Publication information

Title	Stability analysis of rainfall-induced slope failure: a review
Author(s)	Zhang, L.L.; Zhang, J.; Zhang, L.M.; Tang, W.H.
Source	Proceedings of the Institution of Civil Engineers - Geotechnical Engineering , v. 164, (5), October 2011, p. 299-316
Version	Published version
DOI	https://doi.org/10.1680/geng.2011.164.5.299
Publisher	ICE Publishing

Copyright information

Copyright © ICE Publishing 2015. The journal, Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, can be found via <http://www.icevirtuallibrary.com/journal/jgeen>

Notice

This version is available at HKUST Institutional Repository via
<http://hdl.handle.net/1783.1/8009>

If it is the author's pre-published version, changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published version.

Stability analysis of rainfall-induced slope failure: a review

1 L. L. Zhang MSc, PhD

Associate Professor, Centre for Marine Geotechnics Research, Department of Civil Engineering, Shanghai Jiaotong University, China

2 J. Zhang MSc, PhD

Lecturer, Department of Geotechnical Engineering, Tongji University, Shanghai, China; formerly Research Associate, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

3 L. M. Zhang MSc, PhD

Professor, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

4 W. H. Tang MSc, PhD, PE

Professor Emeritus, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

Rainfall is one of the most significant triggering factors for slope failures in many regions around the world. Numerous research studies have been conducted to investigate infiltration of rainwater into a slope, and the effect of water infiltration on slope stability. In this paper, a review of existing research on infiltration analysis and slope stability analysis under rainfall infiltration is presented. Studies on infiltration analysis with conceptual models, analytical analysis and numerical modelling are first reviewed. The typical pore water pressure profiles in the slope are then discussed. Subsequently, recent developments in analyses of slope instabilities under rainfall conditions using the limit equilibrium method and coupled hydro-mechanical modelling are summarised, and major findings on critical hydrological factors related to rainfall-induced landslides are summarised and discussed. Finally, several research topics are suggested for further study.

Notation

C_s	wetting front capillary suction
c'	effective cohesion
F_s	safety factor
H	depth of slip surface
H_w	depth of groundwater table
h	total head
h_p	pressure head at slip surface
$I_{\min}$	critical rainfall intensity
I_{thr}	threshold rainfall intensity
k	unsaturated permeability of soil
k_{sat}	saturated coefficient of permeability
k_w	coefficient of permeability in wetted zone
m	distance from groundwater table to slip surface
n	porosity
q	ground surface flux
q_0	initial ground surface flux
q_1	final ground surface flux
S_f	final degrees of saturation
S_0	initial degrees of saturation
$T_{\min}$	critical rainfall duration
T_w	time to saturate soil to wetting front depth
t	time

u_a	pore air pressure
u_w	pore water pressure
u_0	initial pore water pressure
u_1	final pore water pressure
$u_a - u_w$	matrix suction
v_i	infiltration rate of soil
x	coordinate in x direction
y	coordinate in y direction
y_s	depth of wetting front
z	coordinate in z direction
z_w	wetting front depth
β	slope angle
γ_{sat}	saturated unit weight of soil
γ_t	total unit weight of soil
γ_w	unit weight of water
$\bar{\gamma}$	average unit weight of soil
θ_0	initial volumetric water content
θ_1	final volumetric water content
θ_w	volumetric water content
σ_n	total normal stress
$\sigma_n - u_a$	net normal stress on slip surface
σ^s	suction stress
ϕ'	effective friction angle

ϕ^b angle indicating rate of increase in shear strength
related to matrix suction
 ψ soil suction

1. Introduction

Storm-induced landslides are common in many regions under tropical or subtropical climates, such as Hong Kong, Taiwan, Singapore, Japan and Brazil (Brand, 1984; Fourie, 1996). These slope failures may occur on natural slopes in a variety of materials, including residual and colluvial soils (Dai *et al.*, 2003; Fourie, 1996). Fill slopes, cut slopes and embankments may also be prone to this type of slope failure (Chen *et al.*, 2004; Day and Axten, 1989). These slope failures are normally shallow, with a depth of failure less than 3 m above the groundwater table, and generally of small volume on steep soil slopes of 30–50° (Dai *et al.*, 2003; Johnson and Sitar, 1990). Deep-seated landslides after rainfall are also reported (Gerscovich *et al.*, 2006; Gostelow, 1991).

Traditional slope stability analyses incorporate rainfall influences by changing the groundwater flow patterns with increasing pressure heads or a rising groundwater table. However, in many cases a rising groundwater table should not be assumed, since in many shallow failures there is not much evidence of a rise of the groundwater table (Fourie *et al.*, 1999). The failures are attributed mainly to the advance of a wetting front and the reduction of shear strength due to the decrease of matrix suction in the unsaturated soils (Fredlund and Rahardjo, 1993; Rahardjo *et al.*, 1995). Hence such failures would not be properly analysed using the traditional approaches (Fourie, 1996).

Numerous research studies have been conducted to investigate infiltration of rainwater into a slope, and slope stability under rainfall conditions. This paper therefore provides a concise review of existing research on these topics. Studies on seepage and infiltration analysis are first reviewed and discussed, with a focus on pore water pressure profiles in slopes. Recent developments in the analysis of slope stability under rainfall conditions are then summarised, and key findings from existing research about critical factors related to rain-induced landslides are summarised and discussed. Finally, several research topics are suggested for further study.

2. Mechanism of rainfall-induced landslides

It is generally recognised that rainfall-induced landslides are caused by changes in pore water pressures and seepage forces (Gerscovich *et al.*, 2006; Zhu and Anderson, 1998). Two distinct failure mechanisms have been observed and analysed for rainfall-induced landslides (Collins and Znidarcic, 2004). In the first mechanism, significant build-up of positive pressures is observed in a low area on the slope or along the soil/bedrock interface. Movements along the sliding surface lead to liquefaction along this surface, resulting in rapid movements, long run-out distances and finally a complete liquefaction of the failed mass (Wang and Sassa, 2001). The in situ stress path can be described by a

constant shear stress path (Anderson and Sitar, 1995). In the second mechanism, the soil is in the unsaturated state, and slope failure is due mainly to rainfall infiltration and a loss in shear strength when soil suctions are decreased or dissipated (Fourie *et al.*, 1999; Fredlund and Rahardjo, 1993).

Recently, Cascini *et al.* (2010) classified rainfall-induced shallow landslides based on the stages of failure. The failure stage is defined as the formation of a continuous shear surface through the entire soil mass. The post-failure stage is represented by the rapid generation of large plastic strains and the consequent sudden acceleration of the failed soil mass. Based on the acceleration of the failed mass, rainfall-induced shallow landslides can be classified as slide, slide to flow (slides turning into flows) and flowslide. Cascini *et al.* suggested that the eventual sudden acceleration of the failed mass in the post-failure stage is a consequence of the slope instability process: therefore the failure and post-failure stages should be analysed separately. This paper focuses mainly on a review of relevant studies of slope instability in the failure stage; analysis of slopes in the post-failure stage will be only briefly discussed in Section 6 on future research topics.

3. Infiltration analysis

Infiltration plays a significant role in the instability of slopes under rainfall conditions. The effect of seepage on slope stability is typically addressed in most analyses by calculating the factor of safety or critical depth for an infinite slope subject to seepage parallel to the slope surface. This type of analysis assumes that saturated steady-state flow is taking place over a given depth. In order to simplify the analysis as a worst-infiltration scenario, it is often assumed that the phreatic surface rises to coincide with the slope surface, and that the slope is completely saturated (Collins and Znidarcic, 2004). For such saturated slopes, additional infiltration is not possible, and rainfall will have no further effect on slope stability.

Field measurements of soil suction show that the soil suction will not necessarily be destroyed, even under long-term conditions of rainfall infiltration. In situ suction measurements were made throughout the year 1980 in a 30 m high, completely weathered rhyolite slope instrumented with tensiometers in Hong Kong (Sweeney, 1982). Matrix suction at shallow depths showed a gradual reduction during the rainy season, but, at 5–17 m depths, the soil suction remained constant throughout the year. The pore water pressures remained negative, even during the rainy season. For slopes that are initially unsaturated, the effect of rainfall at the slope surface will have a different effect. The pore water pressure pattern that develops in the soil will occur as a transient process as the infiltrating water moves downwards into the soil. The shear strength of the soil will depend on soil suction, and hence on the pore water pressure profile. The development of seepage forces in the slope will also depend on the evolution of the pore water pressure profile.

3.1 Conceptual infiltration model

A combination of Darcy's law as applied to unsaturated flow and the equation of continuity is considered the most robust method available for computing infiltration and soil moisture profiles in saturated–unsaturated soil systems. However, because of the natural spatial variability in the field, uncertain initial conditions and boundary conditions, the numerical solution to the partial differential equations is too complex for practical applications. In response to the limitations of complex numerical solutions, infiltration models based on a wetting front concept (Green and Ampt, 1911; Lumb, 1962; Mein and Larson, 1973; Sun *et al.*, 1998) have been proposed.

The Green–Ampt (Green and Ampt, 1911) infiltration model (Figure 1) was initially proposed to describe infiltration through partially saturated soil underlying ponded water, based on Darcy's law. Above the wetting front, the soil is assumed to be completely saturated, while the soil below the wetting front remains at the initial water content. It is assumed that the coefficient of permeability in the wetted zone, k_w , does not change with time, and that there is a constant soil suction just above the wetting front. According to the Green–Ampt model, the time necessary to saturate the soil to a depth z_w is

$$1. \quad T_w = \frac{\theta_1 - \theta_0}{k_w} \left[z_w - C_s \ln \left(\frac{C_s + z_w}{C_s} \right) \right]$$

where θ_0 is the initial volumetric water content before wetting, θ_1 is the final volumetric water content before wetting, k_w is the coefficient of permeability of the soil in the wetted zone and C_s is the wetting front capillary suction. The infiltration rate of soil at which water can enter the soil surface is

$$2. \quad v_i = k_w \frac{z_w + C_s}{z_w}$$

Figure 1. Illustration of Green–Ampt infiltration model

To consider the conditions in which rainfall intensity is initially less than the infiltration capacity of the soil, Mein and Larson (1973) modified the Green–Ampt model, and developed a simple two-stage model for predicting infiltration before and after surface ponding.

Lumb (1962) introduced the wetting front concept in relation to the investigation of slope failures in Hong Kong. Under prolonged and heavy rainfall, the depth, z_w , of the wetting front is defined as

$$3. \quad z_w = \frac{k_{sat} t}{n(S_f - S_0)}$$

where k_{sat} is the saturated coefficient of permeability, S_f is the final degree of saturation, S_0 is the initial degree of saturation, n is the porosity of the soil and t is time. Lumb's wetting front equation implies that ground surface flux q is equal to k_{sat} . In the case where rainfall is less intense, the advance of the wetting front will be slower than that given by Equation 3. Sun *et al.* (1998) proposed a generalised wetting band equation based on Lumb's (1962) equation. Figure 2 shows a typical variation of soil suction with depth in an unsaturated soil. For a given ground surface flux q_0 , less than k_{sat} under steady-state conditions, the pore water pressure is u_0 . If the ground surface flux is increased to q_1 , a new infiltration zone with pore water pressure u_1 will be formed that gradually progresses downwards with time. The depth of the wetting front can be calculated using the equation

$$4. \quad z_w = \frac{(k_1 - k_0)t}{\theta_1 - \theta_0}$$

where $k_0 = q_0$; $k_1 = q_1$; θ_0 is the initial volumetric water content,

Figure 2. Transient infiltration in an unsaturated soil (modified from Sun *et al.*, 1998)

which corresponds to u_0 ; and θ_1 is the final volumetric water content, which corresponds to u_1 . In the case where $k_1 = k_{\text{sat}}$ and is much greater than k_0 , Equation 4 reduces to Lumb's equation (Equation 3). Comparison between the predicted advance of the wetting front obtained from Equation 4 and that from numerical seepage analysis of unsaturated and saturated soils indicates that the extended wetting front equation (Equation 4) is reasonably accurate for intense rainfall events in which the transition zone or the wetting front is relatively sharp.

3.2 Analytical and numerical solutions

Serious limitations impose restrictions on the use of the conceptual infiltration models, because they usually do not consider sloping ground conditions, down-slope flows, variation of rainfall intensity or, most importantly, the dependence of soil permeability on moisture content (Ng and Shi, 1998b). In addition, there will not always be a distinct difference between the infiltration zone and the zone in which the negative pore water pressures have been maintained (the pore water pressure profile will be discussed in Section 3.3). To obtain a more rigorous distribution of pore water pressure in a slope under complex boundary conditions, the equations for the flow of water through an unsaturated-saturated soil system must be solved.

Based on Darcy's law and the mass conservation for water flow, the three-dimensional water flow in unsaturated soil can be described as (Fredlund and Rahardjo, 1993; Richards, 1931)

$$5. \quad \frac{\partial}{\partial x} \left(k \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial h}{\partial z} \right) = - \frac{\partial \theta_w}{\partial t}$$

where x, y, z are three Cartesian coordinates; θ_w is the volumetric water content; k is the unsaturated hydraulic conductivity or permeability; and h is the total head. The soil-water characteristic curve (SWCC, which is the relationship between soil suction, ψ , and the volumetric water content, θ_w), and the unsaturated permeability function ($\psi-k$) define the properties of unsaturated soils.

The solution of the above second-order partial differential equation is complicated, because the soil-water characteristic curve ($\psi-\theta_w$) and the unsaturated permeability function ($\psi-k$) are strongly non-linear. Analytical solutions, if available, have the advantages of explicitness and simplicity over numerical simulations (Zhan and Ng, 2001). Several analytical and quasi-analytical solutions to unsaturated flow problems without considering coupling effects have been developed. Basha (1999, 2000) used Green's function to derive multidimensional non-steady solutions for domains with prescribed surface flux boundary conditions and bottom boundary conditions. Chen *et al.* (2001) employed a Fourier integral transformation to obtain a series solution that has the merit of easy calculation. Srivastava and Yeh (1991) assumed that the soil-water characteristic curve and the unsaturated permeability function are both exponential, and presented analytical

solutions to the one-dimensional infiltration problem in a homogeneous soil layer and a two-layered soil system. With the same exponential equations for θ_w and k , Yuan and Lu (2005) further developed analytical solutions to transient flow in rooted, homogeneous soils with time-dependent varying surface fluxes.

Iverson (2000) approximated the governing equation (Equation 5) in a local rectangular Cartesian coordinate system for rainfall infiltration in a soil slope for the case of shallow soil and rainfall time shorter than the time necessary for the transmission of lateral water pressure. Assuming the soils are initially wet ($k \approx k_{\text{sat}}$), an analytical solution for pressure head was obtained. It was assumed the rainfall can infiltrate totally into the soil if the rainfall intensity is less than or equal to the saturated permeability. When the rainfall intensity is greater than the saturated permeability, the infiltration rate is equal to the saturated permeability, and the surplus rainfall runs off the slope as surface flow. This assumption is also adopted in some models for infiltration capacity prediction, such as the Green-Ampt infiltration model and the Mein-Larson model (Mein and Larson, 1973) model. The assumption may not be reasonable (Xue and Gavin, 2008), as both field measurements (Li *et al.*, 2005; Rahardjo *et al.*, 2005) and numerical modelling results (Gasmo *et al.*, 2000) have shown that this is not the case. Li *et al.* (2005) recorded the infiltration rate into a completely decomposed granite slope in Hong Kong during the rainy season in 2001. The saturated permeability of the soils is in the range 1×10^{-6} to 1×10^{-5} m/s. The rainfall intensity during the test period ranged from 2.8×10^{-7} to 2.3×10^{-6} m/s. The study showed that runoff began before the near-surface soils became fully saturated. Rahardjo *et al.* (2005) applied an artificial rainfall, 13×10^{-6} m/s in intensity, to an initially unsaturated soil slope with k_{sat} of 5.18×10^{-6} m/s and found that the infiltration capacity of the slope converged to 2.0×10^{-6} m/s ($\approx 0.4k_{\text{sat}}$). Results from Gasmo *et al.* (2000) showed that the initial infiltration rate can be larger than k_{sat} and gradually decreases to a steady-state value that is less than k_{sat} (Figure 3). Tsai and Yang (2006) showed that unrealistically high pressure heads obtained using Iverson's solution are due mainly to the overestimation of infiltration rate. They modified the boundary condition at the ground surface by assuming that the pressure at the slope surface is zero when ponding occurs, and applied the Crank-Nicolson Galerkin finite-element method (Gersho and Sani, 1998) together with an iterative procedure to solve the problem.

Because of the high non-linearity of hydraulic parameters involved in the governing equation of unsaturated flow, analytical solutions for the infiltration problem can be obtained only by making some assumptions, and under some given initial and boundary conditions (Zhan and Ng, 2001). The advantage of a numerical analysis is that it can incorporate more sophisticated and advanced models of soil hydraulic properties (Leong and Rahardjo, 1997a, 1997b). Numerous numerical studies (Blatz *et al.*, 2004; Gasmo *et al.*, 2000; Ng and Shi, 1998a; Rahardjo *et al.*, 2007; Rahimi *et al.*, 2010; Tsaparas *et al.*, 2002; Zhang *et al.*, 2004) have been carried out to simulate seepage and infiltration

Figure 3. Infiltration rate at the crest of a slope (Gasmo *et al.*, 2000; reprinted with permission from Elsevier)

in soil slopes under rainfall conditions. Computer programs that have been applied for numerical modelling of seepage and infiltration in unsaturated slopes include: Seep/W (Geo-slope Ltd, 2001a); SVflux (SoilVision System Ltd, 2001), as in Tami *et al.* (2004), Chen and Zhang (2006) and Zhang and Chen (2006); Flow3D (Gerscovich, 1994); and FEMWATER (Lin *et al.*, 1997), as in Ng *et al.* (2001). Of particular concern is that, when an interface between two porous media is present, preferential infiltration may take place along the interface (Chen and Zhang, 2006; Zhang and Chen, 2006). This may form a hazardous perched water table at a high elevation.

Many analytical and numerical studies have been conducted to investigate the pore water pressure profiles in soil slopes, and the controlling factors for slope instability under rainfall conditions. In the next section, the typical pore water pressure profiles based on these studies will be discussed. As the discussion about controlling factors for rainfall-induced landslides relates to both infiltration analysis and slope stability analysis, the major findings about controlling factors for rainfall-induced landslides from these studies will be summarised later in Section 5.

3.3 Pore water pressure profiles under rainfall condition

The wetting front concept provides a simplified methodology for considering changes in soil saturation (or matrix suction) under a change in rainfall conditions. However, there is not always a distinct difference between the infiltration zone and the zone where the negative pore water pressures have been maintained. Typical pore water pressure distributions under various ground surface fluxes are shown in Figure 4. Figure 4(a) illustrates the pore water pressure distributions for steady-state conditions.

According to Kisch (1959), the gradient of pore water pressure under steady-state conditions can be written as

$$6. \quad \frac{du_w}{dy} = \gamma_w [(q/k) - 1]$$

where γ_w is the unit weight of water.

Under hydrostatic conditions there is no ground flux. According to Equation 6, the gradient of the pore water pressure head is -1 , as shown in Figure 4(a). Whenever the magnitude of the ground surface flux q approaches the coefficient of permeability of the unsaturated soil, k , at a particular value of matrix suction, the pressure gradient is zero, as shown in Figure 4(a). Figures 4(b) and 4(c) show the pore water pressure profiles under transient seepage condition for the cases where $q/k_{sat} < 1$ and $q/k_{sat} \geq 1$ respectively. Infiltration under transient seepage conditions can be considered as a transitional state between the initial state and the final steady states. The initial states of the left diagrams in Figures 4(b) and 4(c) are the hydrostatic condition ($q = 0$). The initial states of the right diagrams in Figures 4(b) and 4(c) are a steady-state condition with ground flux q greater than zero. The time to reach the steady state is a function of the ground surface flux, the coefficient of permeability of the soil and the water storage of the soil. When the ground flux is less than the saturated coefficient of permeability (Figure 4(b)), the matrix suction in the unsaturated soil can decrease, but does not disappear. Only when the ground surface flux is equal to or greater than the saturated coefficient of permeability (Figure 4(c)) can the matrix suction be eliminated if the duration of the rainfall is long enough.

Rahardjo *et al.* (1995) suggested three idealised pore water pressure profiles for the non-hydrostatic condition (Figure 5). Profile a represents the situation where matrix suction is reduced to zero at the ground surface. Profile b represents the condition with a sharp wetting front with a depth of y_s . Profile c corresponds to the condition with a perched water table at depth y_s . According to Lee *et al.* (2009), the potential pore water pressure profile in a coarse-grained soil is profile b. The sharp wetting front in profile b is due mainly to the steep slopes of the soil-water characteristic curve and the permeability function for the soil. For fine-grained soils, the slopes of the soil-water characteristic curve and permeability function are generally gentler. Thus profile a can be considered as the potential pore water pressure profile in a fine-grained soil. The perched water table (profile c) commonly occurs in layered soils (Cho, 2009; Ng and Bruce, 2007). Most recently, Lee *et al.* (2009) proposed a rational approach to determine critical pore water pressure profiles, considering both major and antecedent rainfalls. They defined a rainfall as a major rainfall if the duration is less than 24 h. The antecedent rainfall is defined as a rainfall with duration greater than 1 day. Suction distributions (Figure 6) from nine rainfall patterns (i.e. 1-day, 2-day, 3-day, 5-day, 7-day, 14-day and

Figure 4. Typical pore water pressure files in an unsaturated soil with various ground surface fluxes: (a) steady-state condition; (b) transient condition, $q/k_{sat} < 1$; (c) transient condition, $q/k_{sat} \geq 1$

Figure 5. Possible pore water pressure profiles in a residual soil slope (modified from Rahardjo *et al.*, 1995. © 2008 NRC Canada or its licensors; reproduced with permission)

30-day antecedent rainfalls, plus two critical combinations of antecedent and major rainfalls) as well as the suction redistribution patterns can be used to determine the worst suction distribution for the assessment of slope stability based on unsaturated soil mechanics.

Although numerous field investigations (Blatz *et al.*, 2004; Cui *et al.*, 2005, 2010; Gasmol *et al.*, 1999; Kim and Lee, 2010; Li *et al.*, 2005; Li *et al.*, 2011; Lim *et al.*, 1996; Ng *et al.*, 2003; Rahardjo *et al.*, 2005; Tsaparas *et al.*, 2003; Tu *et al.*, 2009; Zhan *et al.*, 2007; Zhang *et al.*, 2000) and laboratory model tests (Huang *et al.*, 2008; Huat *et al.*, 2006; Li *et al.*, 2009b; Moriwaki

et al., 2004; Take *et al.*, 2004; Tohari *et al.*, 2007) have been conducted on soil moisture responses to rainfall, comparisons of measured and calculated pore water pressure profiles (Trandafir *et al.*, 2008) and changes in pore water pressure with time (Alonso *et al.*, 2003; Huat *et al.*, 2006; Lan *et al.*, 2003; Sako *et al.*, 2006) are still limited. It is very difficult to find a unique set of soil hydraulic parameters that could match all transient pore water pressure responses (Trandafir *et al.*, 2008). This is probably due to the large spatial variability and significant heterogeneity of in situ soils, the uncertain initial conditions and groundwater conditions, and the sensitivity of pore water pressure in soils to rainfall influx.

4. Slope stability analysis

4.1 Limit equilibrium method

Since initial failures due to rainfall infiltration often have small depth-to-length ratios, and form failure planes parallel to the slope surface, the use of infinite slope stability analysis for the evaluation of rainfall-induced landslides is justified, and is often preferred for its simplicity. The methods used in traditional infinite slope analysis (Duncan and Wright, 1995; Skempton and Deloy, 1957) must be modified to take into account the variation of the pore water pressure profile that results from the infiltration process. For an infinite slope with seepage parallel to the slope surface, the safety factor for the slip surface at depth H (Duncan and Wright, 1995; Skempton and Deloy, 1957) is

$$F_s = \frac{c'}{\gamma_{\text{sat}} H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} - \frac{m \gamma_w \tan \phi'}{\gamma_{\text{sat}} \tan \beta}$$

where F_s is the safety factor, c' is the effective cohesion, ϕ' is

Figure 6. Suction envelopes computed from PERISI model (Lee *et al.*, 2009; reprinted with permission from Elsevier)

the effective friction angle, β is the slope angle, γ_{sat} is the saturated unit weight of the soil and m is the distance from the groundwater table to the slip surface. Here the slip surface is below the groundwater table in the saturated zone.

Based on the extended Mohr–Coulomb failure criterion (Fredlund *et al.*, 1978), the safety factor of an unsaturated uniform soil slope can be expressed as (Cho and Lee, 2002)

$$8. \quad F_s = \frac{c' + (u_a - u_w) \tan \phi^b + (\sigma_n - u_a) \tan \phi'}{\gamma_t H \sin \beta \cos \beta}$$

where γ_t is the total unit weight of the soil, u_a is the pore air pressure, u_w is the pore water pressure, $u_a - u_w$ is the matrix suction, σ_n is the total normal stress, $\sigma_n - u_a$ is the net normal stress on the slip surface and ϕ^b is an angle indicating the rate of increase in shear strength related to matrix suction. Iverson (2000), Cho and Lee (2002) and Muntohar and Liao (2009) presented a safety factor equation considering the pore water pressure in the slope

$$9. \quad F_s = \frac{c'}{\gamma_t H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} - \frac{h_p \gamma_w \tan \phi'}{\gamma_t H \tan \beta}$$

where h_p is the pressure head at the slip surface. Equation 9 can be considered as a special case of Equation 8 with $\sigma_n - u_a = \gamma_t H \cos^2 \beta$, $u_a - u_w = -h_p \gamma_w$ and $\phi^b = \phi'$. The pressure head, h_p , is determined using analytical solutions (Iverson, 2000), or simply assumed to be the wetting front suction head in the Green–Ampt infiltration model (Cho and Lee, 2001; Muntohar and Liao, 2009). Rahardjo *et al.* (1995) presented safety factor equations for the different pore water pressure profiles in Figure 5.

For the hydrostatic condition

$$10. \quad F_s = \frac{c'}{\gamma_t H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} + \left(\frac{H_w}{H} - 1 \right) \left(\frac{\gamma_w}{\gamma_t} \right) \left(\frac{\tan \phi^b}{\tan \beta} \right)$$

For profile a (smooth wetting front)

$$11. \quad F_s = \frac{c'}{\gamma_t H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} + \left(\frac{H_w}{y_s} - 1 \right) \left(\frac{\gamma_w}{\gamma_t} \right) \left(\frac{\tan \phi^b}{\tan \beta} \right)$$

For profile b (sharp wetting front)

$$12. \quad F_s = \frac{c'}{\gamma_t H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta}$$

For profile c (perched water table)

$$13. \quad F_s = \frac{c'}{\gamma_t H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} - \left(\frac{\gamma_w}{\gamma_t} \right) \left(\frac{\tan \phi^b}{\tan \beta} \right)$$

where H_w is the depth of the groundwater table, and y_s is the depth of wetting front (Figure 5).

Lu and Godt (2008) developed an analytical framework for the stability of infinite slopes under steady unsaturated seepage conditions with the inclusion of the suction stress (Lu and Griffiths, 2004). A factor of safety under steady vertical seepage for both saturated and unsaturated conditions is given by

$$14. \quad F_s = \frac{c'}{\gamma_{\text{sat}} H \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} - \frac{\sigma^s \tan \phi'}{\gamma_{\text{sat}} H} (\tan \beta + \cot \beta)$$

where σ^s is the suction stress. The change in soil friction angle with depth, which was often omitted in the conventional slope stability analysis, can be considered in this framework.

Travis *et al.* (2010) developed the analytical solutions for the matrix suction and degree of saturation profiles under steady-state unsaturated infiltration flow, and coupled them with the equations of safety factor for an infinite slope. The general equation for the factor of safety for an infinite slope is

$$15. \quad F_s = \frac{c' + H \bar{\gamma}(H) \cos \beta \tan \phi' + \psi(H) \tan [\phi^b(H)]}{H \bar{\gamma}(H) \sin \beta}$$

where $\bar{\gamma}(H)$ is the average soil unit weight, which is a function of H . ψ and ϕ^b are also functions of H .

Besides the infinite slope-stability analysis method, two-dimensional methods of slices for slope stability are also widely adopted. The inputs required for the slope stability model are the geometry and soil profiles of the slope, the shear strength parameters and soil densities, and the pore water pressure distribution throughout the slope. The pore water pressure distributions used as input data in the limit equilibrium slope stability analysis can be classified into three types: calculated pore water pressure distribution from numerical seepage analyses

(Tsaparas *et al.*, 2002), assumed pore water pressure distribution based on the wetting front concept (Chen *et al.*, 2009) and actual field-measured pore water pressures (Gasmo *et al.*, 2000). Commercial software such as Slope/W (Geo-slope Ltd, 2001b) and Seep/W is often used. Other adopted computer programs for slope stability analysis include STABL (Chen *et al.*, 2009) and SVSlope (SoilVision System Ltd, 2010). Various methods of slices were chosen to calculate the safety factor of the slope, for example Bishop's simplified method with circular slip surfaces (Ng and Shi, 1998b; Rahardjo *et al.*, 2001, 2007; Tsaparas *et al.*, 2002), Morgenstern and Price's method (Blatz *et al.*, 2004; Cascini *et al.*, 2010), and Janbu's method with non-circular slip surfaces (Wilkinson *et al.*, 2002). The extended Mohr–Coulomb failure criterion (Fredlund *et al.*, 1978) is usually adopted. Stability charts for slope stability analysis under rainfall conditions based on the finite-element seepage analyses and limit equilibrium stability analyses were developed by Huat *et al.* (2006). These stability charts provide geotechnical engineers with a tool for rapid assessment of the safety factor in response to a rainfall event. However, special care should be taken when using these charts, as they were developed for a given range of soil parameters and rainfall conditions. For example, the saturated permeability in the study is between 10^{-8} and 10^{-6} m/s; the rainfall intensity is assumed to be the same as the saturated permeability; and the rainfall duration is 24 h.

Comparing the results from an infinite slope stability analysis together with the approximate method (Pradel and Raad, 1993) based on the Green–Ampt model and the numerical analysis together with the limit equilibrium method, Fourie *et al.* (1999) and Cho and Lee (2001) found that the approximate method is more conservative than the finite-element approach. The approximate method based on the Green–Ampt infiltration model predicts much less time for the wetting front to reach a critical depth within the soil, for a given rainfall event. The approximate method appears to provide a conservative approach for evaluating the susceptibility of a slope to instabilities resulting from prolonged infiltration. However, when using the approximate method it is essential that correct assumptions about the capillary suction at wetting front and ϕ^b be made (Fourie *et al.*, 1999; Kim *et al.*, 2004).

4.2 Coupled hydro-mechanical analysis

In the previously described methods of seepage analysis and slope stability analysis, the deformation of the soils in the slope during rainfall is not considered. The behaviour of a soil slope under rainfall conditions is closely related not only to the distribution of pore water pressure but also to the stress state during infiltration. Pore water pressure changes due to rainfall infiltration and seepage will lead to changes in stresses and, in turn, deformation of a soil. Conversely, stress changes will modify the seepage process, because soil hydraulic properties such as porosity, permeability and water storage capacity are affected by the changes in stresses. Hence the seepage and stress–deformation problems are strongly linked in unsaturated

soils under rainfall conditions (Zhang *et al.*, 2005). More rigorous solutions to the coupled governing equations for deformation and seepage should be obtained when the soils in the slope are considered deformable.

Because of the complexity of the governing equations, a numerical approach is usually adopted. Constitutive models for the hydro-mechanical behaviour of unsaturated soils can be divided into two groups: elastic models (Lloret *et al.*, 1987; Thomas and He, 1997) and elasto-plastic models (Chiu and Ng, 2003; Georgiadis, 2003; Thomas and He, 1998; Toll, 1990; Wheeler and Sivakumar, 1995; Wheeler *et al.*, 2003). Alonso and his colleagues have developed a series of coupled hydro-mechanical models with increasing complexity to deal with problems of the flow in saturated and unsaturated soil systems and the mechanical interaction associated with changes in soil suction (Alonso *et al.*, 2003; Lloret and Alonso, 1980; Olivella *et al.*, 1996). The general approach is to solve the continuity equations for air and water flow, coupled with mechanical equilibrium conditions. Improved understanding of the mechanical and hydraulic behaviour of unsaturated soils has resulted in improved constitutive relations. The computer codes developed include NOSAT (Alonso *et al.*, 1996) for coupled unsaturated flow-deformation analysis, and CODE BRIGHT (Olivella *et al.*, 1996) for thermo-hydro-mechanical coupled analysis in unsaturated soils. Problems such as moisture transfer and deformation behaviour of pavements under different climate conditions (Alonso *et al.*, 2002), the deformation and stability of a slope in overconsolidated clays under rainfall (Alonso *et al.*, 2003), and the deformation and seepage in an unsaturated expansive slope subjected to artificial rainfall infiltration (Zhan, 2003) have been solved using these computer codes.

Cho and Lee (2001) examined the process of infiltration into a soil slope due to rainfall and the mechanical behaviour of the slope using a two-dimensional finite-element flow-deformation coupled analysis program. The stress–strain relationship was formulated under the framework of elastic modelling. Void ratio was related with suction and net mean stress using the state surface equation (Lloret and Alonso, 1985). A hyperbolic model was assumed for the shear modulus. The extended Mohr–Coulomb failure criterion was adopted for unsaturated soil shear strength. Smith (2003) investigated the behaviour of unsaturated soil slopes under infiltration through numerical simulations of a slope in Tung Chung, Hong Kong. The Imperial College Finite Element Program (ICFEP) (Potts and Zdravkovic, 1999) was used for analysis. Chen *et al.* (2009) utilised the finite-element program ABAQUS (ABAQUS, 2001). The equivalent effective stress for unsaturated soil was calculated based on the pore pressure equation for unsaturated soil by Bishop and Blight (1963). Biot consolidation theory was adopted to calculate the pore water pressures in the soil. The elasto-plastic finite-element model with the Mohr–Coulomb yield criterion was adopted, which is similar to the approach by Cascini *et al.* (2010) using the code for coupled hydro-mechanical analysis GeHoMadrid (Mira McWilliams, 2002).

Since the stress state and pore water pressure can be obtained from the coupled hydro-mechanical modelling, a local safety factor (Alonso *et al.*, 2003) at a certain point in the slope or a global safety factor for the slope along a specified slip surface (Cho and Lee, 2001) can be readily calculated, based on the stress field obtained from numerical modelling. Alternatively, a finite-element method with the shear strength reduction technique (Cai and Ugai, 2004) can be used to obtain the safety factor of the slope, which is equal to the shear strength reduction factor just before the elasto-plastic finite-element analysis is unable to converge within a user-specified number of iterations.

Until now, analytical solutions for coupled hydro-mechanical modelling have been very limited. Wu and Zhang (2009) presented an analytical solution to one-dimensional coupled water infiltration and deformation, which is derived by adopting the exponential functional forms for soil–water characteristic curve and permeability function.

5. Controlling factors for rainfall-induced landslides

Analysis of seepage and infiltration in an unsaturated soil and slope stability can be readily performed using available computer programs. However, the results are sometimes difficult to interpret, because the analysis involves many parameters related to soil properties, slope geometry, groundwater condition, initial conditions and rainfall characteristics. The main objective of many research studies has been to separate the influence of the various factors, and determine the controlling parameters.

Slopes with a high slope angle, a high slope height and a shallow initial depth of groundwater table constitute the worst combination of factors for failure, and are more likely to fail as a result of rainfall (Ng and Shi, 1998b; Rahardjo *et al.*, 2007). According to Rahardjo *et al.* (2007), the slope geometry and the initial water table determine the initial safety factor, and the actual failure conditions are much affected by rainfall characteristics and properties of the soils in the slope. Therefore attention should be paid to soil properties and rainfall characteristics when dealing with rainfall-induced slope failures.

5.1 Soil properties

Based on either the extended Mohr–Coulomb failure criterion (Fredlund *et al.*, 1978) or the suction stress concept (Lu and Likos, 2004), it is generally accepted that the presence of soil suction will increase the shear strength of the soil and hence the safety factor of the slope (Fredlund and Rahardjo, 1993; Griffiths and Lu, 2005). Rahardjo *et al.* (1995) showed that the safety factor increases with an increase of ϕ^b , and that the increase of safety factor can be very significant when the slip surface is high above the groundwater table. According to Fredlund and Rahardjo (1993), the safety factor increases approximately linearly with the ratio ϕ^b/ϕ' . The safety factor continues to decrease until the rainfall stops, and the decrease in the safety factor is more substantial as the ratio ϕ^b/ϕ' increases.

According to Equation 5, the soil hydraulic properties related to rainfall-induced landslide include the soil–water characteristic curve and the unsaturated permeability function. Research studies show that the saturated permeability of soil has been considered one of the most important soil properties in rainwater infiltration. Tsaparas *et al.* (2002) (Figure 7) showed that for the same rainfall, the higher the value of k_{sat} , the greater the increment of pore water pressures from the initial conditions, and the deeper the wetting front will advance. Hence the safety factor of the slope with a higher value of k_{sat} is smaller. This observation is in agreement with the findings by Zhang *et al.* (2004) and Collins and Znidarcic (2004). The studies by Ng and Shi (1998b), however, showed that for soils with lower k_{sat} , the reduction of matrix suction and the rise of groundwater table are more significant. Hence the decrease of safety factor is more significant for soil slopes with lower k_{sat} . Results in Rahardjo *et al.* (2007) may be used to explain these contradictory conclusions about the influence of k_{sat} on slope stability. Figure 8(a) shows the relationship between rainfall intensity and minimum safety factor for a homogeneous slope (10 m high, slope angle of 45°) subject to rainfall for 24 h. For the same rainfall intensity, the effect of k_{sat} on the reduction of safety factor can be different. When the rainfall intensity is less than 10 mm/h, the minimum safety factor for the slope with soil type $f_{100,-6}$ ($k_{\text{sat}} = 10^{-6}$ m/s) is the lowest, followed by that of $f_{50,-5}$ ($k_{\text{sat}} = 10^{-5}$ m/s) and $f_{10,-4}$ ($k_{\text{sat}} = 10^{-4}$ m/s). When the rainfall intensity is greater than about 200 mm/h, the minimum safety factor for the slope with soil type $f_{50,-5}$ ($k_{\text{sat}} = 10^{-5}$ m/s) is the lowest. Figure 8(b) is plotted with I/k_{sat} as the x axis. It can be seen that, for the same I/k_{sat} , a higher value of k_{sat} corresponds to a lower safety factor. There-

Figure 7. Comparison of the pore water pressure profiles at the crest of a slope, at the end of the rainfall for different saturated coefficients of permeability (Tsaparas *et al.*, 2002; reprinted with permission from Elsevier)

Figure 8. Relationship between rainfall intensity and minimum factor of safety for homogeneous soil slope subjected to rainfall for 24 h (modified from Rahardjo *et al.*, 2007)

fore the ratio I/k_{sat} should be used rather than I to investigate the effect of soil hydraulic properties, which is consistent with suggestions by Kasim (1997), Zhang *et al.* (2004) and Lee *et al.* (2009).

5.2 Rainfall characteristics

Critical rainfall conditions to initiate slope failures are traditionally investigated using statistical approaches (Brand *et al.*, 1984; Dai and Lee, 2001; Finlay *et al.*, 1997; Lumb, 1975; Premchitt *et al.*, 1994; Pun *et al.*, 1999). For example, Brand *et al.* (1984) suggested that an intensity of about 70 mm/h appeared to be the threshold or critical rainfall intensity above which landslides would occur in Hong Kong, and a 24 h rainfall of less than 100 mm is very unlikely to result in a large number of landslides occurring in a short time. Kay and Chen (1995) proposed that the combination of maximum hourly rainfall and 24 h rainfall be used as an indicator of landslide activity. These studies are generally based on the assumption that there exists a direct relationship between the occurrence of landslides and the rainfall characteristics, in terms of rainfall intensity, duration, major rainfall and antecedent rainfall. However, the influence of initial geological and hydrological conditions and the physical process

of rainfall seepage and infiltration in a slope are not considered (Rahardjo *et al.*, 2007).

The effects of rainfall intensity, rainfall duration, rainfall pattern and antecedent rainfall on slope stability have been studied systematically through infiltration analysis and slope stability analysis. It is generally accepted that more intense rainfall can lead to more reduction of negative pore water pressure in the slope, and a more significant rise of the groundwater table (Ng and Shi, 1998b; Rahardjo *et al.*, 2007). However, rainfall intensity and duration are dependent parameters. For a certain return period, the rainfall intensity and duration follow a certain relationship, called the intensity–duration–frequency (IDF) curve (i.e. the relationship between the rainfall intensity and duration for various return periods), which can be determined from statistical analysis of regional rainfall data. Pradel and Raad (1993) proposed an approximate method based on the Green–Ampt model to determine the critical rainfall intensity and duration for a rainfall-induced slope failure. The critical rainfall duration T_{min} and intensity I_{min} must not be smaller than T_w (Equation 1) and v_i (Equation 2) respectively. The threshold rainfall intensity and duration for a given wetting front depth, z_w , therefore follows the relationship

$$14. \quad I_{min} = \frac{\theta_w - \theta_i}{T_{min}} \left[z_w - C_s \ln \left(\frac{C_s + z_w}{C_s} \right) \right] \left(\frac{C_s + z_w}{z_w} \right)$$

Combining this with the IDF curves, the rainfall that can saturate soil to the corresponding depth of wetting front can be determined (Figure 9). The curve of critical rainfall intensity and duration for coarse-grained soils is higher than that for fine-grained soils, as shown in Figure 9 (Cho and Lee, 2002; Pradel and Raad, 1993). Therefore a more significant storm with a longer return period will be needed to trigger failure in coarse-grained soil slopes than in fine-grained soil slopes. This probably explains why field observations indicate that soil slopes with high saturated permeability may be less likely to fail (Lumb, 1962; Pradel and Raad, 1993). Rahardjo *et al.* (2007) suggested that the threshold rainfall intensity can be determined by the maximum reduction of the factor of safety (I_{thr} in Figure 8). It was found that the threshold rainfall intensity is larger for soils with a higher k_{sat} , and that a rainfall intensity equal to k_{sat} will not necessarily produce the lowest safety factor. Based on their study, soil slopes with a high k_{sat} are more likely to be affected by short-duration, high-intensity rainfalls. By examining the critical suction distribution (defined as the lowest minimum suction value and deepest wetting front) under extreme rainfalls of a 10-year return period, Lee *et al.* (2009) suggested that the critical major rainfall can be determined based on the ratio I/k_{sat} .

Although contradictory conclusions are drawn about the relative role of antecedent rainfall in landslides for different regions (Brand *et al.*, 1984; Pitts, 1985), antecedent rainfall has usually been considered as an important factor to influence slope

Figure 9. Threshold rainfall capable of saturating the soil up to depth z_w based on the Green–Ampt model (modified; based on Cho and Lee, 2002; Pradel and Raad, 1993)

stability under rainfall, as the negative pore water pressure can be reduced by rain flux, and the slope can be marginally safe before the major rainfall (Ng and Shi, 1998b; Rahardjo *et al.*, 2001; Tsaparas *et al.*, 2002). Rahardjo *et al.* (2007) demonstrated (Figure 10) that, for the same rainfall intensity and the same slope angle, the rate of reduction in safety factor is the fastest for soil type $f_{10,-4}$ ($k_{sat} = 10^{-4}$ m/s), followed by soil types $f_{50,-5}$ ($k_{sat} = 10^{-5}$ m/s) and $f_{100,-6}$ ($k_{sat} = 10^{-6}$ m/s). After the rainfall ceases, F_s recovered fastest for soil type $f_{10,-4}$, followed by soil types $f_{50,-5}$ and $f_{100,-6}$. They deduced that the effect of antecedent rainfalls is more significant in affecting the stability of homogeneous soil slopes with low k_{sat} ($k_{sat} \leq 10^{-6}$ m/s) than those with high k_{sat} ($k_{sat} \geq 10^{-5}$ m/s). The conclusions are also in agreement with the findings from previous numerical studies by Tsaparas *et al.* (2002) and Cai and Ugai (2004), and field observations (Rahardjo *et al.*, 2001).

Ng *et al.* (2001) and Tsaparas *et al.* (2002) investigated the effect of different rainfall patterns on the pore water pressure response in slopes. According to Ng *et al.* (2001), for a 24 h rainfall with the same total rainfall amount, the pore water pressure increases most rapidly and significantly in response to the advance rainfall pattern, followed by the central pattern, and then the delayed pattern. This observation is consistent with the results in Tsai (2008). Ng *et al.* (2001) also found that the effect of rainfall pattern is less significant with increase in the depth of the slip surface, and under conditions of low rainfall intensity and long duration. Tsaparas *et al.* (2002) found that the changes of pore water pressure in the scenarios of short rain events followed by a period of no rain are more limited than that in the scenario of continuous rainfall, because the soils are able to drain during the period of no rain.

Figure 10. Effect of soil properties on variation of factor of safety with time for a homogeneous soil slope of constant slope height: (a) soil $f_{10,-4}$, $\alpha = 33.7^\circ$; (b) soil $f_{50,-5}$, $\alpha = 33.7^\circ$; (c) soil $f_{100,-6}$, $\alpha = 33.7^\circ$ (Rahardjo *et al.*, 2007; reproduced with permission from ASCE)

6. Future research topics

6.1 Mechanism of transition from rainfall-induced slide to flow

Rainfall-triggered slope failures may sometimes result in debris that travels a considerable distance on the sloping terrain below the debris source (Dai *et al.*, 1999). The transition from a slide to flow has been attributed to static liquefaction in saturated soils (Anderson and Sitar, 1995; Cheuk *et al.*, 2005; Wang and Sassa, 2001). Infiltration and near-surface flow create an increase in pore

water pressure that causes the stress path to move nearly horizontally to intersect a failure envelope, initiating a slope failure. A debris flow is then mobilised when the soil is in a loose state, and the onset of large shear strains causes a rapid reduction in strength associated with undrained failure (Anderson and Sitar, 1995). In unsaturated loose soils, suction decrease and coupled volumetric collapse may be involved in the failure process (Olivares and Picarelli, 2003). Localised transient pore water pressures due to particular hydraulic boundary conditions may also be a triggering mechanism for the transition from slide to flow. Experimental evidence from centrifuge model tests (Take *et al.*, 2004), however, has indicated that static liquefaction is unlikely to occur if the soil is unsaturated and the depth to bedrock is large. From the existing literature, the mechanism of a rain-induced slide turning into debris flow is not fully understood. Geomechanical modelling that might utilise existing findings about strain-softening soils (e.g. Potts *et al.*, 1997) should be conducted to model the transition from slide to flow, and further experimental studies are needed to verify the hypothetical failure mechanisms and provide a rational approach to analysing rainfall-induced landslides in both the failure stage and the post-failure stage.

6.2 Infiltration in heterogeneous media

The assumption of uniform porous media normally adopted in infiltration analysis is not actually valid for natural soil slopes. Soils often exhibit a variety of heterogeneities, such as fractures, cracks, macropores of biotic origin, and interaggregate pores (Novak *et al.*, 2000; Zhang and Li, 2010). Preferential flow due to anisotropy of hydraulic conductivity or due to flow through relic joints may be present in natural soils (Zhang *et al.*, 2000). Ignoring the infiltration of water by way of soil cracks into the soil matrix usually leads to severely underestimated infiltration rates, too high predictions of water accumulating at or near the soil surface, overestimation of surface runoff, and, consequently, unrealistic descriptions of the soil water regime (Novak *et al.*, 2000). If tubular voids or passageways in soil, which are called soil pipes, are blocked or close-ended, localised increases in pore water pressures can be generated, which may be sufficient to trigger landslides (Pierson, 1983). Bedrock is also considered to contribute to the rapid development of positive pore water pressure within the soil mass (Gerscovich *et al.*, 2006). Most of the models that have been used to simulate water flow in unsaturated fractured media are continuum mechanics methods (Gerke and van Genuchten, 1993). The continuum models face difficulties when the flow occurring on small scales within the unsaturated soils results in strong heterogeneity in the spatial distributions of pressure and flux. Hence further study on the numerical simulation of flow in discrete fracture networks under unsaturated conditions is needed. In addition, more well-instrumented rainfall infiltration tests and calibration of prediction models should be conducted to provide better understanding of rainfall infiltration in heterogeneous media, quantify the model errors, and enhance engineers' confidence in rational infiltration analysis.

6.3 Role of cracks in rain-induced slope instability

The presence of cracks in a slope decreases the shear strength of the slope soils and increases the hydraulic conductivity of the soils. Water-filled cracks also lead to additional driving forces. In addition, the cracks may form part of the slip surface when landslide occurs. Therefore cracks have an important influence on slope stability, and analysis of the stability of slopes with cracks can help in understanding the mechanisms of rainfall-induced landslides. Existing research studies on basic properties of cracks, the formation of cracks in soils, and flow in fractured media (Li *et al.*, 2009a; Li and Zhang, 2010; Morris *et al.*, 1992; Novak *et al.*, 2000; Peron *et al.*, 2009) provide a basis for analysing the influence of cracks on slope stability. Further studies are needed on the influence on slope stability of the characteristics of the crack, such as type, location, density, aperture, length and depth.

6.4 Consideration of uncertainties

A large number of uncertainties are involved in the analysis of rainfall infiltration and slope stability, including the geological formation of the slope, spatial variability of soils, uncertainty in boundary conditions and initial conditions, measurement errors, sampling errors and prediction model errors. Uncertainties in model parameters and soil spatial variability can lead to significant errors in predicted pore water pressure profiles and the estimated safety factor of the slope (Zhang *et al.*, 2003). Very limited research studies on stochastic analysis of rainfall-induced slope instability (Chan, 2001; Zhang *et al.*, 2005) have been conducted, owing to the complexity of the problem. Further efforts are needed to quantify the uncertainties and understand the propagation of these uncertainties in the analysis of rainfall infiltration and slope stability, to make such analysis more robust in engineering applications.

7. Summary

This paper has presented a concise review of existing research on infiltration analysis and slope stability analysis for rainfall-induced slope failures. Seepage and infiltration analysis with conceptual models, analytical analysis and numerical modelling are summarised, with a discussion of the typical pore water pressure profiles in the slope. Recent developments in the limit equilibrium method and the coupled hydro-mechanical modelling for slope stability under rainfall conditions are also presented. From this review, substantial progress has been made in the investigation of changes in pore water pressures and critical hydrological factors related to rainfall-induced landslides. Further efforts must be made to better understand the mechanisms of transition from rainfall-induced slide to flow, infiltration in heterogeneous media and the role of cracks in rain-induced slope instability.

Acknowledgements

The work in this paper was substantially supported by grants from the Natural Science Foundation of China (Project No. 50809038), the Shanghai Educational Development Foundation (Project No. 2008CG17), the PhD Programs Foundation of the

Ministry of Education of China (Project No. 200802481128), the Shanghai Leading Academic Discipline Project (Project No. B208) and the Research Grants Council (RGC) of the Hong Kong Special Administration Region (Project No. 622210).

REFERENCES

- ABAQUS (2001) *Standard User's Manual v6.1*. Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA.
- Alonso EE, Canete A and Olivella S (2002) Moisture transfer and deformation behaviour of pavements: effect of climate, materials and drainage. In *Unsaturated Soils: Proceedings of the 3rd International Conference on Unsaturated Soils, Recife* (Jucá JFT, de Campos TMP and Marinho FAM (eds)). Swets & Zeitlinger, Lisse, the Netherlands, vol. 2, pp. 671–677.
- Alonso EE, Gens A and Delahaye CH (2003) Influence of rainfall on the deformation and stability of a slope in overconsolidated clays: a case study. *Hydrogeology Journal* **11**(1): 174–192.
- Alonso EE, Lloret A and Romero E (1996) Rainfall induced deformation of road embankments. In *Landslides: Proceedings of the 7th International Symposium on Landslides, Trondheim, Norway* (Senneset K (ed.)). Balkema, Rotterdam, the Netherlands, vol. 1, pp. 97–108.
- Anderson SA and Sitar N (1995) Analysis of rainfall-induced debris flows. *Journal of Geotechnical Engineering, ASCE* **121**(7): 544–552.
- Basha HA (1999) Multidimensional linearised nonsteady infiltration with prescribed boundary conditions at the soil surface. *Water Resources Research* **35**(1): 75–83.
- Basha HA (2000) Multidimensional linearised nonsteady infiltration toward a shallow water table. *Water Resources Research* **36**(9): 2567–2573.
- Bishop AW and Blight GE (1963) Some aspects of effective stress in saturated and unsaturated soils. *Géotechnique* **13**(3): 177–197.
- Blatz JA, Ferreira NJ and Graham J (2004) Effects of near-surface environmental conditions on instability of an unsaturated soil slope. *Canadian Geotechnical Journal* **41**(6): 1111–1126.
- Brand EW (1984) Landslides in South Asia: a state-of-art report. In *Proceedings of the 4th International Symposium on Landslides, Toronto*. Balkema, Rotterdam, the Netherlands, vol. 1, pp. 17–59.
- Brand EW, Premchitt J and Phillipson HB (1984) Relationship between rainfall and landslides. In *Proceedings of the 4th International Symposium on Landslides, Toronto*. Balkema, Rotterdam, the Netherlands, vol. 1, pp. 377–384.
- Cai F and Ugai K (2004) Numerical analysis of rainfall effects on slope stability. *International Journal of Geomechanics* **4**(2): 69–78.
- Cascini L, Cuomo S, Pastor M and Sorbin G (2010) Modelling of rainfall-induced shallow landslides of the flow-type. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(1): 85–98.
- Chan CC (2001) *Stochastic Analysis of Infiltration and Slope Stability Considering Uncertainties in Soil-Water Retention and Shear Strength Parameters*. MPhil thesis, Hong Kong University of Science and Technology, Hong Kong.
- Chen H, Lee CF and Law KT (2004) Causative mechanisms of rainfall-induced fill slope failures. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **130**(6): 593–602.
- Chen JM, Tan YC and Chen CH (2001) Multidimensional infiltration with arbitrary surface fluxes. *Journal of Irrigation and Drainage Engineering, ASCE* **127**(6): 370–377.
- Chen Q and Zhang LM (2006) Three-dimensional analysis of water infiltration into the Gouhou rockfill dam using saturated-unsaturated seepage theory. *Canadian Geotechnical Journal* **43**(5): 449–461.
- Chen RH, Chen HP, Chen KS and Zhung HB (2009) Simulation of a slope failure induced by rainfall infiltration. *Environmental Geology* **58**(5): 943–952.
- Cheuk CY, Ng CWW and Sun HW (2005) Numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects. *Computers and Geotechnics* **32**(4): 290–303.
- Chiu CF and Ng CWW (2003) A state-dependent elasto-plastic model for saturated and unsaturated soils. *Géotechnique* **53**(9): 809–829.
- Cho SE (2009) Infiltration analysis to evaluate the surficial stability of two-layered slopes considering rainfall characteristics. *Engineering Geology* **105**(1–2): 32–43.
- Cho SE and Lee SR (2001) Instability of unsaturated soil slopes due to infiltration. *Computers and Geotechnics* **28**(3): 185–208.
- Cho SE and Lee SR (2002) Evaluation of surficial stability for homogeneous slopes considering rainfall characteristics. *Journal of Geotechnical and Geoenvironmental Engineering* **128**(9): 756–763.
- Collins BD and Znidarcic D (2004) Stability analyses of rainfall induced landslides. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **130**(4): 362–372.
- Cui YJ, Gao YB and Ferber V (2010) Simulating the water content and temperature changes in an experimental embankment using meteorological data. *Engineering Geology* **114**(3–4): 456–471.
- Cui YJ, Lu YF, Delage P and Riffard M (2005) Field simulation of in situ water content and temperature changes due to ground-atmospheric interactions. *Géotechnique* **55**(7): 557–567.
- Dai FC and Lee CF (2001) Frequency-volume relation and prediction of rainfall-induced landslides. *Engineering Geology* **59**(3–4): 253–266.
- Dai FC, Lee CF and Wang SJ (1999) Analysis of rainstorm-induced slide-debris flows on natural terrain of Lantau Island, Hong Kong. *Engineering Geology* **51**(4): 279–290.
- Dai FC, Lee CF and Wang SJ (2003) Characterization of rainfall-induced landslides. *International Journal of Remote Sensing* **24**(23): 4817–4834.
- Day RW and Axten GW (1989) Surficial stability of compacted clay slopes. *Journal of Geotechnical Engineering, ASCE* **115**(4): 577–580.
- Duncan JM and Wright SG (1995) *Soil Strength and Slope Stability*. Wiley, Hoboken, NJ, USA.
- Finlay PJ, Fell R and Maguire PK (1997) The relationship between

- the probability of landslide occurrence and rainfall. *Canadian Geotechnical Journal* **34**(6): 811–824.
- Fourie AB (1996) Predicting rainfall-induced slope instability. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **119**(4): 211–218.
- Fourie AB, Rowe D and Blight GE (1999) The effect of infiltration on the stability of the slopes of a dry ash dump. *Géotechnique* **49**(1): 1–13.
- Fredlund DG, Morgenstern NR and Widger RA (1978) The shear strength of unsaturated soils. *Canadian Geotechnical Journal* **15**(3): 313–321.
- Fredlund DG and Rahardjo H (1993) *Soil Mechanics for Unsaturated Soils*. Wiley, New York, NY, USA.
- Gasmo J, Hritzuk KJ, Rahardjo H and Leong EC (1999) Instrumentation of an unsaturated residual soil slope. *Geotechnical Testing Journal* **22**(2): 134–143.
- Gasmo JM, Rahardjo H and Leong EC (2000) Infiltration effects on stability of a residual soil slope. *Computers and Geotechnics* **26**(2): 145–165.
- Geo-slope Ltd (2001a) *Seep/W for Finite Element Seepage Analysis: User's Guide*. Geo-Slope Ltd, Calgary, Canada.
- Geo-slope Ltd (2001b) *Slope/W for Slope Stability Analysis: User's Guide*. Geo-Slope Ltd, Calgary, Canada.
- Georgiadis K (2003) *Development, Implementation and Application of Partially Saturated Soil Models in Finite Element Analysis*. PhD thesis, Imperial College of Science, Technology and Medicine, University of London, UK.
- Gerke HH and van Genuchten MT (1993) A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. *Water Resources Research* **29**(2): 305–319.
- Gerscovich DMS (1994) *Flow Through Saturated-Unsaturated Porous Media: Numerical Modelling and Slope Stability Studies of Rio de Janeiro Natural Slopes*. PhD thesis, Catholic University of Rio de Janeiro, Brazil.
- Gerscovich DMS, Vargas EA and de Campos TMP (2006) On the evaluation of unsaturated flow in a natural slope in Rio de Janeiro, Brazil. *Engineering Geology* **88**(1–2): 23–40.
- Gersho PM and Sani RL (1998) *Incompressible Flow and the Finite-Element Method*. Wiley, New York, USA.
- Gostelow TP (1991) Rainfall and landslides. In *Prevention and Control of Landslides and Other Movements* (Almeida-Teixeira ME, Fantechi R, Oliveira R and Gomes Coelho A (eds)). European Commission, Brussels, Belgium, CEC Report Eur 12918 EN, pp. 139–161.
- Green WH and Ampt CA (1911) Studies on soil physics: flow of air and water through soils. *Journal of Agricultural Science* **4**: 1–24.
- Griffiths DV and Lu N (2005) Unsaturated slope stability analysis with steady infiltration or evaporation using elasto-plastic finite elements. *International Journal for Numerical and Analytical Methods in Geomechanics* **29**(3): 249–267.
- Huang CC, Ju YJ, Hwu LK and Lee JL (2009) Internal soil moisture and piezometric responses to rainfall-induced shallow slope failures. *Journal of Hydrology* **370**(1–4): 39–51.
- Huang CC, Lo CL, Jang JS and Hwu LK (2008) Internal soil moisture response to rainfall-induced slope failures and debris discharge. *Engineering Geology* **101**(3–4): 134–145.
- Huat BBK, Ali FH and Low TH (2006) Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. *Geotechnical and Geological Engineering* **24**(5): 1293–1306.
- Iverson RM (2000) Landslide triggering by rain infiltration. *Water Resources Research* **36**(7): 1897–1910.
- Johnson Ka and Sitar N (1990) Hydrologic conditions leading to debris-flow initiation. *Canadian Geotechnical Journal* **27**(6): 789–801.
- Kasim FB (1997) *Effects of Steady State Rainfall on Long Term Matric Suction Conditions in Slopes*. Unsaturated Soils Group, University of Saskatchewan, Saskatoon, Canada.
- Kay JN and Chen T (1995) Rainfall–landslide relationship for Hong Kong. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **113**(2): 117–118.
- Kim J, Jeong S, Park S and Sharma J (2004) Influence of rainfall-induced wetting on the stability of slopes in weathered soils. *Engineering Geology* **75**(3–4): 251–262.
- Kim YK and Lee SR (2010) Field infiltration characteristics of natural rainfall in compacted roadside slopes. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(1): 248–252.
- Kisch M (1959) The theory of seepage from clay-blanketed reservoirs. *Géotechnique* **9**(1): 9–21.
- Lan HX, Zhou CH, Lee CF, Wang SJ and Wu FQ (2003) Rainfall-induced landslide stability analysis in response to transient pore pressure: a case study of natural terrain landslide in Hong Kong. *Science in China Series E: Engineering and Materials Science* **46**(S1): 52–68.
- Lee LM, Gofar N and Rahardjo H (2009) A simple model for preliminary evaluation of rainfall-induced slope instability. *Engineering Geology* **108**(3–4): 272–285.
- Leong EC and Rahardjo H (1997a) Permeability functions for unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering* **123**(12): 1118–1126.
- Leong EC and Rahardjo H (1997b) Review of soil-water characteristic curve equations. *Journal of Geotechnical and Geoenvironmental Engineering* **123**(12): 1106–1117.
- Li AG, Yue ZQ, Tham LG, Lee CF and Law KT (2005) Field-monitored variations of soil moisture and matric suction in a saprolite slope. *Canadian Geotechnical Journal* **42**(1): 13–26.
- Li JH and Zhang LM (2010) Geometric parameters and REV of a crack network in soil. *Computers and Geotechnics* **37**(4): 466–475.
- Li JH, Zhang LM, Wang Y and Fredlund DG (2009a) Permeability tensor and representative elementary volume of saturated cracked soil. *Canadian Geotechnical Journal* **46**(8): 928–942.
- Li JH, Zhang LM and Kwong BCP (2011) Field permeability at

- shallow depth in a compacted fill. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **164**(3): 211–221.
- Li X, Zhang LM and Fredlund DG (2009b) Wetting front advancing column test for measuring unsaturated hydraulic conductivity. *Canadian Geotechnical Journal* **46**(12): 1431–1445.
- Lim TT, Rahardjo H, Chang MF and Fredlund DG (1996) Effect of rainfall on matric suctions in a residual soil slope. *Canadian Geotechnical Journal* **33**(4): 618–628.
- Lin HC, Richards DR, Talbot CA, Yeh GT, Cheng JR, Cheng HP and Jones NL (1997) *Femwater: A Three-Dimensional Finite Element Computer Model for Simulation of Density-Dependent Flow and Transport in Variably Saturated Media*. United States Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS, USA, Technical Report CHI-97-12.
- Lloret A and Alonso EE (1980) Consolidation of unsaturated soils including swelling and collapse behaviour. *Géotechnique* **30**(4): 449–477.
- Lloret A and Alonso EE (1985) State surfaces for partially saturated soils. In *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco*. Taylor & Francis, Abingdon, UK, vol. 2, pp. 557–562.
- Lloret A, Gens A, Batlle F and Alonso EE (1987) Flow and deformation analysis of partially saturated soils. In *Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin* (Hanrahan ET, Orr TLL and Widdis TF (eds)). Balkema, Rotterdam, the Netherlands, vol. 2, pp. 565–568.
- Lu N and Godt J (2008) Infinite slope stability under steady unsaturated seepage conditions. *Water Resources Research* **44**(11), w11404, doi:10.1029/2008wr006976
- Lu N and Griffiths DV (2004) Profiles of steady-state suction stress in unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering* **130**(10): 1063–1076.
- Lu N and Likos WJ (2004) *Unsaturated Soil Mechanics*. Wiley, Hoboken, NJ, USA.
- Lumb P (1962) Effect of rain storms on slope stability. *Proceedings of the symposium on Hong Kong Soils, Hong Kong*, pp. 73–87.
- Lumb P (1975) Slope failures in Hong Kong. *Quarterly Journal of Engineering Geology* **8**(1): 31–65.
- Mein RG and Larson CL (1973) Modelling infiltration during a steady rain. *Water Resources Research* **9**(2): 384–394.
- Mira McWilliams P (2002) *Análisis por Elementos Finitos de Problemas de Rotura en Geomateriales*. PhD thesis, Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, Spain (in Spanish).
- Moriwaki H, Inokuchi T, Hattanji T, Sassa K, Ochiai H and Wang G (2004) Failure processes in a full-scale landslide experiment using a rainfall simulator. *Landslides* **1**(4): 277–288.
- Morris PH, Graham J and Williams DJ (1992) Cracking in drying soils. *Canadian Geotechnical Journal* **29**(2): 263–277.
- Muntohar AS and Liao HJ (2009) Analysis of rainfall-induced infinite slope failure during typhoon using a hydrological-geotechnical model. *Environmental Geology* **56**(6): 1145–1159.
- Ng CWW and Bruce KM (2007) *Advanced Unsaturated Soil Mechanics and Engineering*. Taylor & Francis, Abingdon, UK.
- Ng CWW and Shi Q (1998a) Influence of rainfall intensity and duration on slope stability in unsaturated soils. *Quarterly Journal of Engineering Geology* **31**(2): 105–113.
- Ng CWW and Shi Q (1998b) Numerical investigation of the stability of unsaturated soil slopes subjected to transient seepage. *Computers and Geotechnics* **22**(1): 1–28.
- Ng CWW, Wang B and Tung YK (2001) Three-dimensional numerical investigations of groundwater responses in an unsaturated slope subjected to various rainfall patterns. *Canadian Geotechnical Journal* **38**(5): 1049–1062.
- Ng CWW, Zhan LT, Bao CG, Fredlund DG and Gong BW (2003) Performance of an unsaturated expansive soil slope subjected to artificial rainfall infiltration. *Géotechnique* **53**(2): 143–157.
- Novak V, Simunek J and van Genuchten MT (2000) Infiltration of water into soil with cracks. *Journal of Irrigation and Drainage Engineering, ASCE* **126**(1): 41–47.
- Olivares L and Picarelli L (2003) Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils. *Géotechnique* **53**(2): 283–287.
- Olivella S, Gens A, Carrera J and Alonso EE (1996) Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. *Engineering Computations* **13**(7): 87–112.
- Peron H, Delenne JY, Laloui L and El Yousoufi MS (2009) Discrete element modelling of drying shrinkage and cracking of soils. *Computers and Geotechnics* **36**(1–2): 61–69.
- Pierson TC (1983) Soil pipes and slope stability. *Quarterly Journal of Engineering Geology and Hydrogeology* **16**(1): 1–11.
- Pitts J (1985) *An Investigation of Slope Stability on the NTI Campus, Singapore*. Nanyang Technological Institute, Singapore, Applied Research Project RPI/83.
- Potts DM, Kovacevic N and Vaughan PR (1997) Delayed collapse of cut slopes in stiff clay. *Géotechnique* **47**(5): 953–982.
- Potts DM and Zdravkovic LT (1999) *Finite Element Analysis in Geotechnical Engineering: Theory*. Thomas Telford, London, UK.
- Pradel D and Raad G (1993) Effect of permeability on surficial stability of homogeneous slopes. *Journal of Geotechnical Engineering* **109**(1): 62–70.
- Premchitt J, Brand EW and Chen PYM (1994) Rain-induced landslides in Hong Kong. *Asia Engineer* **22**(6): 43–51.
- Pun WK, Wong ACW and Pang PLR (1999) *Review of Landslip Warning Criteria*. Geotechnical Engineering Office, The Government of the Hong Kong Special Administrative Region, Special Project Report SPR 4/99.

- Rahardjo H, Lee T, Leong E and Rezaury R (2005) Response of a residual soil slope to rainfall. *Canadian Geotechnical Journal* **42**(2): 340–351.
- Rahardjo H, Li XW, Toll DG and Leong EC (2001) The effect of antecedent rainfall on slope stability. *Geotechnical and Geological Engineering* **19**(3–4): 371–399.
- Rahardjo H, Lim TT, Chang MF and Fredlund DG (1995) Shear strength characteristics of a residual soil. *Canadian Geotechnical Journal* **32**(1): 60–77.
- Rahardjo H, Ong TH, Rezaury RB and Leong EC (2007) Factors controlling instability of homogeneous soil slopes under rainfall. *Journal of Geotechnical and Geoenvironmental Engineering* **133**(12): 1532–1543.
- Rahimi A, Rahardjo H and Leong EC (2010) Effect of hydraulic properties of soil on rainfall-induced slope failure. *Engineering Geology* **114**(3–4): 135–143.
- Richards LA (1931) Capillary conduction of liquids through porous mediums. *Physics* **1**: 318–333.
- Sako K, Kitamura R and Fukagawa R (2006) Study of slope failure due to rainfall: a comparison between experiment and simulation. In *Unsaturated Soils 2006* (Miller GA, Zapata CE, Houston SL and Fredlund DG (eds)). American Society of Civil Engineers, Reston, VA, USA, Geotechnical Special Publication No. 147, pp. 2324–2335.
- Skempton AW and Deloy FA (1957) Stability of natural slopes in London Clay. *Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering*, vol. 2, pp. 378–381.
- Smith PGC (2003) *Numerical Analysis of Infiltration into Partially Saturated Soil Slopes*. PhD thesis, Imperial College of Science, Technology and Medicine, University of London, UK.
- SoilVision System Ltd (2001) *SVFlux User's Manual*. SoilVision System Ltd, Saskatoon, Canada.
- SoilVision System Ltd (2010) *SVSlope User's Manual*. SoilVision System Ltd, Saskatoon, Canada.
- Srivastava R and Yeh TCJ (1991) Analytical solutions for one dimension transient infiltration toward the water table in homogeneous and layered soils. *Water Resources Research* **27**(5): 753–762.
- Sun HW, Wong HN and Ho KKS (1998) Analysis of infiltration in unsaturated ground. In *Slope Engineering in Hong Kong* (Li KS, Kay JN and Ho KKS (eds)). Balkema, Rotterdam, the Netherlands, pp. 101–109.
- Sweeney DJ (1982) Some in situ soil suction measurements in Hong Kong's residual soil slopes. In *Proceedings of the 7th Southeast Asian Geotechnical Conference, Hong Kong*. Southeast Asian Geotechnical Society and Hong Kong Institution of Engineers, Hong Kong, vol. 1, pp. 91–106.
- Take WA, Bolton MD, Wong PCP and Yeung FJ (2004) Evaluation of landslide triggering mechanisms in model fill slopes. *Landslides* **1**(3): 173–184.
- Tami D, Rahardjo H and Leong EC (2004) Effects of hysteresis on steady-state infiltration in unsaturated slopes. *Journal of Geotechnical and Geoenvironmental Engineering* **130**(9): 956–967.
- Thomas HR and He Y (1997) A coupled heat-moisture transfer theory for deformable unsaturated soil and its algorithmic implementation. *International Journal for Numerical Methods in Engineering* **40**(18): 3421–3441.
- Thomas HR and He Y (1998) Modelling the behaviour of unsaturated soil using an elastoplastic constitutive model. *Géotechnique* **48**(5): 589–603.
- Tohari A, Nishigaki M and Komatsu M (2007) Laboratory rainfall-induced slope failure with moisture content measurement. *Journal of Geotechnical and Geoenvironmental Engineering* **133**(5): 575–587.
- Toll DG (1990) A framework for unsaturated soil behaviour. *Géotechnique* **40**(1): 31–44.
- Trandafir AC, Sidle RC, Gomi T and Kamai T (2008) Monitored and simulated variations in matric suction during rainfall in a residual soil slope. *Environmental Geology* **55**(5): 951–961.
- Travis QB, Houston SL, Marinho FAM and Schmeeckle M (2010) Unsaturated infinite slope stability considering surface flux conditions. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(7): 963–974.
- Tsai TL (2008) The influence of rainstorm pattern on shallow landslide. *Environmental Geology* **53**(7): 1563–1569.
- Tsai TL and Yang JC (2006) Modelling of rainfall-triggered shallow landslide. *Environmental Geology* **50**(4): 525–534.
- Tsaparas I, Rahardjo H, Toll DG and Leong EC (2002) Controlling parameters for rainfall-induced landslides. *Computers and Geotechnics* **29**(1): 1–27.
- Tsaparas I, Rahardjo H, Toll DG and Leong EC (2003) Infiltration characteristics of two instrumented residual soil slopes. *Canadian Geotechnical Journal* **40**(5): 1012–1032.
- Tu XB, Kwong AKL, Dai FC, Tham LG and Min H (2009) Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. *Engineering Geology* **105**(1–2): 134–150.
- Wang G and Sassa K (2001) Factors affecting rainfall-induced flowslides in laboratory flume tests. *Géotechnique* **51**(7): 587–599.
- Wheeler SJ, Sharma RS and Buisson MSR (2003) Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. *Géotechnique* **53**(1): 41–54.
- Wheeler SJ and Sivakumar V (1995) An elasto-plastic critical state framework for unsaturated soil. *Géotechnique* **45**(1): 35–53.
- Wilkinson PL, Anderson MG and Lloyd DM (2002) An integrated hydrological model for rain-induced landslide prediction. *Earth Surface Processes and Landforms* **27**(12): 1285–1297.
- Wu LZ and Zhang LM (2009) Analytical solution to 1d coupled water infiltration and deformation in unsaturated soils. *International Journal for Numerical and Analytical Methods in Geomechanics* **33**(6): 773–790.
- Xue J and Gavin K (2008) Effect of rainfall intensity on infiltration into partly saturated slopes. *Geotechnical and Geological Engineering* **26**(2): 199–209.
- Yuan FS and Lu ZM (2005) Analytical solutions for vertical flow in unsaturated, rooted soils with variable surface fluxes. *Vadose Zone Journal* **4**(4): 1210–1218.

- Zhan LT (2003) *Field and Laboratory Study of an Unsaturated Expansive Soil Associated with Rain-Induced Slope Instability*. PhD thesis, Hong Kong University of Science and Technology, Hong Kong.
- Zhan LT and Ng CWW (2001) Analytical analysis of rainfall infiltration mechanism in unsaturated soils. *International Journal of Geomechanics* **4**(4): 273–284.
- Zhan TLT, Ng CWW and Fredlund DG (2007) Field study of rainfall infiltration into a grassed unsaturated expansive soil slope. *Canadian Geotechnical Journal* **44**(4): 392–408.
- Zhang J, Jiao JJ and Yang J (2000) In situ rainfall infiltration studies at a hillside in Hubei Province, China. *Engineering Geology* **57**(1–2): 31–38.
- Zhang LL, Fredlund DG, Zhang LM and Tang WH (2004) Numerical study of soil conditions under which matric suction can be maintained. *Canadian Geotechnical Journal* **41**(4): 569–582.
- Zhang LL, Zhang LM and Tang WH (2005) Rainfall-induced slope failure considering variability of soil properties. *Géotechnique* **55**(2): 183–188.
- Zhang LM and Chen Q (2006) Seepage failure mechanism of the Gouhou rockfill dam during reservoir water infiltration. *Soils and Foundations* **46**(5): 557–568.
- Zhang LM and Li X (2010) Micro-porosity structure of coarse granular soils. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(10): 1425–1436.
- Zhang LM, Zheng YR and Wang JL (2003) Errors in calculating hydrodynamic pressures for stability analysis of soil slopes subject to rainfall. In *Applications of Statistics and Probability in Civil Engineering (ICASP9)*, San Francisco (Der Kiureghian A, Madonat S and Pestana JM (eds)). IOS Press, Fairfax, VA, USA, vol. 2, pp. 1431–1438.
- Zhu JH and Anderson SA (1998) Determination of shear strength of Hawaiian residual soil subjected to rainfall-induced landslides. *Géotechnique* **48**(1): 73–82.

WHAT DO YOU THINK?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as a discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via www.icevirtuallibrary.com/content/journals, where you will also find detailed author guidelines.