MODELLING THE EFFECT OF HETEROGENEITIES ON SUCTION DISTRIBUTION BEHAVIOUR IN TROPICAL RESIDUAL SOIL

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In the name of ALLAH, the most beneficent and merciful.

To my beloved family

Ir Norhashimah Hashim

Sarah Aida

Sarah Aina

Amin Fuad and

Mak

In memory of Sergeant 14606 Kassim bin Mohd Amin.

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ABSTRACT

The formation of tropical residual soils introduces heterogeneities in soil mantle. While the hydraulic conductivity of Grade VI soil is controlled only by the variation *at the material scale* i.e. grain size, void ratio, and mineralogy, the hydraulic conductivity of Grade V soil is also influenced by the presence of heterogeneity features *at the field scale*. One of the important features of heterogeneity is relict discontinuities which affects the saturated hydraulic conductivity, k_{sat}. This study focuses on the effect of the heterogeneities on the mechanism of rainfall infiltration and the resulting suction distribution within residual soil mass when subjected to different rainfall patterns. Three approaches were employed in this research i.e. field observation, laboratory experiment, and numerical modelling. Field observation was carried out at an instrumented site for a period of one year to monitor soil response, in term of suction distribution, when subjected to actual rainfall. Forty two (42) series of laboratory infiltration tests were performed on homogeneous and two-layered soils with relict discontinuities subjected to various rainfall intensities to study the effect of different rainfall patterns on suction distribution. The field response was then simulated numerically based on the mechanism found in the laboratory tests to obtain the most appropriate approach in modelling the heterogeneities within soil mass. The field observation shows rainfall patterns play an important role in the propagation of wetting front and suction variation in the soil slope. There was an upper limit of the soil suction in the residual soil slope, even during prolonged dry period which approximately identical to minimum suction, ψ_{min} corresponding to the residual water content, θ_r in the soil water characteristic curve, SWCC of the soils. The laboratory study also shows that heterogeneities cause the k_{sat} of the soil to vary from one to five orders of magnitude. The flow mechanisms in the residual soils are controlled by the ratio of rainfall intensity to saturated hydraulic conductivity of the soil, q/k_{sat}, the suction potential at the interface between two layers, and the physical flowing conduit within the heterogeneous soil mass resulting in disparate suction distribution profile. Continuum model is capable of modelling the effect of heterogeneities in Grade V material on the mechanism of rainfall infiltration and suction distribution in tropical residual soil. In this method, the relict discontinuities in Grade V soil were simulated by subdividing the layer into multiple isolated zones with an identical SWCC but with different average k_{sat}. The study indicated that the presence of thin Grade VI layer and the relict discontinuities in Grade V layer should be considered in the analysis of suction distributions in residual soil slope subjected to rainfall infiltration.

ABSTRAK

Pembentukan tanah baki tropika menghasilkan keheterogenan dalam mantel tanah. Konduktiviti hidraulik tanah Gred VI hanya dikawal oleh variasi *pada skala bahan* iaitu saiz zarah, nisbah lompang dan mineralogi manakala bagi tanah Gred V ianya juga dipengaruhi oleh kehadiran ciri-ciri keheterogenan *pada skala lapangan*. Salah satu dari ciri-ciri utama keheterogenan ialah ketakselanjaran relikta yang memberi kesan ke atas konduktiviti hidraulik tepu, k_{sat}. Kajian ini fokus kepada kesan heterogenan terhadap mekanisme penyusupan hujan dan taburan sedutan yang terhasil dalam massa tanah baki akibat kenaan pelbagai corak hujan. Penyelidikan ini menggunakan tiga pendekatan iaitu pemerhatian lapangan, ujian makmal dan pemodelan berangka. Pemerhatian lapangan dilakukan di tapak teralat bagi tempoh setahun untuk memantau tindakbalas tanah dalam sebutan taburan sedutan apabila dikenakan hujan sebenar. Empat puluh dua (42) siri ujian penyusupan makmal dijalankan ke atas tanah homogen dan tanah dua-lapisan dengan relikta takselanjar yang dikenakan pelbagai keamatan hujan untuk mengkaji kesan corak hujan yang berbeza ke atas taburan sedutan. Tindakbalas lapangan disimulasi secara berangka berdasarkan mekanisme yang diperolehi daripada ujian makmal bagi mendapatkan pendekatan paling sesuai untuk memodelkan keheterogenan dalam massa tanah. Pemerhatian di lapangan menunjukkan corak hujan memainkan peranan penting dalam perambatan garis basah hadapan dan kepelbagaian sedutan dalam cerun tanah. Terdapat had atasan bagi sedutan tanah dalam cerun tanah baki, walaupun dalam tempoh kering yang berpanjangan di mana nilainya hampir sama dengan sedutan minimum, ψ_{min} yang merujuk kepada kandungan air baki, θ_r pada lengkung ciri air tanah, SWCC bagi tanah tersebut. Kajian makmal juga menunjukkan bahawa keheterogenan menyebabkan k_{sat} tanah boleh berubah dari satu hingga lima aras magnitud. Mekanisme aliran dalam tanah baki dikawal oleh nisbah keamatan hujan kepada konduktiviti hidraulik tepu tanah, q/k_{sat}, keupayaan sedutan di antara muka dua lapisan dan fisikal pembuluh aliran dalam tanah heterogen tersebut yang menghasilkan profil taburan sedutan yang berbeza. Model selanjar berkebolehan memodelkan kesan keheterogenan dalam bahan Gred V terhadap mekanisme penyusupan hujan dan taburan sedutan dalam tanah baki tropika. Dalam kaedah ini, ketakselanjaran relikta dalam tanah Gred V disimulasikan dengan membahagikan lapisan tanah tersebut kepada berbilang zon terasing yang mempunyai SWCC yang sama tetapi berlainan purata k_{sat}. Kajian ini menunjukkan bahawa kehadiran lapisan nipis Gred VI dan ketakselanjaran relikta dalam lapisan tanah Gred V perlu dipertimbangkan untuk analisa taburan sedutan dalam cerun tanah baki di bawah kenaan penyusupan hujan.

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A	-	Cross sectional area
A_{ev}	-	Air entry value
C	-	Specific moisture capacity
c'	-	Effective cohesion
e	-	Void ratio
g	-	Gravity = 9.81 m/s^2
G_s	-	Specific gravity
h	-	Hydraulic head
I	-	Rainfall intensity
i	-	Hydraulic gradient
I_f	-	Infiltration rate
I_p	-	Infiltrability
k	-	Water coefficient of permeability
k_{sat}	-	Saturated permeability
k_w	-	Hydraulic conductivity of wetted zone
L_a	-	Wetting front depth as the result of antecedent rainfall
L_{cr}	-	Critical wetting front depth
L_f	-	Wetting front depth
L_m	-	Wetting front depth as the result of major rainfall
L_r	-	Redistribution depth
m_w	-	Slope of soil water characteristic curve (SWCC)
n	-	Porosity
P	-	Rainfall amount
q	-	Rainfall unit flux

Q	-	Rainfall total flux
q_f	-	Water flow rate
R	-	Rainfall return period
R_f	-	Surface Runoff
R_{AC}	-	AC Resistance
${}^{R}I_t$	-	Average rainfall intensity for a particular return period
S	-	Wetting front capillary suction
S_r	-	Degree of saturation
S_{ri}	-	Initial degree of saturation
S_{rf}	-	Degree of saturation in wetting front
S_x	-	Standard deviation of annual maximum rainfall intensities
t	-	Time
t_p	-	Time when surface runoff start to occur
u_a	-	Pore-air pressure
u_w	-	Pore-water pressure
$(u_a - u_w)$	-	Matric suction
W	-	Total weight of soil
W_{ev}	-	Water entry value
X	-	Extreme rainfall intensity for a particular rainfall duration
$\overline{X}$	-	Mean of annual maximum rainfall intensities
Y	-	Gumbel's reduced variate
$\overline{Y}$	-	Mean of Gumbel's reduced variates
z	-	Elevation head
β	-	Slope inclination angle
χ	-	Parameter related to the soil degree of saturation
ϕ'	-	Effective friction angle
ϕ^b	-	Unsaturated friction angle
γ_d	-	Unit weight of dry soil
γ_w	-	Unit weight of water = 9.81 kN/m^3

μ	-	Differences between the volumetric water content before and after wetting
υ	-	Water velocity
π	-	Osmotic suction
θ	-	Volumetric water content
θ_a	-	Average volumetric water content in the wetted zone
θ_i	-	Initial volumetric water content
θ_r	-	Residual volumetric water content
θ_s	-	Volumetric water content at saturation of desorption curve
θ'_s	-	Volumetric water content at saturation of absorption curve
ρ_b	-	Bulk density
ρ_d	-	Dry density
ρ_w	-	Density of water
σ	-	Total normal stress
σ'	-	Effective normal stress
σ_y	-	Standard deviation of Gumbel's reduced variates
τ_f	-	Shear stress at failure
ψ	-	Suction
ψ_{min}	-	Minimum Suction value
ψ_T	-	Total suction
Θ	-	Normalized volumetric water content

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Rainfall-induced failures in residual soil slope are common in tropical or subtropical climates that experience periods of intense or prolonged rainfall (Huat *et al.*, 2005; Shaw-Shong, 2004; Brand, 1984). In Malaysia, the most common type of these failures is the shallow slide typically 1.0 m to 1.5 m depths occurs during or immediately after intense rainfall, and the slip surfaces are frequently orientated parallel to the slope surface (Ali Jawaid, 2000; Abdullah & Ali, 1994).

Tan (2004) defines residual soils as soils which are derived from the weathering of rocks, formed in-situ and which have not been subjected to any movement or transportation (in contrast to transported soils such as alluvium, colluviums, etc.). In humid tropical climate, residual soils have a wide range of properties depending on their parent material and degree of weathering. The tropical residual soil mantle derived from igneous rocks mainly consists of materials dominantly decomposed to Grades IV and V according to the six-fold weathering classification system of International Society for Rock Mechanics (ISRM) (1981) of saprolitic soils, and true or mature residual soil (Grade VI) of laterites (Bland & Rolls, 1998; Taylor & Eggleton, 2001; Aydin, 2006).

As many classical geotechnical concepts related to soil properties and soil behaviours have been developed for temperate zone soils, there is difficulty in accurately modelling procedures and conditions to which tropical residual soils are subjected. For instance, the slope stability analysis based on the assumption of saturated soil behaviour is not warranted because the residual soils forming the slope are naturally in an unsaturated condition (Rahardjo & Han, 1995; Gasmo *et al.* 2000). Often, the use of conventional saturated soil mechanics theory for the study of the tropical residual soils gives anomalous results.

Recent studies (e.g., Brand, 1984; Fourie, 1996; Tsaparas *et al.*, 2002) have proven that the assumption of saturated conditions cannot be applied successfully for the stability analysis of the residual soil slopes. In unsaturated conditions, negative pore-water pressure or matric suction is found to play an important role in the stability of the slopes, and have an important bearing on water entry, structural stability, stiffness, shear strength and volume change of the soils. The additional shear strength that exists in unsaturated soils due to matric suction however is lost as a result of rainwater infiltration into the soil.

The distribution and variation of negative pore-water pressure (or suction distribution) in unsaturated residual soils are governed by the water flow, which in turn is affected by many intrinsic and external factors. The intrinsic factors are mainly the hydraulic properties of the soils, including water retention characteristics and water coefficient of permeability, and the external factors mainly refer to climatic conditions such as rainfall intensity and duration, rainfall pattern and evapotranspiration rate. The effects of these factors on rainfall infiltration and hence on the pore-water pressure responses have been investigated by several researchers (e.g., Green & Ampt, 1911; Kasim *et al.*, 1998; Ng *et al.*, 1999).

The behaviours of tropical residual soils are complex due to the variable hydraulic conductivity of the soil matrix *at the material scale*. Weathering in parent rocks tends to form zones of material with different hydraulic conductivities, which are commonly aligned parallel to natural surfaces (Chigira, 2001). Agus *et al.* (2005) works on Bukit Timah granitic residual soil in Singapore found the effect of depth of weathering on saturated coefficient of hydraulic conductivity, k_{sat} shows no discernible trend, which highlights the difficulty of generalising the properties of residual soils. Agus *et al.* observed the variation of saturated of hydraulic conductivity in the residual soil mantle is within two orders of magnitude.

The soil hydraulic conductivity is a dominant factor affecting the suction distribution and the stability of slope (Tsaparas *et al.*, 2002; Pradel & Raad, 1993; Cai & Ugai, 2004; Gofar *et al*., 2007). For example, lower permeability layers overlain higher permeability zones parallel to a slope can result in the development excess pore-water pressures in weathered slopes that may precede a slope failure (Deere & Patton, 1971). In natural slope failures, hydraulic conductivities of earth materials often found vary over three orders of magnitude (Iverson & Major, 1987; Reid *et al.*, 1988). Nonetheless, slope stability analysis rarely account for the effect of small hydraulic heterogeneity.

Reid (1997) clearly illustrated that small contrasts in hydraulic conductivity of layered slope materials can greatly modify the suction distribution, effective stress-state field, and the stability within a slope. In earlier work, Reid & Iverson (1992) used a finite-element simulations model that incorporated spatially variable seepage forces to compute effective-stress fields in saturated slopes with layered materials demonstrated that contrasts of three to four orders of magnitude in saturated hydraulic conductivity between material layers greatly modify the seepage-force and effective-stress fields. Reid & Iverson later concluded low hydraulic conductivity layers that impede down slope groundwater flow create localized areas with a high potential for slope failure. Correspondingly, Berago & Anderson (1985) conducted a stochastic analysis of pore pressure effect on slope stability concluded that increased heterogeneity in hydraulic conductivity can lead to increased probability of slope failure.

Other source of heterogeneity in tropical residual soil profiles includes macro structural features *at the field scale*. Numerous studies found a large proportion of rainfall-induced slope failures in tropical residual soils are associated with field scale heterogeneity, e.g., relict joints, bedding planes, foliations, faults, and shears (Gue & Tan, 2006; Jamaluddin, 2007; Wen & Aydin; 2003; Fookes, 1997; Irfan, 1998). As a macro structural feature, relict joints are common form of relict discontinuities normally preserved in the igneous saprolitic soils inherited from the underlying parent bedrock.

The presence of relict joints is a factor that makes the behaviour of tropical residual soil slope far more complex. However, at present only limited researchers have conducted detail study on the effect of this heterogeneity feature on the stability of slopes because in routine engineering practice the relict discontinuities potential occurrences are often ignored until their control on mass strength becomes apparent by movements of failures along them (Deere & Patton, 1971; Howatt, 1985; Sandroni, 1985; Blight, 1989). Generally, slope failures along prominent relict discontinuities are rapid and commonly occur during or shortly after heavy rainfall. Rahardjo *et al.* (2000) suspected that relict discontinuities play a role in the mechanism of failure as these continuities increase the permeability of the slope, allowing the slope to receive more infiltration from given rainfall event as pore-water pressure build-ups are most likely to occur at these discontinuities. However, it is possible that some intermittent slow movements will take place unnoticed along the discontinuities prior to final shearing during periods of less intense rainfall.

In summary, research in unsaturated tropical residual soil slopes has brought about the realization that most slope failures are caused by the infiltration of rainwater into the slope (Gasmo *et al.*, 2000). While most of the previous studies focused on the stress path and weakness fractures forming the slip plane in homogeneous soil (e.g. Fredlund and Rahardjo, 1993), the spatial heterogeneity in properties of soil is another important factor that should be considered for the characterization of subsurface flow and slope instability.

At present the study of infiltration process in a layered soil slope under unsaturated condition have been conducted actively in soil science, agriculture and hydrology to investigate infiltration characteristic in soils (Miyazaki, 1988; Srivastava & Yeh, 1991; Corradini *et al.*, 2000), but only a few studies was carried out in geotechnical engineering (Kisch, 1959; Choo & Yanful, 2000; Tami *et al.*, 2004). These investigations reported that the variety of heterogeneities exhibited in layered soil materials significantly affect water movement by creating non-uniform velocity flow process. Heterogeneities in various forms indeed control the mechanisms and locations of failure, fast build-up and chaotic distribution of pore-water pressure and the factor of safety in residual soil slope. Thus, a better understanding of the interactions among the heterogeneities, rainfall infiltration and suction distribution as a whole should enable the significance of the discrete features in stability to be more consistently assessed in residual soil profile.

1.2 Problem Statement

The tropical weathering process involves in the formation of tropical residual soil introduces heterogeneities in the residual soil mantle that are strongly controlled by macro structural features *at the field scale*, and micro fabric and mineralogical variations *at the material scale*. As a result, these heterogeneities, i.e. field scale heterogeneity and hydraulic heterogeneity greatly modify the suction distribution during rainfall infiltration in the layered residual soil slopes. This situation leads to discrepancies in the saturation profiles developed in soil mass, and eventually affect the slope instabilities, e.g. the influences of heterogeneity features such as relict discontinuities on the stability of slopes in tropical residual soil are often overlooked due to poor understanding on the importance of the discontinuities in controlling the geomechanical behaviour of the soil.

Study on the mechanism of rainfall infiltration through residual soils rarely account for the effect of small contrasts in hydraulic conductivity of the residual soil materials. Hence, the mechanism of rainfall-induced slope failure involving variations in hydraulic heterogeneity in the soils is still exposed to several uncertainties. As heterogeneities are often responsible for the occurrence of localized abnormalities, collection of laboratory and field evidences are required to validate behaviours and properties of the tropical residual soil under rainfall condition. Development of a realistic model incorporating effects of these features can help predict how and where abnormal seepage flow and pore-water pressure pattern may develop.

1.3 Objectives

The aim of this study is to develop an infiltration model for incorporating the effect(s) of heterogeneities on the mechanism of rainfall infiltration and suction distribution behaviour in a tropical residual soil slope under high precipitation rate. In order to fulfil the overall objective, the following specific objectives are set forth:

(i) To investigate the effect of relict discontinuity feature on the residual soil permeability.

(ii) To monitor and assess the changes in pore-water distributions for a residual soil slope associated with local rainfall condition.

(iii) To investigate the suction distribution in homogeneous and two-layered system of residual soil slope, with and without the presence of relict discontinuity feature subjected to various rainfall patterns.

(iv) To determine the mechanics of water flow in residual soil slope subjected to various rainfall patterns by considering the effect of heterogeneities.

1.4 Scope of Study

In this study, the tropical residual soils [Grade V to Grade VI of the six-grade rock weathering classifications of International Society for Rock Mechanics, ISRM (1981)] were intensively investigated. The study focused on a two-layered system of tropical residual soil slope with and without relict joints present within its mantle. Two vital research approaches have been undertaken in this study, i.e., field study and laboratory modelling. In addition, numerical simulation was also performed by undertaking the results of field study and laboratory modelling as the basis for modelling the effect of heterogeneities on the suction distribution in the residual soil as a response to rainfall infiltration.

A single sloping site located within the compound of Johor Bahru campus of Universiti Teknologi Malaysia was selected as the study area. The site was instrumented with rain gauge, runoff collector, and tensiometers for monitoring the response of suction to rainfall infiltration in a period of one year. The main objective of the determination of suction and rainfall distribution in the field works was to establish dependable initial condition of soil materials for the subsequent infiltration tests in the laboratory modelling, and to compare with the simulated suction distributions generated from the numerical model simulation subjected to local rainfall condition.

Soil samples from the study area were collected to obtain representative properties as input in infiltration tests. The soil characterization was also required to establish the stratigraphy of the study area (i.e., layering or zones), and to determine the properties of each layer for numerical analyses.

Laboratory modelling experiments, i.e., infiltration tests were conducted in a specially fabricated infiltration model and a soil column for two-dimensional and one-dimensional tests, respectively. The infiltration model comprised a soil slope of 600 mm in height and 2000 mm in length which tilted at two optional angles of 18^o and 27^o. The relatively gentle angles were chosen because they represent the typical angle found in natural residual soil slope. Moreover, the study mainly focused on infiltration behaviour in the unsaturated residual soils, and the slope was not tested for failure. Monitoring instruments with automated data acquisition system were installed on the models to allow continuous pore-water pressure (and suction) measurements. The behaviours of tropical residual soil were investigated subjected to various rainfall conditions account for the coupled effect of heterogeneities in two residual soils with different and small contrast in hydraulic conductivity at three main configurations, i.e. homogeneous-layered, two-layered soil systems and two-layered soil systems with artificial relict joints.

The laboratory experiment is the main approach in this study because of the difficulties of sampling representative volumes of heterogeneous residual soil and the poor control of boundary conditions in the field experiments. Thus, the study was technically exposed to certain assumptions as follows:

(i) The artificial relict joints introduced in the system were assumed to be representative of the actual relict discontinuities in soil mass.

(ii) The ideal environment in the laboratory with controlled precipitation and room temperature was assumed to be representative of the actual climate condition.

(iii) The soil materials used in the laboratory modelling are assumed to be homogeneous.

1.5 Significance of Study

The findings of this research may be viewed as an alternative or/and improvement to the existing and realistic laboratory models for residual soils. The benefits that would be gained from the study may include the followings:

(i) Providing essential information on the nature of pore-water pressure changes related to measureable rainfall and soil parameters for assessing stability of a residual soil slope.

(ii) Development of an infiltration model incorporating a relict discontinuity feature for rainfall infiltration study, especially on tropical residual soil slope under high precipitation rate.

1.6 Thesis Organization

This thesis consists of seven chapters: *Introduction* (Chapter 1), *Literature Review* (Chapter 2), *Research Methodology* (Chapter 3), *Preliminary Data* (Chapter 4), *Laboratory Modelling* (Chapter 5), *Modelling of Heterogeneity* (Chapter 6) and *Summary, Conclusions and Recommendations* (Chapter 7). In the end of each chapter, concluding remarks are provided to briefly discuss and summarize the content of the chapter.

Chapter 1 generally describes the background of problems associated with the rainfall-induced slope failure in tropical residual soils as well as the objectives, scope and significance of the present study. Brief description on the heterogeneities in tropical residual mantle *at the material scale* and *at the field scale* that strongly control the behaviours of the residual soils was also presented.

Review of literatures is presented in Chapter 2. This chapter provides descriptions, comparisons, concepts of appropriate theories published in literature pertaining to this thesis. In addition, Chapter 2 also outlines the laboratory modelling techniques and methodologies employed in the previous studies.

Research methodology and laboratory experiments exercised in this study are explained in Chapter 3. Other than the discussion on basic data collection, Chapter 3 also describes the design and implementations of the two main methodologies adopted in this research, i.e., field monitoring and laboratory modelling.

The results and analyses are discussed separately in three chapters, i.e. Chapter 4, Chapter 5 and Chapter 6. Chapter 4 presents and discusses the preliminary data obtained from two main natures of experimental data as described in Chapter 3. The results comprise the characterization of residual soil and the response of suction distribution through field observation.

The laboratory modelling setup is presented in Chapter 5. The discussion mainly focuses the results of laboratory experiments considering the effect of layering as results of the formation of tropical residual soil. The laboratory experiments also focus on the effect of field scale heterogeneity as intrinsic characteristic of residual soil on mass permeability and suction distribution.

Chapter 6 presents numerical simulation performed to model the effect of heterogeneities on the mechanism of rainfall infiltration and suction distribution in the residual soil that has earlier identified in Chapter 4 and Chapter 5. The model serves as the final outcome of the study.

The final chapter of the thesis (Chapter 7) covers summary of the thesis and conclusions drawn from the present study as well as the recommendations for further researches.

REFERENCES

Ali, M. H., Lee, T. S., Kwok, C. Y., and Eloubaidy, A. F. (2000). Modelling Evaporation and Evapotranspiration under Temperature Change in Malaysia. *Pertanika Journal of Science & Technology*. 8(2): 191–204.

Abdullah, A.M.L.B. and Ali, F.H. (1994). Field Measurement of Soil Suction. *Proceeding 13th International Conference on Soil Mechanics and Foundation Engineering*. New Delhi, India. 3: 1013-1016.

Ahmad, K. (2004). *Improvement of a Tropical Residual Soil by Electrokinetic Process*. Universiti Teknologi Malaysia: PhD Thesis.

Agus, S.S., Leong, E.C. and Rahardjo, H. (2001). Soil-Water Characteristic Curves of Singapore Residual Soils. *Journal of Geotechnical and Geological Engineering*. 19: 285-309.

Agus, S.S., Leong, E.C. and Rahardjo, H. (2005). Estimating Permeability Functions of Singapore Residual Soils. *Engineering Geology*. 78: 119-133.

Akindunni, F.F., Gillham, R.W., and Nicholson, R.V. (1991). Numerical Simulations to Investigate Moisture-Retention Characteristics in the Design of Oxygen-Limiting Covers for Reactive Mine Tailings. *Canadian Geotechnical Journal*. 28: 446-451.

Ali Jawaid, S.M. (2000). Risk Assessment of Landslide Using Fuzzy Theory. *Landslides in Research, Theory and Practice*. London: Thomas Telford: 31-36.

Aitchison, G.D. (1961). Relationships of Moisture Stress and Effective Stress Functions in Unsaturated Soils. *Pore Pressure and Suction in Soils Conference*. London, England: 47-52.

ASTM (2000). *Standard Test Method for Capillary-Moisture Relationships for Coarse- and Medium-Textured Soils by Porous-Plate Apparatus, Designation D2325-68*. American Society for Testing and Materials, West Conshohocken, Pennsylvania: 723-773.

Au, S. W. C. (1998). Rain-Induced Slope Instability in Hong Kong. *Engineering Geology*. 51: 1–36.

Aydin, A. (2006). Stability of Saprolitic Slopes: Nature and Role of Field Scale Heterogeneities. *Natural Hazards and Earth System Sciences*. 6: 89- 6.

Aydin, A. and Duzgoren-Aydin, N.S. (2002). Indices in Scaling and Predicting Weathering-Induced Changes in Rock Properties. *Environmental and Engineering Geoscience*. 4(2): 121-135.

Aydin, A., Duzgoren-Aydin, N.S. and Malpas, J. (2000). A Review of Igneous and Metamorphic Saprolites. *Journal of Nepal Geological Society*. 22: 11-16.

Babu, G.L.S. and Murthy, D.S.N. (2005). Reliability Analysis of Unsaturated Soil Slopes. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 131(11): 1423-1428.

Bao, C.G., Gong, B. and Zhan, L. (1998). Properties of Unsaturated Soils and Slope Stability of Expansive Soil. Keynote Lecture, *2nd International Conference on Unsaturated Soils*. Beijing, China.

Bardet, J.P. (1997). *Experimental Soil Mechanics*. Prentice-Hall, Inc. Upper Saddle River, New Jersey.

Berago, D.T. and Anderson, L.R. (1985). Stochastic Analysis of Pore Pressure Uncertainty for the Probability Assessment of the Safety of Earth Slope. *Soils and Foundations*. 25(2): 87-105.

Berry, P.L. and Reid, D. (1987). *An Introduction to Soil Mechanics*. London: McGraw-Hill Book Company.

Bishop, A.W. (1959). *The Principle of Effective Stress*. Norwegian Geotechnical Institute. Oslo, Norway.

Bland, W. and Rolls, D (1998). *Weathering*. London: Arnold.

Blight, G.E. (1985). *Residual Soils in South Africa*. Technical Committee on Sampling and Testing of Residual Soils, International Society for Soil Mechanics and Foundation Engineering: 159–168.

Blight, G.E. (1989). Design Assessment of Saprolites and Laterites. *Proceedings 12th International Conference SMFE*. 4: 2477-2484.

Blight, G.E. (1997). Origin and Formation of Residual Soils. *In: Mechanics of Residual Soil*. Rotterdam, Balkema: 1-15.

Boosinsuk, P. and Yung, R.N. (1992). Analysis of Hong Kong Residual Soil Slopes. *Engineering and Construction in Tropical Residual Soils; Proceedings of the 1981 Special Conference*. *ASCE*. Hawai: 463-482.

Bouwer, H. (1966). Rapid Field Measurement of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis. *Water Resources Research*. 2(4): 729-738.

Brand, E. W. (1982). Analysis and Design in Residual Soils. *Proceedings ASCE Conference on Engineering Construction in Tropical and Residual Soils*: 89-143.

Brand, E. W. (1984). Landslides in South Asia: A State-of-Art Report. *Proceedings 4th International Symposium on Landslides*. 1: 17–59.

Brand, E. W. (1985). Predicting the Performance of Residual Soil Slopes. *Proceedings 11th International Conference on Soil Mechanics and Foundation Engineering*. San Francisco. 1: 17–59.

Brand, G.E. and Philipson, H.B. (1985). *Sampling and Testing of Residual Soils – A Review of International Practices*. Technical Committee on Sampling and Testing of Residual Soils, International Society for Soil mechanics and Foundation Engineering: 7–22.

Brand, E. W., Dale, M. J., and Nash, J. M. (1986). Soil Pipes and Slope Stability in Hong Kong. *Quarterly J. Engineering Geology*. 19: 301–303.

Brisson, P., Garga, V.K. and Vanapalli, S.K. (2002) Determination of Unsaturated Flow Characteristics of Nickel Mine Tailings. *55th Canadian Geotechnical Conference*. October 2002, Niagara, Canada.

BSI (1999). *Code of Practice for Site Investigations, (BS 5930)*. British Standards Institution, London.

BSI. (1990). *Methods of Test for Soils for Civil Engineering Purposes, (BS 1377: Part 1-9)*. British Standards Institution, London.

Burton, C.K. (1973). *Geology and Mineral Resources Johore Bahru-Kulai Area South Johore*. Geological Survey of Malaysia, Ministry of Primary Industries Malaysia.

Bussiere, B., Aubertin, M. and Chapuis, R.P. (2003). The Behavior of Inclined Covers Used as Oxygen Barriers. *Canadian Geotechnical Journal*. 40: 512-535.

Cai, F. and Ugai, K. (2004). Numerical Analysis of Rainfall Effects on Slope Stability. *International Journal of Geomechanics, ASCE.* 4(2): 69-78.

Cesano, D., Bagtzoglou, A. C., and Olofsson, B. (2003). Quantifying Fractured Rock Hydraulic Heterogeneity and GroundWater Inflow Prediction in Underground Excavations: The Heterogeneity Index. *Tunnelling and Underground Space Technology*. 18: 19–34.

Chapuis, R.P., Chenaf, D., Bussiere, B, Aubertin, M. and Crespo, R. (2001). A User’s Approach to Assess Numerical Codes for Saturated and Unsaturated Seepage Conditions. *Canadian Geotechnical Journal*. 38: 1113-1126.

Chigira, M. (2001). Micro-Sheeting of Granite and Its Relationship with Landsliding Specifically after the Heavy Rainstorm in June 1999, Hiroshima Prefecture, Japan. *Engineering Geology*. 59: 219-231.

Chigira, M. and Yokoyama, O. (2005). Weathering Profile of Non-Welded Ignimbrite and the Water Infiltration Behavior within it in Relation to the Generation of Shallow Landslides. *Engineering Geology*. 78: 187-207.

Chin, F.K. (1988). Construction of Dams, Roads, Air Fields, Land Reclamation in and on Tropical Soils-General Report. *Proceedings of the 2nd International Conference on Geomechanics in Tropical Soils (Supplementary Documentations)*. 12-14 December: 92-102.

Choo. L.P. and Yanful, E.K. (2000). Water Flow through Cover Soils Using Modeling and Experimental Methods. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 126(4): 324-334.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988). *Applied Hydrology*. New York: McGraw-Hill.

Collins, B.D. and Znidarcic, D. (2004). Stability Analyses of Rainfall Induced Landslides. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 130 (4): 362-372.

Collins, K., and McGown, A. (1974). The Form and Function of Microfabric Features in a Variety of Natural Soils. *Geotechnique*. 24(2): 223–254.

Corradini, C., Melone, F., and Smith, R. E. (2000). Modeling Local Infiltration for a Two-layered Soil under Complex Rainfall Patterns. *Journal Hydrology*. 237: 58–73.

Costa, A. J. and Fernandes, C. E. M. (1985). Slides in Saprolites from Gneissic Rocks with Relict Slip Surfaces, The B.N.E.D.E.S. Case History. *Proceedings 1st International Conference on Tropical Lateritic and Saprolitic Soils*. 2: 49–55.

Costa, L.M., Dobereiner, L., de Campos, T.M.P. and Vargas, E. (1989). Fabric and Engineering Properties of Saprolites and Laterites. *Proceedings 12th International Conference SMFE*. 4: 2763-2476.

Cowland, J. W. and Carbray, A. M. (1988). Three Cut Slope Failures on Relict Discontinuities in Saprolitic Soils. *Proceedings 2nd International Conference on Geomechanics in Tropical Soils*. 1: 253–258.

Craig, R.F. (2004). *Soil Mechanics.* 7th Edition. London: Taylor & Francis.

Darcy, H. (1850). Rapport à M. le Ministre des Travaux Publics, sur le pavage et le macadamisage des chaussées de Londres et de Paris. *Annales des Ponts et Chaussées*. Series 2, 10: 1-264.

Dearman, W.R. (1976). Weathering Classification in the Characterisation of Rocks: A Revision. *Prediction Soil Mechanics*. London: Thomas Telford.

Deere, D.U. and Patton, F.D. (1971). Slope Stability in Residual Soils. *Fourth Panam. Conference SMFE*. San Juan, Puerto Rico. 1: 87-170.

Dietrich, W.E., Reiss, R., Hsu, M and Montgomery, D.R. (1995). A Process-Based Model for Colluvial Soil Depth and Shallow Landsliding Using Digital Elevation Data. *Hydrological Process*es 9: 383-400.

Department of Drainage and Irrigation. (2001). *Urban Stormwater Management Manual for Malaysia (MASMA)*. Percetakan Nasional Berhad, Malaysia.

Eaton, T. T. (2006). On the Importance of Geological Heterogeneity for Flow Simulation. *Sedimentary Geology*. 184: 187-201.

Frank, C.A.M., Pun, W.K. and Yeo, K.C. (1996). Landslip Investigation of a Failed Cut Slope with Complex Geology. *Proceedings of the 7th International Symposium On Landslides*. Trondheim: 539–556.

Flintoff, W. T. and Cowland, J. W. (1982). Excavation Design in Residual Soil Slopes. *Proc. ASCE Conference on Engineering and Construction in Tropical and Residual Soils*: 539–556.

Fookes, P.G. (1997). Tropical Residual Soils. *Geological Society Engineering Group Working Party Revised Report*. The Geological Society, London.

Fourie, A.B. (1996). Predicting Rainfall-Induced Slope Instability. *Proceedings Institute Civil Engineering and Geotechnical Engineering* 119 (4): 211-218

Fredlund, D. G. and Morgenstern, N. R. (1977). Stress State Variable for Unsaturated Soil. *ASCE Journal Geotechnical Engineering Divisions GT5*. 103: 447-466.

Fredlund, D. G., Morgenstern, N. R., and Widger, R. A. (1978). The Shear Strength of Unsaturated Soil. *Canadian Geotechical Journal*. 15: 313–321.

Fredlund, D. G., Ng, C. W. W., Rahardjo, H. and Leong, E. C. (2001). Unsaturated Soil Mechanics: Who Needs It? *Geotechnical News, December*. GeoSpec., Bi-Tech Publishing. Vancouver, B.C., Canada: 43–45.

Fredlund, D.G. and Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*. New York: John Wiley & Sons, Inc.

Fredlund, D. G. and Xing, A. (1994). Equations for the Soil-Water Characteristic Curve. *Canadian Geotechical Journal*. 31: 521–532.

Fredlund, D.G., Xing, A. and Huang, S. (1994). Predicting the Permeability Function for Unsaturated Soils Using the Soil-Water Character Curve. *Canadian Geotechnical Journal*. 31(3): 533-546

Freeze, R. A. and Cherry, J. A. (1979). *Groundwater*. New York: Prentice-Hall, Inc.

Futai, M.M., Almeida, M.S.S. and Lacerda, W.A. (2004). Yield Strength, and Critical State Behavior of a Tropical Saturated Soil. *Geotechnique.* 130(11): 1169-1179.

Gardner, W.R. (1960). *Water Movement in Soil*. Washington State University.

Gasmo, J. M., Rahardjo, H., and Leong, E. C. (2000). Infiltration Effects on Stability of a Residual Soil Slope. *Computer and Geotechnique.* 26: 145–165.

GCO (1984). *Geotechnical Manual for Slopes.* 2nd Edition. Geotechnical Control Office, Hong Kong.

Geiger, S.L., and Durnford, D.S. (2000). Infiltration in Homogeneous Sands and a Mechanistic Model of Unstable Flow. *Soil Science Society of America Journal*. 64: 460-469.

GEO-SLOPE International Ltd. (2004a). *Stability Modeling with SLOPE/W*. Calgary, Alta., Canada.

GEO-SLOPE International Ltd. (2004b). *Seepage Modeling with SEEP/W*. Calgary, Alta., Canada.

Gitirana, G.Jr. and Fredlund, D.G. (2004). Soil-Water Characteristic Curve Equation with Independent Properties. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 130(2): 209-212.

Glass, R.J., Steenhuis, T.S., and Parlange, J.Y. (1989). Wetting Front Instability, Experimental Determination of Relationships between System Parameters and Two Dimensional Unstable Flow Field Behavior in Initially Dry Porous Media. *Water Resources Research*. 25: 1195-1207.

Gofar, N., Lee, M.L. and Kassim, A. (2007) Stability of Unsaturated Slopes Subjected to Rainfall Infiltration. *Proceedings of the Fourth International Conference on Disaster Prevention and Rehabilitation*, Semarang 10-11 September 2007: 158-167.

Gofar, N., Lee, M.L. and Kassim, A. (2008). Response of Suction Distribution to Rainfall Infiltration in Soil Slope. *Electronic Journal of Geotechnical Engineering, EJGE*. 13E.

Gofar, N. and Lee, M.L. (2008). Extreme Rainfall Characteristics for Surface Slope Stability in the Malaysian Peninsular. *Georisk.* 2(2): 65-78.

Golden Software. (1996). *Surfer, version 6.03*. Golden Software, Golden, CO.

Green, W.H. and Ampt, G.A.. (1911). Studies on Soil Physics I. The Flow of Air and Water through Soils. *Journal of Agricultural Research*. 4: 1-24.

Gribb, M.M., Kodesova, R. and Ordway, S.E. (2004). Comparison of Soil Hydraulic Property Measurement Methods. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 130(10): 1084-1095.

Gue, S. S. and Tan, Y. C. (2006). Landslides: Abuses of the Prescriptive Method. *International Conference on Slope 2006*. 7 - 8 August, Kuala Lumpur.

Gumbel, E. J. (1958). *Statistics of Extremes*. New York: Columbia University Press.

Han, K.K., Rahardjo, H. and Broms, B.B. (1995). Effect of Hysteresis on the Shear-Strength of a Residual Soil, Unsaturated Soils. *Proceedings 1st International Conference on Unsaturated Soils (UNSAT 95)*. Paris, France: 499-504.

Hasan, M.M.Z. (2007). *Personal Communication*.

Head, K.H. (1986). *Manual of Soil Laboratory Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests. ELE International Ltd*. London: Pentech Press.

Hencher, S. R. and Martin, R. P. (1982). The Description and Classification of Weathered Rocks in Hong Kong for Engineering Purposes. *Proceedings 7th Southeast Asian Geotechnical Conference*: 125–142.

Hencher, S.R., Massey, J.B. and Brand, E.W. (1984). Application of Back-Analysis to some Hong Kong Landslides. *Proceedings 4th International Symposium on Landslide*: 631-638.

Hillel, D. (1998). *Environmental Soil Physics*. New York: Academic.

Hillel, D. and Baker, R.S. (1988). A Descriptive Theory of Fingering during Infiltration in Layered Soils. *Soil Science*. 146: 51-56.

Hillel, D. and Gardner, W.R. (1970). Measurement of Unsaturated Conductivity and Diffusivity by Infiltration through an Impeding Layer. *Soil Science*. 109: 149-153.

Hincapié, I., Fässler, J., Vogt, P. and Germann, P. (2007). Rivulet Approach to Preferential Infiltration in a Soil Column. *Geophysical Research*. 9: 1539-1547.

Horton, R.E. (1933). The Role of Infiltration in the Hydrological Cycle. *Trans. American Geophysics Union*. 14: 446-460.

Howatt, M.D. (1985). Completely Weathered Granite-Soil or Rock?. *Quarterly Journal Engineering Geology*. 18: 199-206.

Huat, B.K., Ali, F.H. and Mariappan, S. (2005). Effect of Surface Cover on Water Infiltration Rate and Stability of Cut Slope in Residual Soils. *Electronic Journal of Geotechnical Engineering, EJGE*. 10C.

Hudson, R.R. and Hencher, S.R. (1984). The Delayed Failure of a Large Cutting in Hong Kong. *Proceedings of International Conf. on Case Histories in Geotechnical Engineering*. St Louis, MO: 679-682.

IAEG (1981). Rock and Soil Description for Engineering Geological Mapping. *International Association of Engineering Geology Bulletin*. 24: 235-274.

Irfan, T.Y. (1998). Structurally Controlled Landslides in Saprolitic Soils in Hong Kong. *Geotechnical and Geological Engineering*. 16: 215-238.

Irfan, T.Y. (1999). Characterization of Weathered Volcanic Rocks in Hong Kong. *Quarterly Journal Engineering Geology*. 32: 317-348.

Irfan, T.Y., Koirala, N.P. and Tang, K.Y. (1987). A Complex Slope Failure in a Highly Weathered Rock Mass. *Proceedings 6th International Congress on Rock Mechanics*. Montreal: 397-402.

Irfan, T.Y. and Wood, N.W. (1988). The Influence of Relict Discontinuities on Slope Stability in Saprolitic Soils. *Proceedings 2nd International Conference on Geomechanics in Tropical Soils*. 1: 267-276.

ISRM (1981). Basic Geotechnical Description for Rock Masses. *International Journal of Rock Mechanics, Mining Science and Geomechanics*. 18: 85-110.

Iverson, R.M. and Major, J.J. (2004). Rainfall, Groundwater Flow and Seasonal Movement at Minor Creek Landslide, Northwestern California: Physical Interpretration of Emperical Relations. *Geological Society America Bulletin*. 99(4): 579-594.

Jamaluddin, T.A. (2007). Relict Discontinuity and Slope Instability in Humid Tropical Terrain. *Proceedings of the Workshop on Tropical Rock Engineering*. 14-15 July, Bangi: 4(1)-4(9).

Japanese Society of Soil Mechanics and Foundation Engineering (1982). Application of Composite Slip Surface for Stability Analysis. *Soil Testing Methods*. 2nd Revised Edition. Tokyo: JSSMFE.

Jarvis, N.J. (1998). Modeling the Impact of Preferential Flow on Non-Point Source Pollution. *Physical Nonequilibrium in Soils: Modeling and Application*. Chelsea, Michigan: Ann Arbor Press.

Jason, B.B. and Joel, C.R. (2004). Effect of Grasses on Herbicide Fate in the Soil Column: Infiltration of Runoff, Movement, and Degradation. *Environmental Toxicology and Chemistry*. 23(9): 2251-2258.

Jennings, J.E. (1961). A Revised Effective Stress Law for Use in the Prediction of the Behavior of Unsaturated soils. *Pore Pressure and Suction in Soils Conference*. London, England: 26-30.

Jennings, J.E. and Burland, J.B. (1962). Limitations to the Use of Effective Stresses in Partly Saturated Soils. *Géotechnique*. 12(2): 125-144.

Joel, A., Messing, I., Seguel, O., and Casanova, M. (2002). Measurement of Surface Water Runoff from Plots of Two Different Sizes. *Hydrological Processes*. 16(7): 1467-1478.

Jury, W.A., Wang, Z. and Tuli, A. (2003). A Conceptual Model of Unstable Flow in Unsaturated Soil during Redistribution. *Vadose Zone Journal*. 2: 61-67.

Kämpf, M., Holfelder, T. and Montenegro, H. (1998). Inspection and Numerical Simulation of Flow Processes in Capillary Barrier Cover Systems. *Proceedings of 3rd International Conference on Hyro-Science and Engineering (ICHE)*. Berlin, Germany.

Kasim, F. (1998). Soil-Water Characteristic Curve and Seepage Flow in Unsaturated Soils. *Jurnal Teknologi*. 30(B): 69-86.

Kasim, F., Fredlund, D. G., and Gan, J. K. M. (1998). Effect of Steady State Rainfall on Long Term Matric Suction Conditions in Slopes. *Proceedings, 2nd International Conference on Unsaturated Soils*. Beijing, China: 78–83.

Kassim, K.A. and Kok, K.C. (1999). Mix Design for Lime Modification and Stabilisation. *Proceedings of the 5th Geotechnical Conference (GEOTROPIKA 99)*. 22-24 November 1999, Universiti Teknologi Malaysia: 235-244.

Kim, J., Park, S. and Jeong, S. (2006). Effect of Wetting Front Suction Loss on Stability of Unsaturated Soil Slopes. *Unsaturated Soils, Seepage, and Environmental Geotechnics, ASCE*. 148: 70-77.

Kisch, M. (1959). The Theory of Seepage from Clay-Blanketed Reservoirs. *Geotechnique*. 9: 9-21.

Koo, Y. C. (1982). Relict Joints in Completely Decomposed Volcanics in Hong Kong. *Canadian Geotechnical Journal*. 19: 117–123.

Kung, K.J.S. (1990). Preferential Flow in a Sandy Vadose Zone: A Mechanism and Implication. *Geoderma*. 46: 59-71.

Lam, C.C. and Leung, Y.K. (1995). Extreme Rainfall Statistics and Design Rainstorm Profiles at Selected Locations in Hong Kong. *Technical Note No. 86. Royal Observatory*. Hong Kong.

Lee, M. L. (2008). *Influence of Rainfall Pattern on Suction Distribution and Slope Stability*. Universiti Teknologi Malaysia: PhD Thesis.

Lee, M.L., Gofar, N., Kassim, A. and Rahardjo, H. (2009). A Simple Model for Preliminary Evaluation of Rainfall-Induced Slope Instability. *Engineering Geology*. 108(3-4): 272-285.

Lee, M.L., Kassim, A. and Gofar, N. (2010). Performance of Two Instrumented Laboratory Models for the Study of Rainfall Infiltration into Unsaturated Soils. *Engineering Geology*. 117: 78-89.

Lee, S.G. and de Freitas, M.H. (1989). A Revision of the Description and Classification of Weathered Granite and Its Application to Granite in Korea. *Quarterly Journal of Engineering Geology*. 22: 31-48.

Leong, E.C. and Rahardjo, H. (1997). Permeability Functions for Unsaturated Soils. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 123(12): 1118-1126.

Leroueil, S. and Vaughan, P.R. (1990). The General and Congruent Effects of Structure in Natural Soils and Weak Rocks. *Géotechnique*. 40(3): 467-488.

Li, C. and Young, M.H. (2006). Green-Ampt Infiltration Model for Sloping Surfaces. *Water Resources Research*. 42(7): W07420.

Liew, S.S. (2005). Soil Nailing for Slope Strengthening. *Seminar on Geotechnical Engineering*. The Institution of Engineers, Malaysia. Penang, Malaysia.

Lim, T.T., Rahardjo, H., Chang, M.F. and Fredlund, D.G. (1996) Effect of Rainfall on Matric Suctions in a Residual Soil Slope. *Canadian Geotechnical Journal*. 33(4): 618 – 628.

Little, A.L. (1969) The Engineering Classification of Residual Tropical Soils. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*. Mexico. 1: 1-10.

Liu, Y., Bierck, B.R., Selker, J.S., Steenhuis, T.S. and Parlange, J.Y. (1993). High Density X-Ray and Tensiometer Measurements in Rapidly Changing Preferential Flow Fields. *Soil Science Society of America Journal*. 57: 1188-1192.

Lindquist, E. S. and Goodman, R. E. (1994). Strength and Deformation Properties of a Physical Model Melange. *Proceedings 1st NARM Symposium*: 843–850.

Loáiciga, H.A. and Huang, A. (2007). Ponding Analysis with Green-and-Ampt Infiltration. *Journal of Hydrologic Engineering, ASCE*. 12(1): 109-112.

Lo, K.W., Leung, C.F., Hayata, K. and Lee, S.L. (1988). Stability of Excavated Slopes in the Weathered Jurong Formation of Singapore. *Proceedings of 2nd International Conference Geomechanics in Tropical Soils*: 277-284. Singapore.

Long, J. C. S., Gilmour, P., Witherspoon, P. A. (1985). A Model for Steady Fluid Flow in Random Three-Dimensional Networks of Discshaped Fractures. *Water Resources Research*. 21: 1105–1115.

Lumb, P. B. (1962). The Properties of Decomposed Granite. *Geotechnique*. 12: 226-243.

Marto, A., Kasim, F. and Yusof, M.F. (2002). Engineering Characteristics of Residual Granite Soils of Southern Peninsular Malaysia. *Proceedings of the Research Seminar on Materials and Construction*. 29-30 October 2002, Universiti Teknologi Malaysia: 315-325.

Marto, A., and Novrial (1999). The Effect of Lime-Soil Cylinders on Laterite Slope Model. *Proceedings Of the 5th Geotechnical Conference (GEOTROPIKA 99).* 22-24 November 1999, Universiti Teknologi Malaysia: 223-234.

Massad, F. and Teixeira, H. R. (1985). Deep Cut on Saprolitic Soils Conditioned by Relict Structures. *Proceedings 1st International Conference on Tropical Lateritic and Saprolitic Soils*. 2: 381–391.

McLean, A.C. and Gribble, C.D. (1979). *Geology for Civil Engineers*. London: E & FN Spon.

Mein, R.G. and Larson, C.L. (1973). Modeling Infiltration during a Steady Rain. *Water Resources Research*. 9(2): 384-394.

Mitchell, J.K. (1993). *Fundamentals of Soil Behavior*. 2nd Edition. New York: John Wiley & Sons.

Miyazaki, T. (1988). Water Flow in Unsaturated Soil in Layered Slopes. *Journal Hydrology*. 102: 201-214.

Morgan, R.P.C. (1996). *Soil Erosion & Conservation.* 2nd Edition. London: Longman.

Morris, C. E., and Stormont, J. C., (1997). Capillary Barriers and Subtle D Covers: Estimating Equivalency. *Journal of Environmental Engineering*. 123: 3-10.

Morris, C. E., and Stormont, J. C., (1999). Parametric Study of Unsaturated Drainage Layers in a Capillary Barrier. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 125(12): 1057–1065.

Moye, O.G. (1955). Engineering Geology for Snowy Mountains Scheme. *Journal of Institution Engineers*. Australia. 27: 281-299.

Nahlawi, H., Bouazza, A. and Kodikara, J. (2007). Surface Water Infiltration in a 1-Dimensional Soil-Geotextile Column. *Proceedings of the 10th Australia New Zealand Conference on Geomechanics*, *Brisbane*. 21-24 October 2007, Brisbane, Australia. 1: 368-373.

Nakajima, H., Garcia, J. and Podgorney, R. (2006). Modeling of Physical Observations of Water Diversion in a Capillary Barrier Using a Centrifuge. *Proceedings TOUGH Symposium*. 15-17 May, California.

Nash, C.M., Cornides, A.T. and Fernandes, A.J. (1987). A Proposed Erosion Model for Cut Slopes in Hong Kong. *Proceedings of the 8th Asian Regional Conf. on Soil Mechanics and Foundation Engineering*. Kyoto: 477-482.

Nieble, C.M., Cornides, A.T. and Fernandes, A.J. (1985). Regressive Failures Originated by Relict Structures in Saprolites. *Proceedings of the 1st Conference on Tropical Lateritic and Saprolitic Soils*. Brasilia: 41-48

Neuman, S.P. (1976). Wetting Front Pressure Head in the Infiltration Model of Green and Ampt. *Water Resources Research*. 12(3): 564-566.

Ng, C. W. W., Chen, S. Y., and Pang, Y. W. (1999). Parametric Study of the Effects of Rain Infiltration on Unsaturated Slopes. *Rock Soil Mechanics*. 20(1): 1–14.

Ng, C. W. W. and Shi, Q. (1998). A Numerical Investigation of the Stability of Unsaturated Soil Slopes Subjected to Transient Seepage. *Computer and Géotechnique*. 22(1): 1–28.

Ng, C.W.W., Wang, B. and Tung, Y.K. (2001) Three-Dimensional Numerical Investigation of Groundwater Responses in an Unsaturated Slope Subjected to Various Rainfall Patterns. *Canadian Geotechnical Journal*. 38:1049–1062

Ng, C.W.W., Zhan, L.T., Bao, C.G., Fredlund, D.G., and Gong, B.W. (2003). Performance of Unsaturated Expansive Soil Slope Subjected to Artificial Rainfall Infiltration. *Géotechnique*. 53(2): 143–157.

Novak, V., Simunek, J. and Van Genuchten, M.T. (2000). Infiltration of Water into Soil with Cracks. *Journal of Irrigation and Drainage Engineering*. 126(1): 41-47.

O'Kane, M., Wison, G.W., and Barbour, S.L. (1998). Instrumentation and Monitoring of an Engineered Soil Cover System for Mine Waste Rock. *Canadian Geotechnical Journal*. 35: 282-846.

Onset Computer Corporation (2005). *Data Logging Rain Gauge RG3 and RG3-M User's Manual*.

Parent, S.E. and Cabral, A. (2006). Design of Inclined Covers with Capillary Barrier Effect. *Geotechnical and Geological Engineering*. 24: 689-710.

Pierson, T. C. (1983). Soil Pipes and Slope Stability. *Quarterly Journal of Engineering Geology*. 16: 1–11.

Pradel, D. and Raad, G. (1993). Effect of Permeability on Surficial Stability of Homogeneous Slopes. *Journal of Geotechnical Engineering, ASCE*. 119(2): 315-332.

Public Works Institute Malaysia (1996). Tropical Weathered In-Situ Materials. *Geoguides*: 1-5.

Rahardjo, H. and Fredlund, D.G. (1995). Procedures for Slope Stability Analyses Involving Unsaturated Soils. *Developments in Deep Foundations and Ground Improvement Schemes*. Balkema, Rotterdam: 33-56.

Rahardjo, H. and Han, K. K. (1995). Shear Strength of Unsaturated Soils as it Applies to Slope Stability Analysis. *Symposium on Unsaturated Soil Behaviour and Applications*. Nairobi Kenya. 1-31.

Rahardjo, H., Lee T.T., Leong E. C., Deutcher, M.S., Gasmo, J.M. and Kwan, T.S. (2000). *Rainfall-Induced Slope Failures*. Geotechnical Engineering Monograph, Vol. 3. NTU-PWD Geotechnical Research Centre, Nanyang Technological University, Singapore.

Rahardjo, H., Lee T.T., Leong E. C., and Rezaur R.B. (2004a). A Flume for Assessing Flux Boundary Characteristics in Rainfall-Induced Slope Failure Studies. *Geotechnical Testing Journal*. 27(2): 145-153.

Rahardjo, H., Leong E. C. and Tami, D (2004b). Capillary Barrier for Slope Stabilisation. *Civil Engineering Research*. January: 70-72.

Rahardjo, H., Aung, K.K., Leong, E.C. and Rezaur, R.B. (2004c). Characteristics of Residual Soils in Singapore as Formed by Weathering. *Engineering Geology*. 73: 157-169.

Rahardjo, H., Li X. W., Toll D. G. and Leong E. C. (2001). The Effect of Antecedent Rainfall on Slope Stability. *Journal of Geotechnical and Geological Engineering*. Netherlands. 19: 371-399.

Reid, M.E. (1997). Slope Instability Caused by Small Variations in Hydraulic Conductivity. *Journal of Geotechnical and Geoenviromental Engineering*: 717-725

Reid, M.E. and Iverson, R.M. (1992). Gravity-Driven Groundwater Flow and Slow Failure Potential. 2; Effects of Slope Morphology, Material Properties, and Hydraulic Heterogeneity. *Water Resources Research*. 28(3): 939-950.

Reid, M.E., Nielsen, H.P. and Dreiss, S.J. (1988). Hydrological Factors Triggering a Shallow Hillslope Failure. *Bulletin Association Engineering Geology*. 23(3): 349-361.

Richards, L.A. (1931). Capillary Conduction of Liquids through Porous Media. *Physics*. 1: 318-333.

Ross, B. (1990). The Diversion Capacity of Capillary Barriers. *Water Resources Research*. 26: 2625-2629.

Rousseau, M., Pietro, L.D., Angulo, J.R., Tessier, D. and Cabibel, B. (2004). Preferential Transport of Soil Colloidal Particles Physicochemical Effects on Particle Mobilization. *Vadose Zone Journal*. 3:247-261.

Ruxton, B.P., and Berry, L. (1957). Weathering of Granite and Associated Erosional Features in Hong Kong. *Bulletin of Geological Society America* 68:1263-1292.

Sandroni, S.S. (1985). Sampling and Testing of Residual Soil in Brazil. *Sampling and Testing of Residual Soils*. Hong Kong: Scorpion Press.

Shaw-Shong, L. (2004). Slope Failures in Tropical Residual Soil. *Tropical Residual Soils Engineering*: 71-102. London: Taylor and Francis Group.

Simeone, V. and Mancarella, D. (2008). Capillary Barrier Effects on Sloping Layered Covers in Landslide Hazard Modelling. *International Geological Congress*. 6-14 August, Oslo, Norway.

Simms, P.H. and Yanful, T.K. (2004). Estimation of Soil-Water Characteristic Curve of Clayey Till Using Measured Pore-Size Distributions. *Journal of Environmental Engineering, ASCE*. 130(8): 847-854.

Singh, M. (1992). Engineering Geological Assessment Stability Design and Treatment of Core Stones in Residual Cut Slopes in the North-South Expressway. *International Conference of Geotechnical Engineering*. Johor Bahru, Malaysia: 383-391.

Singh, H. and Huat, B.K. (2004). Origin, Formation and Occurrence of Tropical Residual Soils. *Tropical Residual Soils Engineering*: 1-19. London: Taylor and Francis Group.

SoilVision Systems Ltd. (2007). *SVFLUX 2D / 3D Seepage Modeling Software Tutorial Manual*. Saskatoon, Saskatchewan, Canada.

Soilmoisture Equipment Corporation (2005a). *Guelph Permeameter Model 2800K1 Operating Instructions*. Soilmoisture Equipment Corporation, Santa Barbara, California.

Soilmoisture Equipment Corporation (2005b). *Jet-Fill Tensiometers Model 2725 Operating Instructions*. Soilmoisture Equipment Corporation, Santa Barbara, California.

Soilmoisture Equipment Corporation (2005c). *Soil Moisture Probe Model 2100F Operating Instructions*. Soilmoisture Equipment Corporation, Santa Barbara, California.

Sowers, G.F. (1985). *Residual Soils in the United States*. Technical Committee on Sampling and Testing of Residual Soils, International Society for Soil Mechanics and Foundation Engineering.

Srivastava, R. and Yeh, T.C.J. (1991). Analytical Solutions for One-Dimension, Transient Infiltration toward the Water Table in Homogeneous and Layered Soils. *Water Resources Research*. 27(7): 753-762.

St. John, B. J., Sowers, G. F., and Weavers, C. H. E. (1969). Slickensides in Residual Soils and their Engineering Significance. *Proceedings 7th International Conference on SMFE*. 2: 591–597.

Stormont, J.C. and Anderson, C.E. (1999). Capillary Barrier Effect from Underlying Coarser Soil Layer. *Journal of Geotechnical and Geoenvironmental Engineering*. 125(8): 641-648.

Summerfield, M.A. (1996). *Global Geomorphology. An Introduction to the Study of Landforms*. Singapore; Longman.

Sun, H.W., Wong, H.N. and Ho, K.K.S. (1998). Analysis of Infiltration in Unsaturated Ground. *Slope Engineering in Hong Kong*. K.S. Li, J.N. Kay and K.K.S Eds. Holland.

Sung, E.C. and Seung, R.L. (2002). Evaluation of Surficial Stability for Homogeneous Slopes Considering Rainfall Characteristics. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 128(9): 756-763.

Tan, B.K. (2004). Country Case Study: Engineering Geology of Tropical Residual Soils in Malaysia. *Tropical Residual Soils Engineering*: 237-244. London: Taylor and Francis Group.

Tami, D., Rahardjo, H. and Leong, E.C. (2004). Effects of Hysteresis on Steady-State Infiltration in Unsaturated Slopes. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 130(9): 956-967.

Taylor, G. and Eggleton, R. (2001). *Regolith Geology and Geomorphology*. New York: John Wiley & Sons.

Terzaghi, K. (1936). The Shear Resistance of Saturated Soils. *Proceedings 1st International Conference of Soil Mech. Found. Eng.* Cambridge. 1: 54-56

Ting, W.H. (1972). Subsurface Exploration and Foundation Problems in Kuala Lumpur Area. *Journal of Institution of Civil Engineers, Malaysia*. 13: 19-25.

Tsaparas, I., Rahardjo, H., Toll D.G. and Leong E.C. (2002). Controlling Parameters for Rainfall-Induced Landslides. *Computer and Géotechnique*. 29: 1-27.

Tuncer, E.R. and Lohnes, R.A. (1977). An Engineering Classification for Basalt-Derived Lateritic Soils. *Engineering Geology*. 4: 319-339.

Van Genuchten, M.T. (1980). A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal.* 44: 892–898.

Walter, M.T., Kim, J.S., Steenhuis, T.S., Parlange, J.Y., Heilig, A., Braddock, R.D., Selker, J.S. and Boll, J. (2000). Funneled Flow Mechanisms in a Sloping Layered Soil: Laboratory Investigation. *Water Resources Research*. 36(4): 841-849.

Wang, Z., Tuli, A. and Jury,W.A. (2003). Unstable Flow during Redistribution in Homogeneous Soil. *Vadose Zone Journal*. 2: 52-60.

Wen, B.P. and Aydin, A. (2003). Microstructural Study of a Natural Slip Zone, Quantification and Deformation History. *Engineering Geology*. 68: 289-317.

West, L. J., Hencher, S. R., and Cousens, T. W. (1991). Assessing the Stability of Slopes in Heterogeneous Soils. *Proceedings 6th International Symposium on Landslides*: 591–595.

Yang, H., Rahardjo, H. and Leong, E.C. (2006). Behavior of Unsaturated Layered Soil Columns during Infiltration. *Journal of Hydrologic Engineering, ASCE*. 11(4): 329-337.

Yang, H., Rahardjo, H., Wibawa, B. and Leong, E.C. (2004). A Soil Column Apparatus for Laboratory Infiltration Study. *Geotechnical Testing Journal, ASTM*. 27(4): 1-9.

Youngs, E.G. (1958). Redistribution of Moisture in Porous Materials after Infiltration. *Soil Science*. 86: 117-125.

Zhan, T.L.T. and Ng, C.W.W. (2004). Analytical Analysis of Rainfall Infiltration Mechanism in Unsaturated Soils. *International Journal of Geomechanics, ASCE*. 4(4): 273-284

Zhang, Z., Tao, M. and Morvant, M. (2005). Cohesive Slope Surface Failure and Evaluation. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 131(7): 898-906.