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Rainfall-induced landslides: development of a simple screening tool based on rainfall data and unsaturated soil mechanics principles

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ABSTRACT: There is now widespread acceptance that a key trigger mechanism for shallow landslides is the reduction in soil suction that occurs as a wetting front moves through an initially unsaturated soil profile. Slopes often remain stable at angles steeper than would be predicted using effective stress strength parameters. Such slopes may remain stable for many years, if not decades, with failure only being triggered when moisture conditions within the slope reach a critical threshold.

Our understanding of the role of unsaturated soil mechanics in slope stability is now well developed. This paper uses this knowledge to suggest techniques that may be used to provide suitable management tools, the intention being to predict the level of risk associated with a particular slope. The technique combines statistical rainfall data, complemented by confirmation studies using numerical modelling (utilising commercially available software SVFlux and SVSlope), to provide a screening tool that takes account of antecedent conditions; a critical aspect for providing appropriate risk evaluation capability. An approximate approach, which utilizes analytical solutions, is also described.

To implement the risk management strategy discussed in the paper, some form of *in situ* monitoring is required and two alternatives are briefly described: discrete monitoring using buried instruments; and remote sensing of soil water status.

1 INTRODUCTION

Shallow failures are a common occurrence in residual soil slopes with steep angles and deep groundwater tables. These occurrences are usually associated with prolonged periods of heavy rainfall and it is accepted that the failures are caused by reduction of matric suction due to rainwater infiltration. Therefore, rainfall events and unsaturated soil behavior play an important role in the slope failure mechanism.

Numerous studies have attempted to correlate controlling factors with occurrences of slope failure. Initially, direct correlation between only rainfall events and the failure occurrences were established by many authors in different countries such as Vargas (1971), Guidicini and Iwasa (1977), Caine (1980), Crozier and Eyles (1980), Vaughan (1985), Senanayaka et al. (1994), Finlay et al. (1997), and Guzzetti et al. (2007). These correlations were developed, based on some occurrences in a local area, to thorough empirical correlations established from large databases in regional and/or global areas. The controlling factors of rainfall-induced slope failures are, then, recognized not to be dependent solely upon rainfall events but also soil properties. The significant role of both rainfall and soil properties has been clearly indicated by Brand et al. (1984), through a study on typical characteristics of slope failures in Hong Kong, and Rahardjo et al. (2007), based on investigations of slope failures in Singapore. It is now widely accepted that the shallow slope failure mechanism is triggered by infiltration of rainwater to surficial soils (Pradel and Raad 1993, Fourie 1996). This infiltration reduces matric suction until a condition is reached where shear strength is no longer sufficient to maintain stability.

2 APPROXIMATE APPROACH TO PREDICTING CRITICAL EVENTS

Within a particular rainfall event, infiltration rates will vary with precipitation intensity. Pradel and Raad (1993) presented a simplification based on the work of Green and Ampt (1911) that assumes a constant infiltration rate v_i according to Eqn 1. The assumptions used in this model are: *(i)* sufficient water availability at the slope surface; *(ii)* a distinct wetting front; *(iii)* constant hydraulic conductivity in the wetted zone during infiltration; and *(iv)* constant matric suction S, expressed as a pressure head, just ahead of the wetting front. Based on this model, the time required to saturate the soil, T_w, to a depth z_w is presented in Eqn 2.

$$v_i = k_s \frac{z_w + S}{z_w} \tag{1}$$

$$T_w = \frac{\mu}{k_s} \left(z_w - S \ln \left(\frac{S + z_w}{S} \right) \right) \tag{2}$$

where k_s is saturated hydraulic conductivity, μ is the change of volumetric water content at the wetted zone due to infiltration ($\mu = \theta_s - \theta_i$) and θ_s and θ_i are saturated and initial volumetric water contents respectively. Values of S typically range from 80cm for coarse grained soils to 140cm for fine grained soils (Moore 1939). Natural slopes commonly have values of $\mu \geq 20\%$ (Pradel and Raad 1993). Therefore, rainfall intensity must be higher than v_i and rainfall duration must be longer than T_w to achieve saturation to the required depth z_w.

A limiting value of saturated hydraulic conductivity (k_{lim}) required to saturate the surficial soils can be determined using Eqn 3 by combining Eqns 1 and 2 and applying $T_w = T_{min}$ and $v_i = I_{min}$, where I_{min} is the minimum intensity. Hence, soils with hydraulic conductivities higher than k_{lim} cannot be saturated due to rainwater infiltration. Note that, in this infiltration model, the effect of runoff and evapotranspiration is neglected.

$$\begin{aligned} k_{lim} &= I_{min} \left(\frac{z_w}{z_w + S} \right) \\ &= \frac{\mu}{T_{min}} \left(z_w - S \ln \left(\frac{S + z_w}{S} \right) \right) \end{aligned} \tag{3}$$

3 COMPARISON OF APPROXIMATE AND NUMERICAL MODEL USING A CASE STUDY

In situ hydraulic conductivity tests and laboratory shear strength, water retention and index tests were carried out by the first author as part of an investigation of landslides that occurred in 2007 near Jabiru in the Northern Territory of Australia (Saynor et al. 2012). These landslides were triggered by the extremely high rainfall intensity that fell in February and March 2007, with a total of 784mm occurring over a particular 72 hour period (Australian Government 2012). The slope where the investigated landslide occurred had an angle of 19° to the horizontal and a height of 23m. Field observations indicated a relatively thin surface soil with an average thickness of 2m overlying a very low permeability bedrock. Failures were observed to occur at this interface. Properties of the soils at this site are summarized in Table 1, where parameters a, m and n define the Soil Water Characteristic Curve (SWCC) using the Fredlund and Xing (1994) model given in Eqn 4, where ψ denotes soil suction and e is the exponential number.

$$\theta = \theta_s \left(\frac{1}{\ln \left[e + \left(\frac{\psi}{a} \right)^n \right]} \right)^m \tag{4}$$

Eqns 1 and 2 were used to determine the minimum intensity and duration respectively of rainfall required to saturate the surficial soil layer to the failure depth observed in the field (i.e. 2m). Results of this analysis were compared with the intensity-frequency-duration (IFD) curves of rainfall obtained for the site as shown in Figure 1. Initial matric suction was varied based on the SWCC data for soil specimens obtained at the upper layer. This variation was applied to determine rainfall duration required to saturate the soil to the required depth.

Numerical analysis using the finite element method was also performed to confirm results obtained from the approximate method. Coupled analysis was carried out utilizing commercial software SVFlux and SVSlope. Variation of rainfall intensity and initial matric suction was also considered in this analysis. Rainfall intensity was varied either side of the measured saturated hydraulic conductivity. Values of the rainfall intensity applied in the analysis were 2, 4, 6, 8, 12, 16, 32, and 64mm/h. Initial matric suction was also varied around a value (ψ_i=33kPa) associated with the measured *in situ* water content and determined according to SWCC data from soil specimens obtained from the upper soil layer. A series of values applied for the initial matric suction were 5, 10, 20, 33, 42, and 100kPa. To evaluate the contribution of each of these parameters, the remaining parameters used in the analysis were kept constant.

3.1 *Comparison of results*

3.1.1 *The effect of rainfall*

There are minimum requirements for rainfall events to trigger a slope failure. These requirements can be determined using Eqns 1 and 2 as proposed by Pradel and Raad (1993). Parameters used in the analysis for the Jabiru slope were k_s=8mm/h (field test), z_w=2m (field observation), S=100cm (Moore 1939), $\mu = \theta_s - \theta_i = 0.2$ (laboratory test). From this analysis, the minimum requirements of rainfall events to trigger slope failure in the Jabiru site were I_{min}=12mm/h and T_{min}=22.5h, as delineated in the IFD curves in Figure 1. Based on the approximate analysis, only rainfall events located in the marked upper right box of the IFD curves can lead to saturation of the surficial soil, thus potentially leading to slope failure. This rainfall

Table 1: Summary of parameters obtained from field and laboratory tests

Properties	Parameters	Unit	Value		
			Average	Min	Max
Basic and index properties	Specific gravity	-	2.80	2.68	2.89
	Bulk density	g/cm^3	1.80	1.67	1.88
	Water content	%	22.0	13.5	27.8
	Fine particles	%	55	28	73
	Liquid Limit	%	51	41	56
	Plasticity index	%	17	12	26
Hydraulic properties	Sat. hyd. conductivity	m/s	22×10^{-6}	6.1×10^{-8}	8.7×10^{-6}
	Sat. vol. water content	%	0.62	0.57	0.69
	a	kPa	5.070	3.377	15.141
	m	-	0.322	0.175	0.977
	n	-	2.106	1.088	8.139
Shear strength properties	c' (see Note)	kPa	3	0	7
	ϕ'	°	32	25	40
	ϕ^b (see Note)	°	16	-	-

NOTE: c' and ϕ^b are the apparent cohesion and angle of internal friction respectively; ϕ^b is the parameter suggested by Fredlund and Rahardjo (1993) to account for the contribution of matric suction to shear strength in the equation $\tau = c' + (u_a - u_w)\tan\phi^b + (\sigma - u_a)\tan\phi'$.

Table 2: Effect of rainfall intensity on time to reach minimum factor of safety F_{min} (ψ_i=33kPa)

Intensity (mm/h)	2	4	6	8	10	12	16
Time to reach F_{min}	N/A	100	65	55	42	34	30

event only takes place for return periods higher than 50 years.

Numerical analyses were performed to verify the result obtained from the approximate method by varying rainfall intensities around the saturated hydraulic conductivity (k_s=8mm/h). As shown in Table 2, the higher the rainfall intensity the faster the reduction in the factor of safety. The factor of safety was very sensitive to rainfall intensities that are close to k_s (4mm/h $\leq I \leq$ 16mm/h). The time required for this interval of rainfall intensities to produce the minimum factor of safety (F_{min}) for each rainfall event ranges from 30 to 66 h. This agrees with the approximate method of analysis. The time required for rainfall with this range of intensity to develop a wetting front to the critical depth is longer than T_{min} ($T >$ 22.5h).

3.1.2 *The effect of initial suction*

The initial suction in the slope was varied while keeping other parameters constant, as used previously. The time for a wetting front to reach a depth of 2m is compared in Figure 2 for the approximate method and the numerical modelling approach. Although the results differ, the trends are the same. For low values of suction, advancement of the wetting front is very sensitive to rainfall duration. This is of course because low suction values correspond to high degrees of saturation, thus requiring limited infiltration to produce a rapidly advancing wetting front.

A likely reason for the differences seen in Figure 2 is the use of varying hydraulic conductivity with suction in the numerical analysis, whereas a constant hydraulic conductivity is inherent in the approximate method. Very low infiltration rates occur initially in the numerical model due to low hydraulic conductivity associated with the initially unsaturated profile, leading to much longer times required to develop the wetting front using the numerical analysis than found using the approximate method. As the initial suction decreases, the hydraulic conductivity approaches k_{sat} and the results from the two approaches converge. The approximate approach does not account for the hydraulic conductivity varying with degree of saturation and thus remains solely a screening tool.

Table 3: Effect of initial suction (assumed constant through profile) on time to reach minimum factor of safety F_{min} (I_{min}=12mm/h)

Initial suction (kPa)	5	10	20	33	40	100
Time to reach F_{min} (hours)	6	22	30	34	36	40

Results of the analysis with the application of various initial suctions using the numerical method are summarized in Table 3. The hydraulic properties (SWCC parameters) were the same as those used in the approximate analysis and shear strength properties were average values as presented in Table 1. The analysis considered rainfall with a constant intensity (I=1.5k_s=12mm/h), this value being chosen to ensure development of a wetting front. The results again indicate the critical importance of initial suction on the response to a high rainfall event. Any risk management strategy thus somehow needs to take account of this parameter and how it varies with ambient conditions.

3.2 *Application of method when failure surface is unknown*

The discussion in the preceding section was based on a case study when known rainfall triggered a failure at a known depth, which in this case was the interface between the weathered surface soil and the relatively unweathered bedrock. In order to be a truly predictive methodology, there is obviously the need to be

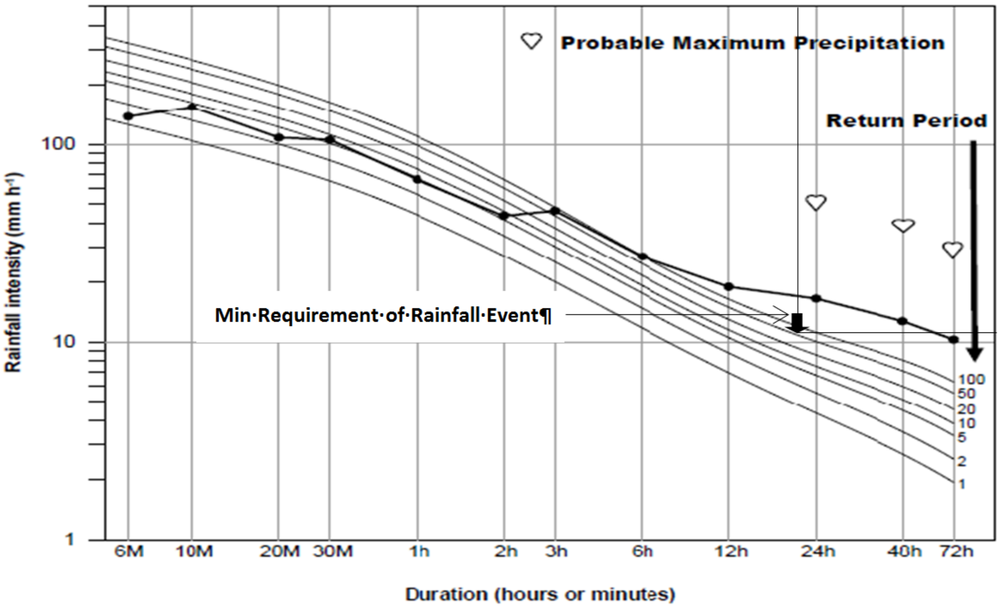

Figure 1: Rainfall intensity-frequency-duration (IFD) curves for the Jabiru site recorded at Gulungul Creek in 2007 (after Moliere et al. (2007)).

able to predict likely slope failures before they occur. Fourie and Blight (1996) discusses the determination of the critical depth, z_w, (at which a slip surface is most likely to occur), which is a function of slope geometry and the shear strength parameters of the soil. Having determined z_w, the approximate method can be used to evaluate combinations of rainfall intensity and duration that are likely to trigger a landslide. Corresponding recurrence intervals (and thus probability of occurrence) can then be determined from the IFD curves. More detailed evaluations could be based on knowledge of approaching weather systems, e.g. if a period of high rainfall is expected, and some estimate of likely precipitation rates are available, the IFD curves can again be used to evaluate the possibility of a landslide-triggering event occurring. In cases where critical rainfall events appear likely, numerical modelling techniques, such as the use of SoilVision described in this paper, can be used to improve risk estimates, remembering that the approximate method tends to be overconservative (as seen in Figure 2).

4 DETERMINATION OF RISK LEVELS

Risk levels were determined based on the result of slope stability assessment with the approximate and numerical methods of analysis. A critical rainfall event resulting from the approximate analysis was plotted on the IFD to ensure such an event could occur. Rainfall events lower than the critical event (in terms of intensity and duration) cannot trigger slope failure, whereas the events beyond the IFD envelope are unlikely to occur. In the methodology used, if a particular result indicates instability of a slope subjected to a rainfall event with a certain value of initial suction, and the rainfall event is likely to occur based on the IFD curves, this condition is categorized as a high risk and thus early warning is required to prevent or minimize any likely hazardous effects of slope failure. Otherwise, it is considered a low risk and the early warning is unnecessary. It is clear that field monitoring of two key parameters, namely rainfall intensity and *in situ* suction, is crucial during the wet season. Data obtained from such monitoring programmes can be used to continuously update risk levels.

4.1 *Assigning risk on the basis of modelling results*

Results obtained from the Jabiru analyses above were used to determine risk levels as outlined. Both rainfall intensity and initial suction were specified and the effect of these parameters on the likelihood of the slope failure evaluated by performing numerical analyses and checking the possibility of the rainfall event using the IFD curves. The risk evaluations are summarised in Table 4.

The results showed that rainfall intensities higher than 4mm/h may trigger slope failure at the site in question, as long as the duration is long enough. However, for some of the high rainfall intensities on a slope with high initial suction values, such as a rainfall intensity of 12mm/h applied to the slope with $\psi_i \geq$ 20kPa, a long duration of rainfall is required to trigger the slope failure and thus this rainfall event is unlikely to occur based on the IFD curves. Therefore, rainfall intensity lower than 4mm/h cannot trigger the slope failure due to inability to develop the wetting front, and some rainfall events with intensity higher than 4mm/h are also categorized as a low risk due to the presence of sufficiently high initial suctions.

The susceptibility of a slope to rainfall-triggered landslides is highly dependent on hydraulic properties. Slopes with sandy soils tend to respond quickly

Table 4: Risk analysis for the Jabiru slope

No	Rainfall intensity, I_{min} (mm/h)	Initial suction, S (kPa)	Minimum rainfall time, T_{min} (h)	Indication of slope failure	Availability of rainfall based on IFD	Risk level
1	<4	33	Unidentified	No	No	Low
2	4	33	100	Yes	No	Low
3	6	33	65	Yes	Yes	High
4	8	33	55	Yes	No	Low
5	10	33	42	Yes	No	Low
6	12	5	6	Yes	Yes	High
7	12	10	22	Yes	Yes	High
8	12	20	30	Yes	No	Low
9	12	33	34	Yes	No	Low
10	12	42	36	Yes	No	Low
20	12	100	40	Yes	No	Low
21	≥16	33	30	Yes	No	Low

to rainfall events due to their high hydraulic conductivity and low water storage capacity, so short duration heavy rainfall can be damaging to these slopes. Conversely, low intensity (and long duration) rainfall may cause failure of a slope with clayey or silty soils, which have low hydraulic conductivity and greater water storage capacity, leading to a slow response of the slope to this type of rainfall. In general, rainfall is unlikely to trigger instability of slopes with very high hydraulic conductivity ($k_s > 80$mm/h) because almost no rainfall event can develop a wetting front ($I < k_{lim}$) in these slopes. On the other hand, rainfall events may not trigger instability of slopes with very low hydraulic conductivity ($k_s < 0.8$mm/h) due to very small infiltration to the slopes, with most of the rainfall reporting as runoff.

These suggestions are in line with the work reported by Rahardjo et al. (2007), who suggested that short-duration rainfall ($T < 24$ hrs), regardless of its intensity, produces a negligible effect on slopes with a low hydraulic conductivity ($k_s < 10^{-6}$m/s) while a short period of heavy rainfall can significantly affect the instability of slopes with a high hydraulic conductivity ($k_s > 10^{-5}$m/s). To produce risk evaluations of a particular slope, it would thus be necessary to, as a minimum, determine the hydraulic and strength parameters, plus monitor *in situ* suctions. However, this approach would soon become prohibitively expensive if an entire region (measuring tens of square kilometres, for example) was of concern. An alternative approach is then required. One option is remote sensing using hyperspectral imaging, as described by Finn et al. (2011). This technology is advancing extremely rapidly and may provide for accurate monitoring over large areas in the future. Use of such data, updated on a daily basis, could be used to quantify the moisture state of a soil slope (through use of appropriate SWCCs) and thus the risk associated with approaching rainfall fronts. Low *in situ* suctions (i.e. a relatively wet slope) would be susceptible to even relatively low recurrence interval events, whereas dry slopes could safely withstand more extreme events (within the constraints offered by the hydraulic properties, as discussed earlier).

5 CONCLUSIONS

Shallow landslides are a common occurrence in residual soil slopes with relatively steep angles and deep groundwater tables subjected to prolonged periods of heavy rainfall. Rainwater infiltration into the surficial layer of the slope, which is in an initially unsaturated condition, is now well recognized as a key trigger mechanism for shallow landslides. Integral to understanding the risk of such a failure is the understanding and quantification of unsaturated soil parameters, both hydraulic and strength.

An approximate method and numerical analyses were used to quantify the likelihood of slope failures, using a field study, where extensive landslides occurred in 2007, as a reference point. Although the approximate method tends to produce more conservative results than the numerical method, it is potentially very useful for identifying a critical rainfall event which may lead to a slope failure. It was found that the minimum intensity and duration of rainfall required to develop a wetting front to a depth of 2m in the Jabiru slope were 12mm/h and 22.5h respectively, based on measured *in situ* suction. This rainfall event corresponds to a minimum return period of 50 years based on the IFD curves obtained for the Gulungul Creek (nearby the Jabiru site). The minimum rainfall time varies with initial suction; the lower the initial suction the shorter the rainfall duration is required to develop a wetting front.

Instruments installed at the site, such as tensiometers buried at several depths in some positions, are potentially very useful for monitoring the water content in the slope in response to rainfall infiltration. The water content is used to determine matric suction of the soil for risk assessment associated with the likelihood of slope failure. This monitoring system would be a simple screening tool that can be used in providing management strategy for anticipation of slope failure and is easily applicable to other sites with different soil types. In cases where a regional approach to risk

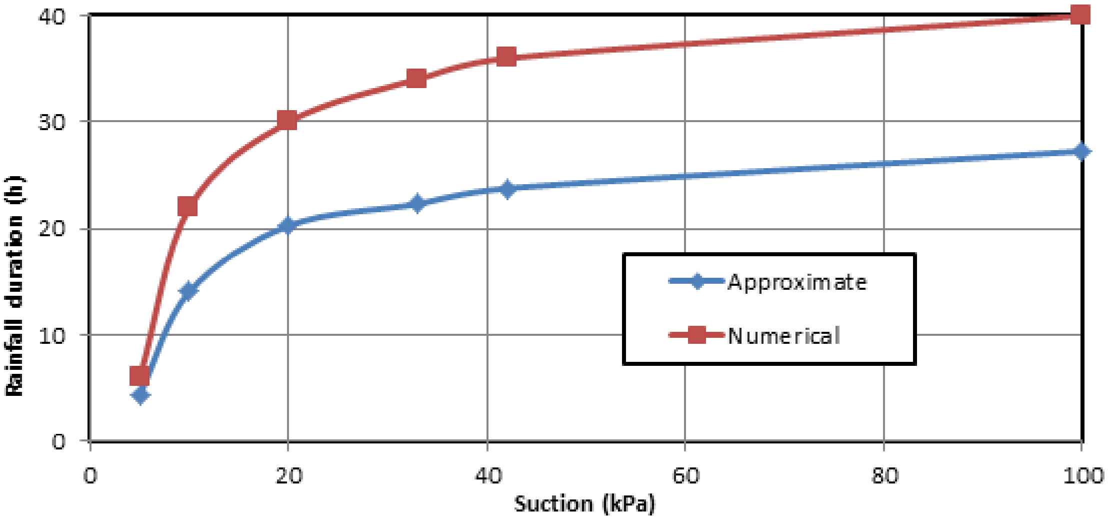

Figure 2: Comparison of minimum rainfall time required to develop a wetting front at a depth of 2m with various initial suction resulting from the approximate and numerical analyses ($I_{min} = 12$mm/h).

estimation is required, techniques such as hyperspectral remote imaging show promise.

REFERENCES

Australian Government (2012). Hourly rainfall data for jabiru aiport, 2007. Technical report, Australian Government Bureau of Meteorology, WA Regional Office, CLimate Serview Centre.

Brand, E. W., J. Premchit, & H. B. Phillipson (1984). Relationship between rainfall and landslides in Hong Kong. In *Proceedings of the Fourth International Symposium on Landslides*, Volume 1, Toronto, Canada, pp. 377–384.

Caine, N. (1980). The rainfall intensity-duration control of shallow landslides and debris flows. *Geografiska Annaler. Series A, Physical Geography 62*, 23–27.

Crozier, M. J. & R. J. Eyles (1980). Assessing the probability of rapid mass movement. In *Proceedings of the Third Australia-New Zealand Conference on Geomechanics*, Wellington, New Zealand, pp. 2.47–2.51.

Finlay, P. J., R. Fell, & P. K. Maguire (1997). The relationship between the probability of landslide occurrence and rainfall. *Canadian Geotechnical Journal 34*, 811–824.

Finn, M., M. Lewis, D. Bosch, M. Giraldo, K. Yamamoto, D. Sullivan, R. Kincaid, R. Luna, G. Allam, C. Kvien, & M. Williams (2011). Remote sensing of soil moisture using airborne hyperspectral data. *GIScience and Remote Sensing 48*(4), 522–540.

Fourie, A. & G. Blight (1996). Tests to determine the suitability of a geotextile for use in the containment of hydraulically placed backfill. *Geotextiles and Geomembranes 14*(9), 465–480.

Fourie, A. B. (1996). Predicting rainfall-induced slope instability. *Proceedings of the Institute of Civil Engineers, Geotechnical Engineering 119*, 211–218.

Fredlund, D. & H. Rahardjo (1993). *Soil mechanics for unsaturated soils*. John Wiley & Sons Inc., New York (USA).

Fredlund, D. G. & A. Xing (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal 31*, 521–532.

Green, W. H. & C. A. Ampt (1911). Studies on soil physics, I. Flow of air and water through soils. *Journal of Agricultural Sciences 4*, 1–24.

Guidicini, G. & O. Y. Iwasa (1977). Tentative correlation between rainfall and landslides in a humid tropical environment. *Bulletin of the International Association of Engineering Geology 16*, 13–20.

Guzzetti, F., S. Perccacci, M. Rossi, & C. P. Stark (2007). Rainfall thresholds for the initiation of landslides in central and southern europe. *Meteorology and Atmospheric Physics 98*, 239–267.

Moliere, D. R., K. G. Evans, & M. J. Saynor (2007). Hydrology and suspended sediment transport in the Gulungul Creek catchment, Northern Territory: 2006-2007 wet season monitoring.

Moore, R. E. (1939). Water conduction on shallow water table. *Hilgardia 12*, 383–426.

Pradel, D. & G. Raad (1993). Effect of permeability on surficial stability of homogeneous slopes. *Journal of Geotechnical Engineering 119*(2), 315–332.

Rahardjo, H., T. H. Ong, R. B. Rezaur, & E. C. Leong (2007). Factors controlling instability of homogeneous soil slopes under rainfall. *Journal of Geotechnical and Geoenvironmental Engineering 133*(12), 1532–1543.

Saynor, M. J., W. D. Erksine, G. Staben, & J. Lowry (2012, 11–15 October). A rare occurrence of landslides initiated by an extreme event in March 2007, in the Alligator Rivers Region, Australia. In *Erosion and Sediment Yields in the Changing Environment, Proceedings of the ICEE Symposium held at Institute of Mountain Hazard and Environment*, Volume 356, Chengdu, China, pp. 303–310. IAHS Publ.

Senanayaka, K., P. Sithamparapillai, & N. Herath (1994). Salient aspect of landslides in Sri Lanka. In *Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering*, New Delhi, India, pp. 1103–1106.

Vargas, M. (1971). Effect of rainfall and ground water levels. In *Proceedings of the 4th Pan American Conference on Soil Mechanics and Foundation Engineering*, San Juan, Puerto Rico, pp. 138–141.

Vaughan, P. R. (1985). Pore pressures due to infiltration into partly saturated slopes. In *Proceedings of the 1st International Conference on Tropical, Lateritic, and Saprolitic Soils*, Brazil, pp. 61–71.