frac{\partial}{\partial x}\left[K_L(\psi)\left(\frac{\partial\psi}{\partial x} - \sin\alpha\right)\right] + \frac{\partial}{\partial y}\left[K_L(\psi)\left(\frac{\partial\psi}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[K_z(\psi)\left(\frac{\partial\psi}{\partial z} - \cos\alpha\right)\right], \quad (1)$$

in which ψ is groundwater pressure head; θ is volumetric water 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 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, Eq. 1 can be simplified in vertical direction (Iverson 2000) as follows:

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

where $C(\psi) = d\theta/d\psi$ is the change in volumetric water content per unit change in groundwater pressure head. The elevation Z is vertically measured downward from a horizontal reference plane that passes through the origin on the ground surface (Tsai et al. 2008).

The appropriate initial and boundary conditions are needed for solving Eq. 2. For the initially steady state with the groundwater table of d_Z in vertical direction shown in Fig. 1, the initial condition in terms of groundwater pressure head can be expressed as:

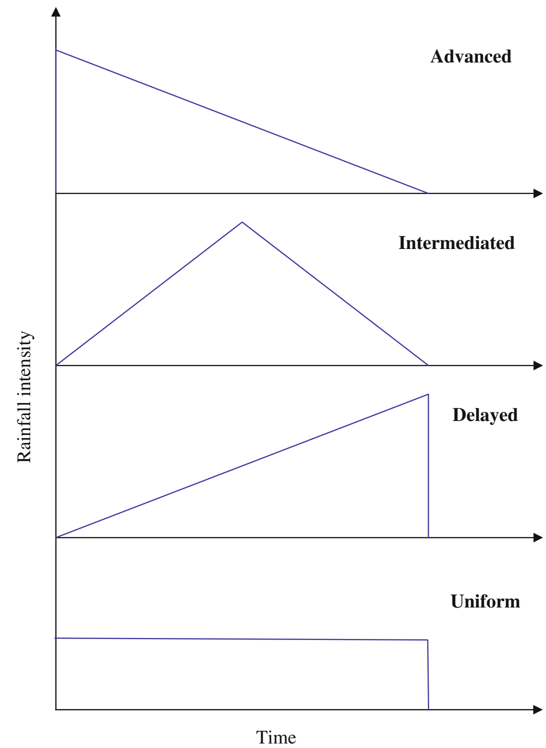

Fig. 1 The four representative rainfall patterns

$$\psi(Z, 0) = (Z - d_Z)\cos^2\alpha. \quad (3)$$

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

$$\frac{\partial\psi}{\partial Z}(d_{LZ}, t) = \cos^2\alpha \quad (4)$$

and

$$\psi(d_{LZ}, t) = (d_{LZ} - d_Z)\cos^2\alpha. \quad (5)$$

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

$$\frac{\partial\psi}{\partial Z}(0, t) = -I_Z/(K_Z)_{Z=0} + \cos^2\alpha \quad \text{if } \psi(0,t) \le 0 \text{ and } t < T, \quad (6)$$

$$\psi(0, t) = 0 \quad \text{if } \psi(0,t) > 0 \text{ and } t < T, \quad (7)$$

$$\frac{\partial\psi}{\partial Z}(0, t) = \cos^2\alpha \quad \text{if } t > T, \quad (8)$$

where T is the rainfall duration. $(K_Z)_{Z=0}$ denotes the hydraulic conductivity at ground surface of hillslope.

Equations 2–8 need to be numerically solved with an iterative procedure. The groundwater pressure head at ground surface of hillslope, i.e., $\psi(0,t)$, is first obtained by assuming that the infiltration rate equals the rainfall intensity shown in Eq. 6. If $\psi(0,t)$ is less than or equals zero, i.e., 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, i.e., the ponding occurs, with neglecting the water depth of overland flow (Hsu et al. 2002; Wallach et al. 1997; Tsai et al. 2008) $\psi(0,t) = 0$ is used as boundary condition to recalculate once more for the same time step.

In addition, for solving the Richards' equation shown in Eq. 2, the implicit finite-difference scheme (Celia et al. 1990) is used in conjunction with the function of water retention curve proposed by van Genuchten (1980) as follows:

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + [\xi|\psi|]^N}\right)^M, \tag{9}$$

$$\frac{K_Z(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/2} \left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{M}}\right]^M\right\}^2, \tag{10}$$

where S is the effective degree of saturation. θ_s denotes the saturated volumetric water content. θ_r represents the residual volumetric water content, and K_s is the saturated hydraulic conductivity. ξ, N, and M are fitting parameters, with M related to N by:

$$M = 1 - \frac{1}{N}. \tag{11}$$

Soil failure modeling

The infinite slope stability analysis is a preferred tool to evaluate shallow landslide because of 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; Tsai and Yang 2006; Tsai 2008). This concept is generally valid for the case of landslide with a small depth compared with its length and width. This assumption is also compatible with that used for the hydrological modeling in hillslope as shown in Eq. 2.

The shear strength of soil can be represented by the extended Mohr–Coulomb failure criterion (Bishop 1954) as follows:

$$\tau = c' + [(\sigma - u_a) + \chi(u_a - u_w)] \tan\phi', \tag{12}$$

where c' is the effective cohesion; ϕ' represents the effective friction angle; σ is the total normal stress; u_a and

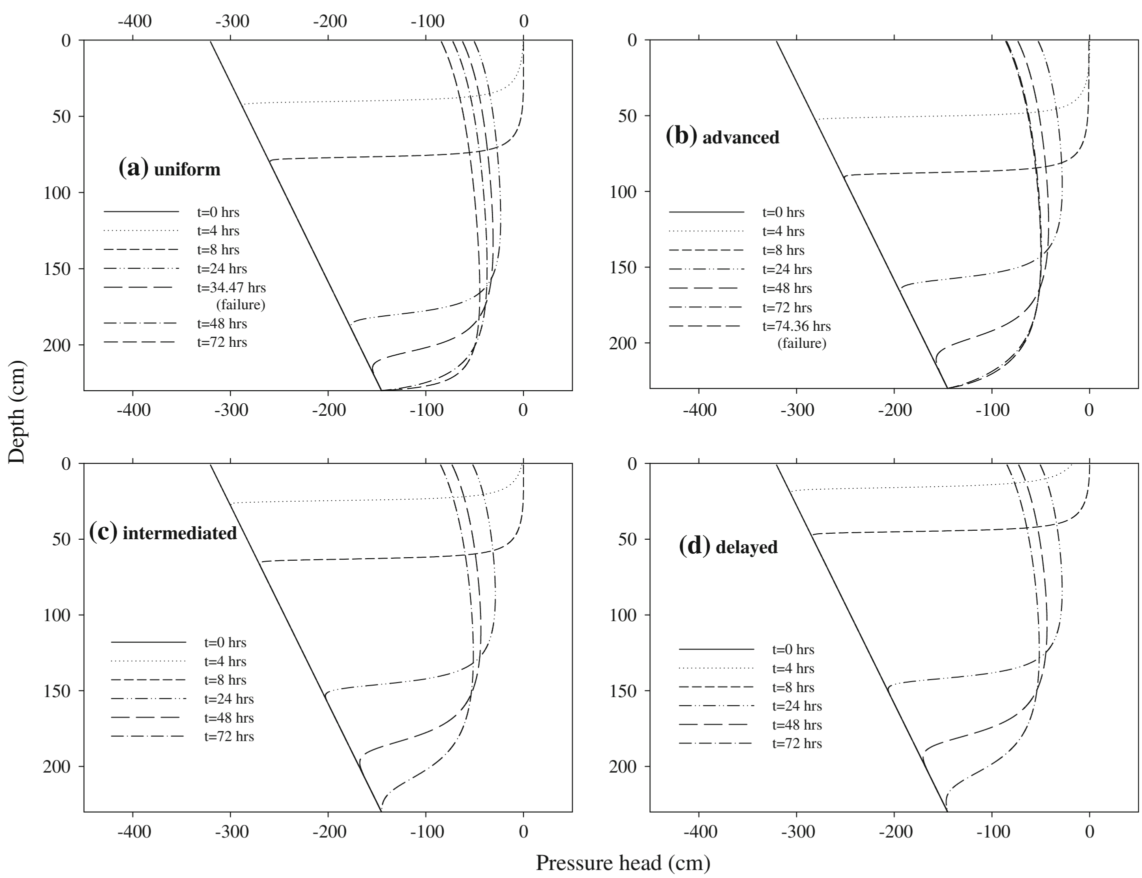

Fig. 2 The simulated results of groundwater pressure heads from different rainfall patterns with 320 mm amount and 14 h duration

u_w denote pore air pressure and pore water pressure, respectively; $u_a - u_w$ is the matric suction; χ is the effective stress parameter. There are many experimental evidences showing that the effective stress parameter of unsaturated soil is a highly nonlinear function of the matric suction (Gan et al. 1988; Escario et al. 1989; Vanapalli et al. 1996). A convenient and accurate representation of effective stress parameter (Vanapalli and Fredlund 2000; Lu and Likos 2004) was proposed as follows:

$$\chi = \frac{\theta - \theta_r}{\theta_s - \theta_r}. \quad (13)$$

Equation 13 can be further expressed as:

$$\chi = S_e = \frac{S - S_r}{1 - S_r}, \quad (14)$$

in which S denotes the degree of saturation. S_r is the residual degree of saturation. S_e represents the effective saturation. We can observe from Eq. 13 and the water retention curve shown in Eq. 9 that there is indeed a highly nonlinear relation between the effective stress parameter and the matric suction for unsaturated soil. In addition, it can be found from Eqs. 12 and 14 that the unsaturated shear strength depends on the degree of saturation. The effective stress parameter ranges between zero and unity. If the soil is saturated the effective stress parameter is identical to unity. The effective stress parameter is zero when the soil has the residual degree of saturation.

The soil failure is induced at depth Z where the acting stress is larger than the resisting stress due to friction and cohesion. Using the infinite slope stability analysis together with the shear strength of soil given by Eq. 12, and assuming that the pore air pressure is atmospheric, the factor of safety can be written as:

$$\mathrm{FS} = \frac{\tan\phi'}{\tan\alpha} + \frac{c' - \gamma_w \psi_c \chi \tan\phi' - \gamma_w \psi_p \tan\phi'}{\bar{\gamma} Z \sin\alpha \cos\alpha}, \quad (15)$$

where γ_w represents the unit weight of water. $\bar{\gamma}$ is the depth-averaged unit weight of soil and can be expressed as:

$$\bar{\gamma} = \frac{1}{Z} \int_0^Z [(1-\theta)\gamma_w G_s + \theta\gamma_w] \mathrm{d}Z, \quad (16)$$

where G_s is the specific gravity of soil solid. In Eq. 15, when the groundwater pressure head is negative, i.e., the soil is unsaturated, ψ_c is equal to ψ which can be obtained

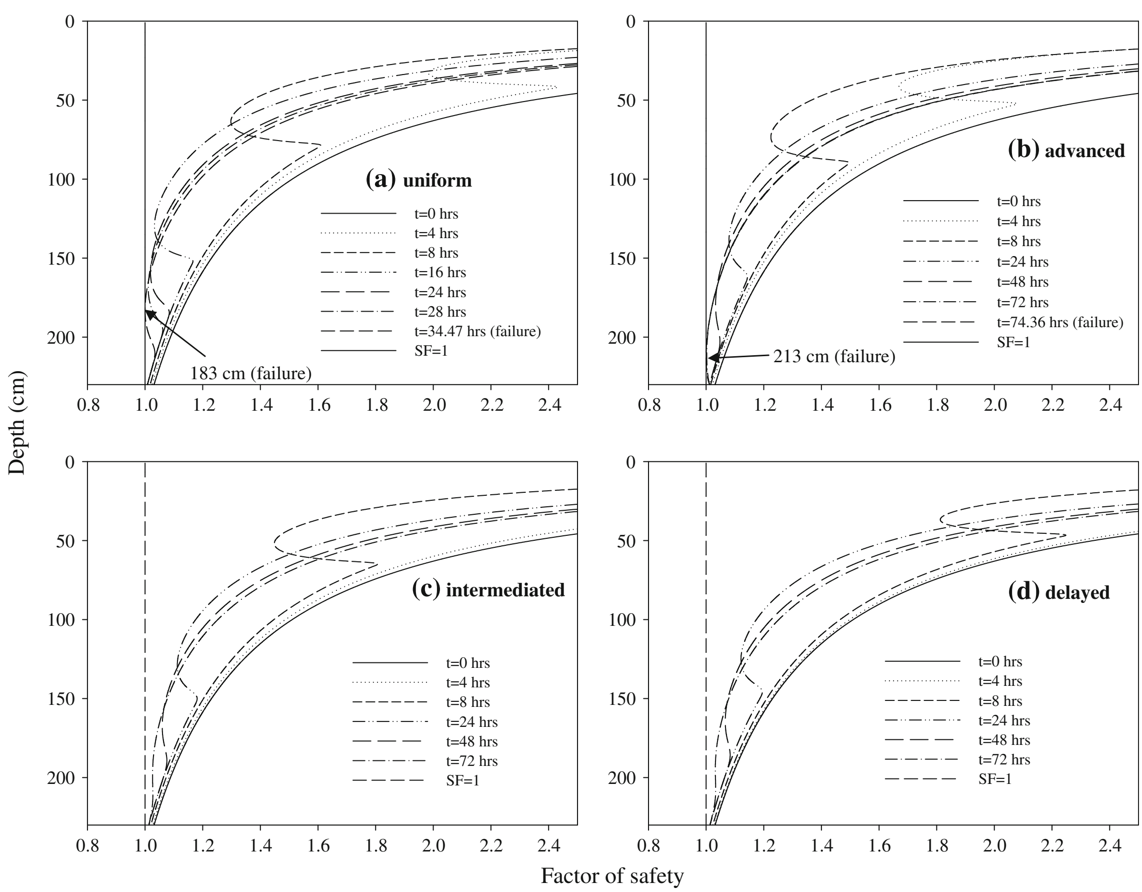

Fig. 3 The simulated results of factors of safety from different rainfall patterns with 320 mm amount and 14 h duration

from Eq. 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, i.e., the soil is saturated.

Examinations

The influences of rainfall patterns, including the uniform, advanced, intermediated, and delayed rainfalls (Tsai 2008), shown in Fig. 1, on shallow landslides in unsaturated soils due to the decrease of matric suction are examined in this section. The shallow soil with slope of 29° and depth of 2.3 m overlies a more permeable bedrock. The groundwater table is located at the depth of 4.2 m below the ground surface of hillslope at the beginning of rainfall. The groundwater table varies, but is assumed to remain in bedrock during and after rainfall. The following soil parameters are adopted: $\phi' = 22°$, $c' = 2.5$ Kpa, $\gamma_w = 9810$ N/m^3, $K_s = 6.42 \times 10^{-6}$ m/s, $N = 1.65$, $\theta_s = 0.41$, $\theta_r = 0.06$, and $\xi = 0.024$. The shallow soil used in this examination could be classified between sandy loam and loam (Carsel and Parrish 1988).

The simulated results of groundwater pressure heads and factors of safety with respect to time from different rainfall patterns with 320 mm amount and 14 h duration are shown in Figs. 2 and 3. We can find from Figs. 2 and 3 that the groundwater pressure heads and the factors of safety are strongly related to the rainfall patterns. In this scenario, the intermediated and delayed rainfalls do not induce soil failure, whereas the shallow landslides are triggered by the uniform and advanced rainfalls at 34.74 and 73.46 h after the rainfall. The uniform rainfall has the failure depth of 1.83 m. The failure depth of the advanced rainfall is larger than that of the uniform rainfall, and the difference of failure depths between two rainfalls reaches 0.3 m. In addition, Figs. 4 and 5 depict the simulated results of groundwater pressure heads and factors of safety from different rainfall patterns when the amount and duration of rainfall are 420 mm and 36 h. We can observe from Figs. 4 and 5 that the four representative rainfall patterns all induce shallow landslides, but they have different failure depths and failure times. It can be clearly known from the above discussions that the rainfall pattern not only influences the occurrence of shallow landslides, but also affects the failure depth and the time of failure.

Effects of rainfall patterns on occurrence of shallow landslides

To further investigate the influences of rainfall pattern on the occurrence of shallow landslides, the rainfall threshold

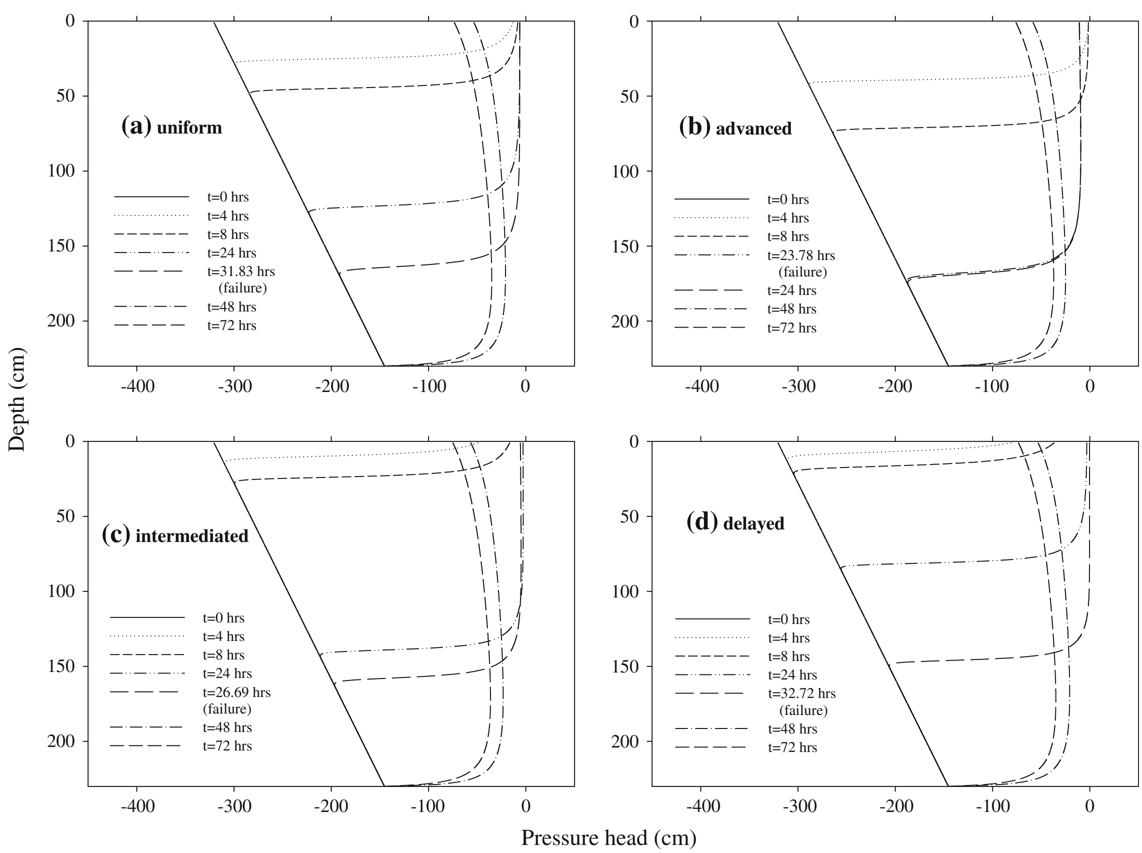

Fig. 4 The simulated results of groundwater pressure heads from different rainfall patterns with 420 mm amount and 36 h duration

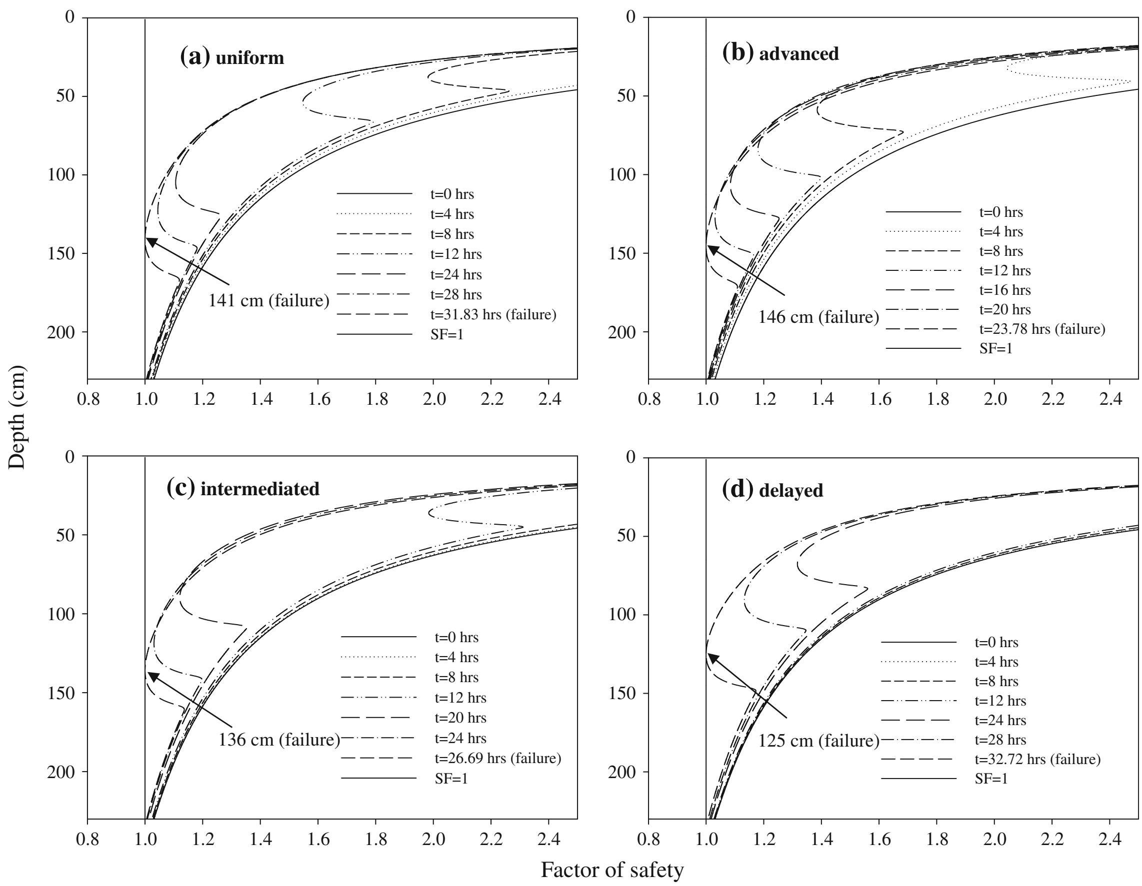

Fig. 5 The simulated results of factors of safety from different rainfall patterns with 420 mm amount and 36 h duration

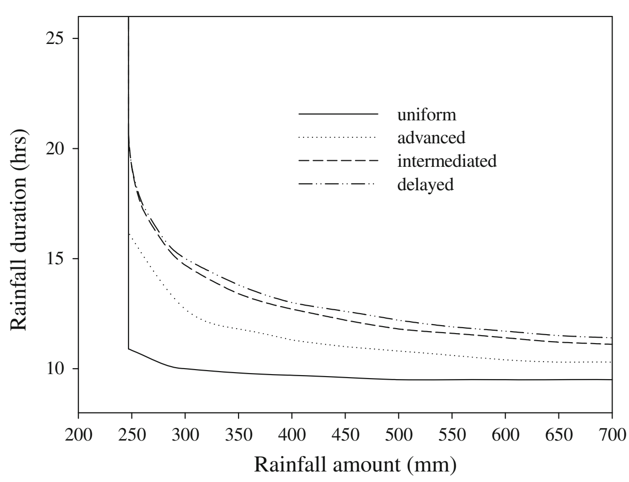

Fig. 6 Rainfall thresholds of landslide occurrence for different rainfall pattern

curves from the four representative rainfall patterns together with different durations and amounts are displayed in Fig. 6. In Fig. 6, for each rainfall pattern, the corresponding rainfall threshold curve can separate the graph into two regions. The rainfall lying to the right side of the threshold curve can trigger shallow landslide. On the contrary, the soil failure cannot be induced if the rainfall lies to the left side of the threshold curve. For example, the delayed rainfall with 300 mm amount and 12 h duration cannot induce shallow landslide, whereas the uniform rainfall with the same amount and duration can cause soil failure.

It can be seen from Fig. 6 that a rainfall event with larger than 250 mm amount has a rainfall duration threshold for landslide occurrence regardless of the rainfall pattern. This is because that for the same amount of rainfall the less rainfall duration, i.e., the larger rainfall intensity, is more likely to cause the ponding. The decrease of rainfall infiltration capacity due to the ponding could not result in enough dissipation of matric suction to trigger the soil failure. For each rainfall pattern, the rainfall duration threshold for landslide occurrence decreases to constant with the increase in the rainfall amount. Among the four representative rainfall patterns, the uniform rainfall has the least rainfall duration threshold for landslide occurrence, followed by the advanced rainfall, and then the intermediated rainfall. However, each rainfall pattern with less than 250 mm amount could not induce the shallow landslide in spite of the rainfall duration. This indicates that

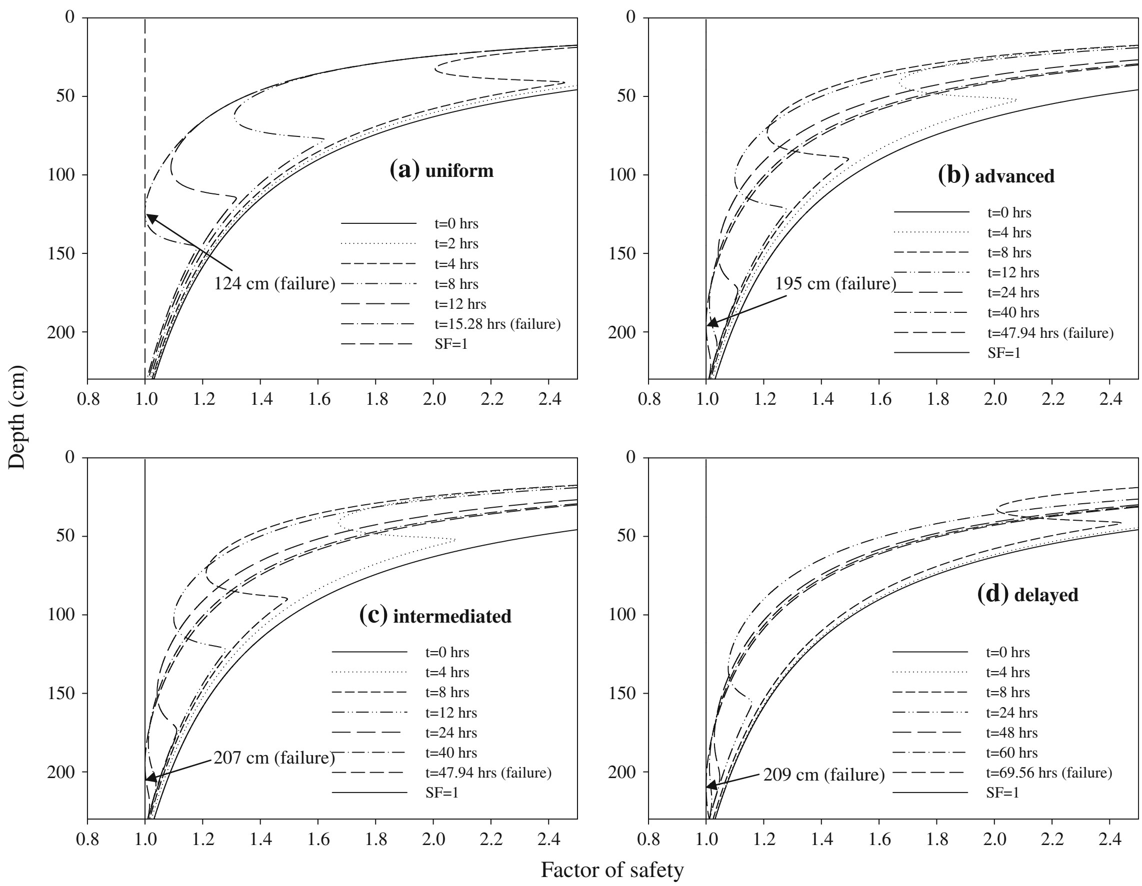

Fig. 7 The simulated results of factor of safety from various rainfall patterns with 16 h duration

there is the same minimum landslide-triggering rainfall amount for different rainfall patterns. This is due to the fact that the rainfall event with less than the minimum landslide-triggering rainfall amount has not enough decrease in matric suction to induce the soil failure even though the rainfall infiltrates totally. The influences of rainfall patterns on the occurrence of shallow landslides in unsaturated soils due to the dissipation of matric suction, as above mentioned, seem similar to those in saturated soils owing to the groundwater table rise (Tsai 2008).

Effects of rainfall patterns on failure depths and times of failure

The simulated results of factors of safety with respect to time from the four representative rainfall patterns with 360 mm amount and different durations of 16 and 48 h are displayed in Figs. 7 and 8. It can be found from the rainfall threshold curves shown in Fig. 6 that the above-mentioned rainfall conditions all induce shallow landslides. However, Figs. 7 and 8 reveal that for each rainfall pattern the failure depths and the times of failure from the same amount of rainfall with different durations could be significantly different. For example, with the durations of 16 and 48 h, the delayed rainfall induces soil failures at depths of 2.09 and 1.35 m, and the failure depths of the uniform rainfall are 1.24 and 1.56 m. The advanced rainfall with the durations of 16 and 48 h has the failure times of 47.94 and 44.31 h. The uniform rainfall triggers shallow landslides at 15.28 and 50.83 h after the rainfall if the durations are 16 and 48 h, respectively. Furthermore, one can find from Figs. 7 and 8 that the various rainfall patterns with the same amount and duration could have largely different failure depths and failure times. It must be mentioned that for shallow landslides in saturated soils due to the groundwater table rise, the slope failures always occur at the bottom of soil layer, i.e., the failure depth is independent of the rainfall condition (Tsai and Yang 2006; Tsai 2008). However, for shallow landslides in unsaturated soils triggered by the dissipation of matric suction, the slope failures could happen at any depth of soil layer which indicates that the failure depth depends on the rainfall condition.

From above examination, it can be clearly known that for the soil failure in unsaturated soil induced by the dissipation of matric suction not only the occurrence of

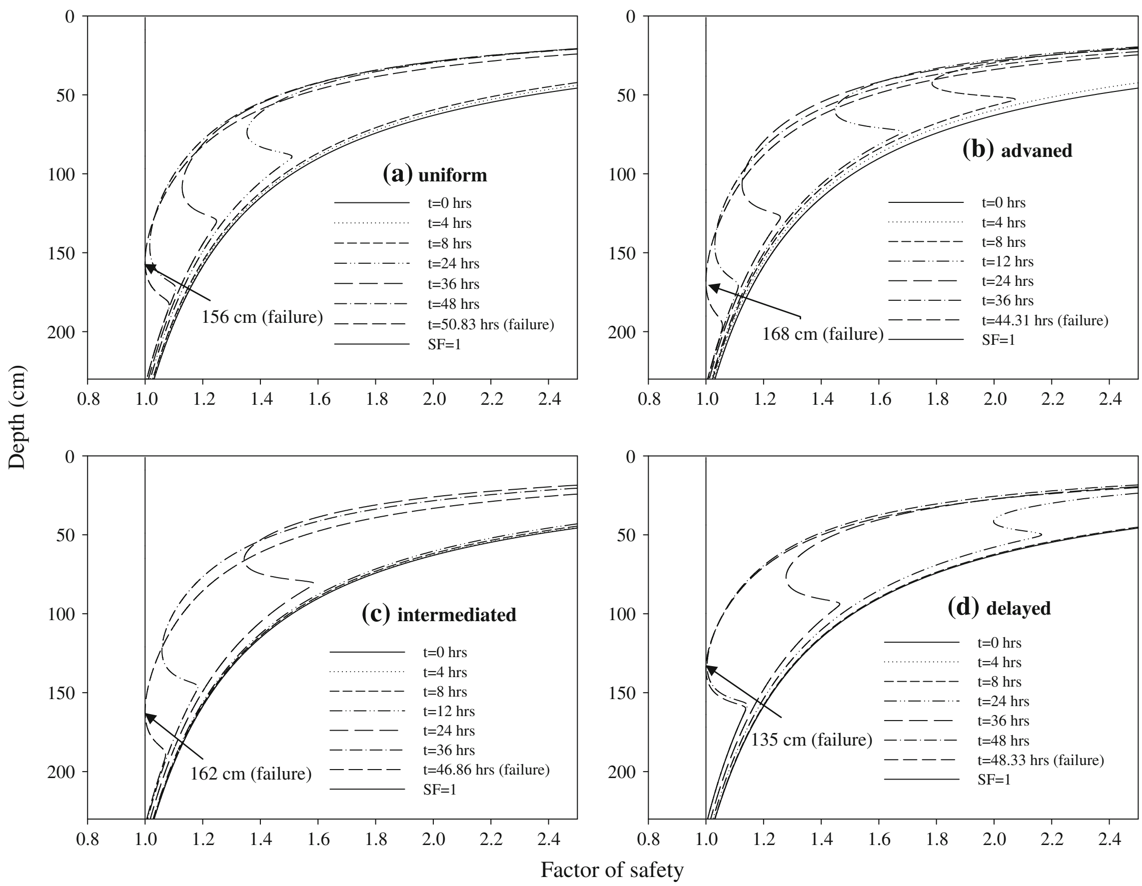

Fig. 8 The simulated results of factor of safety from various rainfall patterns with 48 h duration

shallow landslides but also the failure depth and the time of failure are influenced by the rainfall condition. However, the failure depth and the time of failure, as compared with the occurrence of shallow landslides, are more sensitive to the rainfall condition. Therefore, the more accurate rainfall prediction is needed for reliably estimating the failure depth and the time of failure in comparison with evaluating the occurrence of shallow landslides.

Conclusions

Many places around the world are threatened by rainfall-induced landslides. The empirical rainfall threshold concept associated with the rainfall amount, the rainfall duration, the mean rainfall intensity, the maximum hourly rainfall intensity, or the antecedent rainfall was commonly used to assess the occurrence of landslides. However, the rainfall pattern was not considered in the empirical rainfall threshold concept. Tsai (2008) applied the physical-based model to investigate the effects of rainfall patterns on shallow landslides in saturated soils due to the groundwater table rise. Many researches showed that the shallow landslide could be also induced by the decrease in shear strength of unsaturated soil owing to the dissipation of matric suction. The purpose of this study was to further examine the influences of rainfall patterns on shallow landslides triggered by the decrease of matric suction. The results reveal that the rainfall pattern affects the occurrence of shallow landslides. There is the same minimum landslide-triggering rainfall amount for different rainfall patterns. A rainfall duration threshold for landslide occurrence is existed in a rainfall event with larger than the minimum landslide-triggering rainfall amount, and decreases to constant with the increase in rainfall amount. The delayed rainfall has the largest rainfall duration threshold for landslide occurrence, followed by the intermediated rainfall, whereas the uniform rainfall possesses the least rainfall duration threshold for landslide occurrence. Therefore, the occurrence of shallow landslides could be misevaluated if the rainfall pattern is not taken into account. Furthermore, besides the occurrence of shallow landslides, the failure depth and the time of failure are also related to the rainfall pattern. The various rainfall patterns with the same amount and duration could have largely different failure depths and failure times. For each rainfall pattern, the failure depths and the times of failure from the same amount of rainfall with different durations could be also significantly different. Hence, in comparison with the occurrence of shallow landslides, the failure depth and the time of failure need more accurate rainfall prediction to be reliably estimated because of the great sensitivity to the rainfall condition.

Acknowledgments This study was funded by the National Science Council of the Republic of China under grant nos. NSC 97-2625-M-415-001 and NSC-98-2625-M-415-001-MY2.

References

Anderson MG, Howes S (1985) Development of application of a combined soil water-slope stability model. Q J Eng Geol Lond 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. US Geological Survey Open file report 02-424. US Geological Survey, Virginia

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

Bishop AW (1954) The use of pore pressure coefficients in practice. Geotechnique 4:148–152

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

Brand EW, Premchitt J, Phillipson HB (1984) Relationship between rainfall and landslides in Hong Kong. In: Proceedings of the 4th international symposium on landslides, Toronto, vol 1, pp 377–384

Brooks SM, Richards KS (1994) The significance of rainstorm variations to shallow translational hillslope failure. Earth Surf Process Landf 19(1):85–94

Caine N (1980) The rainfall intensity duration control of shallow landslides and debris flow. Geogr Ann 62(1):23–27

Campbell RH (1975) Debris flow originating from soil slip during rainstorm in southern California. Q Eng Geol 7:339–349

Cannon SH, Ellen SD (1985) Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California. Calif Geol 38(12):267–272

Carsel RF, Parrish RS (1988) Developing joint probability distributions of soil water retention characteristics. Water Resour Res 24(5):755–769

Celia MA, Bouloutas ET, Zarba RL (1990) A general mass-conservation numerical solution for the unsaturated flow equation. Water Resour Res 26(7):1483–1496

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 Hazard 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)

de Lima JLMP, Singh VP (2002) The influence of the pattern of moving rainstorm on overland flow. Adv Water Resour 25:817–828

Dhakal AS, Sidle RC (2004) Distributed simulations of landslides for different rainfall conditions. Hydrol Process 18:757–776

Escario V, Juca J, Coppe MS (1989) Strength and deformation of partly saturated soils. In: Proceeding of 12th international conference on soil mechanics and foundation engineering, vol 3. Rio de Janeiro, pp 43–46

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

Gan JK, Fredlund DG, Rahardjo H (1988) Determination of the shear strength parameters of an unsaturated soil using the direct shear test. Can Geotech J 25:500–510

Glade T (2000) Modelling landslide-triggering rainfalls in different regions of New Zealand—the soil water status model. Z Geomorphol NE 122:63–84

Govi M, Mortara G, Sorzana P (1985) Eventi idrologici e frane. Geol Appl Idrogeol 20(2):395–401

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

Jibson RW (1989) Debris flow in southern Porto Rico. In: Schultz AP, Jibson RW (eds) Landslide processes of the eastern United States and Puerto Rico. Geological Society of American Special Paper 236, pp 29–55

Keim RF, Skauqset 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

Ng CWW, Wang B, Tung YK (2001) Three-dimensional numerical investigation of groundwater responses in an unsaturated slope subjected to various rainfall patterns. Can Geotech J 38:1049–1062

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 (2008) The influence of rainstorm pattern on shallow landslide. Environ Geol 53(7):1563–1570

Tsai TL, Chen HF (2010) Effects of degree of saturation on shallow landslides triggered by rainfall. Environ Earth Sci 59(6): 1285–1295

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

Tsai TL, Chen HE, Yang JC (2008) Numerical modeling of rainfall-induced shallow landslides in saturated and unsaturated soils. Environ Geol 55(4):1269–1277

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

Vanapalli SK, Fredlund DG (2000) Comparison of empirical procedures to predict the shear strength of unsaturated soils using the soil-water characteristic curve. In: Shackelford CD, Houston SL, Chang NY (eds) Advances in unsaturated geotechnics, GPS No.99. ASCE, Reston, pp 195–209

Vanapalli SK, Fredlund DG, Pufahl DE, Clifton AW (1996) Model for the prediction of shear strength with respect to soil suction. Can Geotech J 33:379–392

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

Wieczorek GF, Morgan BA, Campbell RH (2000) Debris flow hazards in the Blue Bridge of Central Virginia. Environ Eng Geosci 1(1):11–27

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