FLOW MECHANISM AND SUCTION DISTRIBUTION IN HETEREGENOUS RESIDUAL SOIL SLOPE UNDER RAINFALL INFILTRATION

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DEDICATION

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ABSTRACT

An imperative factor in rainfall induced slope failure is infiltration rate. Water that infiltrates into residual soil is predominantly controlled by two factors, i.e. rainfall intensity and saturated permeability of soil, which varies with depth as a result of weathering processes. Variation in permeability may either prevent or allow water to seep into deeper soil layers. Therefore, this study aimed to investigate the behaviour of suction distribution in a two-layered residual soil system consisting of Grade V and Grade VI residual soils with various saturated permeability functions using a laboratory physical slope model, in-situ or field work, and numerical modeling. The laboratory physical slope model was developed for the purpose of facilitating infiltration tests with three different permeability functions for each of the Grade V and Grade VI soils. A total of 42 infiltration tests were performed. The two-layered slope was then numerically simulated using SEEP/W GeoStudio software, which served to verify field data and determine the best modelling scheme that later be applied to signify the suction distribution behaviour of the residual soil slope model. Burrow holes present in the Grade VI soil layer caused the loss of the capillary barrier effect, which in turn allowed more rainfall to infiltrate into the soil layers. It was also found that when the ratio of permeability function between Grade V and Grade VI soils was high, an increase in the breakthrough time with corresponding decrease in the breakthrough matric suction occurred. From the seepage analysis, the numerical model incorporating burrow holes in Grade VI residual layer coupled with the effect of two sets of relict joints in Grade V yielded significant improvement in heterogeneous residual soil slope modelling. The findings of this study were then validated with previous findings using Prediction Accuracy (PA) analysis. It was established that burrow holes and two sets of relic joints conclusively improved the modelling of heterogeneous residual soil slope particularly at depths of 1.0 m and 1.5 m.

ABSTRAK

Faktor penting dalam kegagalan cerun disebabkan oleh hujan ialah kadar penyusupan. Air yang menyusup ke tanah sisa kebanyakannya dikawal oleh dua faktor, iaitu intensiti hujan dan kebolehtelapan tepu tanah, yang bervariasi dengan kedalaman akibat proses luluhawa. Variasi kebolehtelapan ini samada mencegah atau membenarkan air untuk menyusup masuk ke dalam lapisan yang lebih dalam. Oleh itu, objektif kajian ini adalah untuk mengenal pasti taburan sedutan bagi dua lapisan sistem tanah iaitu Gred V dan Gred VI dengan ciri-ciri fungsi kebolehtelapan tepu yang berlainan melalui fizikal model cerun makmal, data di tapak dan juga pemodelan berangka. Satu model fizikal cerun telah dibangunkan dalam makmal untuk ujian penyusupan dimana tiga kebolehtelapan yang berbeza bagi setiap lapisan Gred V dan lapisan Gred VI. Sebanyak empat puluh dua (42) ujian penyusupan telah dilakukan. Cerun dengan dua lapisan tanah itu kemudiannya disimulasi secara berangka menggunakan perisian SEEP/W GeoStudio, yang berfungsi untuk mengesahkan data lapangan dan menentukan skema pemodelan terbaik yang kemudiannya digunakan untuk mengesahkan taburan matrik yang terdapat di dalam cerun tanah baki. Kehadiran lubang jara pada Gred VI menyebabkan berlakunya kehilangan penghalang kapilari dan ini membenarkan lebih banyak air menyusup masuk ke dalam lapisan tanah. Keputusan juga mendapati bahawa apabila nisbah fungsi kebolehtelapan di antara Gred V dan Gred VI terlalu tinggi, akan meningkatkan masa keadaan bulus dan mengurang sedutan matrik pada keadaan bulus. Daripada analisis resipan, pembangunan pemodelan berangka dengan mengambil kira kehadiran lubang jara di lapisan Gred VI tanah berbaki bersama-sama dengan kesan dua set ketakselanjaran relikta di lapisan Gred V menunjukkan penambahbaikan yang ketara di dalam pemodelan cerun keheterogenan tanah berbaki. Kajian ini kemudiannya disahkan dengan dapatan kajian lepad dengan menggunakan kaedah Ketepatan Ramalan (PA). Didapati lubang jara dan dua set ketakselanjaran rekta secara menyeluruh telah menambaik pemodelan berangka cerun keheterogenan tanah berbaki terutama pada kedalaman 1.0 m dan 1.5 m.

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LIST OF ABBREVIATIONS

AEV	–	Air-Entry Value
IDF	–	Intensity Duration Frequency
PA	–	Prediction Accuracy
SWCC	–	Soil Water Characteristics Curve

LIST OF SYMBOLS

α	–	Coefficient of Hydraulic Conductivity Function
θr	–	Residual Water Content
ϕ	–	Inclination Angle
γ_w	–	Unit Weight of Water
h_a	–	Air-Entry Head of Fine Soil Layer
h_w	–	Air-Entry Head of Coarse Soil Layer
k_{sat}	–	Coefficient of Permeability
$P_{(t)}$	–	total input (rainfall intensity, irrigation)
Q	–	Storage Capacity
q	–	Infiltration Rate
${}^{R}I_{t}$	–	The average Rainfall Intensity (mm/hr) for ARI and duration t

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Rainfall-induced slope failures are common problems in many tropical areas covered by residual soil. Basically the soil profile in the area is from granitic formation and the existing of rainfall that decreased the matric suction caused a shallow rotational failure (Jamaludin & Hussein, 2006). Slope stability in residual soil and rainfall infiltration has a close relationship between each other. Experience has shown that many slopes failure occurred during or shortly after rainfall (Gavin and Xue, 2007). In general, many factors could govern the slope stability. Rainfall induced slope failure are normally governed by two factors, which are, rainfall intensity and coefficient of saturated permeability, k_{sat} (Chao *et al.,* 2013).

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 matured residual soil (Grade VI) of laterites (Bland & Rolls, 1998; Taylor & Eggleton, 2001; Aydin, 2006). The weathering process involved in the formation of residual soil introduces variation in material scale and also in field scale. In material scale, the weathering process cause the igneous rock to decompose to Grade IV (lateritic layer) and V (saprolitic layer). Therefore, it produced variations in grain size, porosity, mineralogy, lithologic texture, rock mechanical properties, structure and diagenetic processes. In field scale, the variation in residual soil because of discontinuities in soil mass such as relict joints, bedding planes, foliations, faults and shears happen in saprolitic layer. While in lateritic layer, insect population such as burrow holes govern the properties of soil such as density and hydraulic properties of soil (Bastardie, Capowiez, De Dreuzy, & Cluzeau, 2003). The permeability of lateritic layer can be as high as to 0.01 m/s within 1 m depth with the existence of burrow holes (Keith, 1992). Meanwhile, the permeability of saprolitic soil varies with depth, and the variation is within two orders of magnitude (Agus, Leong, & Rahardjo, 2005; Harianto Rahardjo, Satyanaga, Leong, Ng, & Pang, 2012).

Residual soil is commonly found in an unsaturated state because of the location of ground water table is well below the soil layer and possesses high matric suction, especially during dry seasons. However, the different in permeability in the soil layers, results in variation in suction distribution in the residual soil. This permeability value is a dominant factor that contributes to the changes of suction distribution in residual soil. At relatively dry conditions or high matric suctions, the fine-grained soil has a high coefficient of permeability, while the coarse-grained layer has an extremely low coefficient of permeability. When the infiltrating water starts to infiltrate from the surface, the coefficient of permeability of the fine grained layer increases gradually, while that of the coarse grained layer remains extremely low. As the infiltrating water accumulates and reaches the fine-coarse interface, the matric suction of the coarse-grained layer begins to decrease significantly. Once the matric suction of the coarse grained layer reaches its water-entry‟ value, (ψw), the coefficient of permeability of the coarse-grained layer increases rapidly and may exceed the coefficient of permeability of the fine-grained layer (Ross, 1990).

Many studies such as Kassim *et al.*, (2012), Kim and Lee, (2013), Lee, *et al.* (2011) and Trandafir *et al.* (2008) concluded that matric suction plays an important role in slope stability especially in residual soil. The slope failure happens due to total or partial loss of matric suction during rainfall infiltration and causes the shear strength of soil to decrease. At initial condition, when the matric suction is high, there is a greater initial factor of safety and hence the slope is stable. However, during rainfall, the matric suction decreases which eventually decreases the factor of safety of the slope. Previous studies have already demonstrated that matric suction contributes to the shear strength of soil. The rainfall intensity and duration affect the suction distribution in soil with an intermediate saturated permeability such as sandy silt, which is common type of residual soil (Gofar and Lee, 2008). Suction distribution in coarse-grained soil is greatly influenced by short and intense rainfall.

Prolonged rainfall event influences suction distribution in fine-grained soil (Gofar and Lee, 2008).

Many researchers proved that suction distribution is an important factor in slope stability of residual soil. Kassim *et al.* (2012), demonstrated the influence of incorporating relict discontinuities in the analysis of suction distribution. Their findings have shown that the suction distribution in simulated analysis in which relict discontinuities were considered would give the best fitted results with the measured field suction distribution. However, their research findings focused on one set of relict joint only, and could not represent the real site condition. Usually, four to five well-defined major sets of joints are found in the granitic and volcanic rocks at any locality. Two vertical to sub vertical joint sets are commonly developed as the principal sets (Irfan, 1998). The effect of relict joint with more than one set of relict joint is required to validate the flow mechanism and suction distribution in the residual soil slope. The activities of insect or fauna in lateritic layer can also modify the permeability function of this layer. Therefore, this factor should also be take into account in the analysis of suction distribution in residual soil. By considering factors that contribute to the permeability of saprolitic and lateritic layer, the actual hydraulics properties of the residual soil profile can be obtained and suction distribution and flow mechanism in residual soil can be fully understood.

1.2 Problem Statement

Shallow landslides have been studied for practical and scientific reasons. In spite of their limited size, shallow landslides pose a significant hazard to communities because they are often difficult to predict, and they can result in debris flow which is potentially destructive due to their velocity and their bulking capability during propagation. Many factors contribute to this type of failure. These factors can be categorized into two; i.e. intrinsic factor and external factor. The main intrinsic factor is related to hydraulic conductivity of the soil. While the external factors mainly refer to climatic condition such as rainfall duration and intensity.

Studies of residual soil properties from Singapore have shown that the index and engineering properties of residual soil vary with depth (Rahardjo *et al.* 2012). While in the field scale, the relict discontinuities such as joints, faults, foliation, bedding planes appear in saprolitic layer. In lateritic layer, the existence of insect population such as burrow hole results in the variation of permeability of this layer (Keith, 1992). All these factors contribute to the heterogeneity in residual soil. The heterogeneity of this soil profile produced chaotic phenomena which serve as signal before slope failure occurs (Aydin, 2006). However, previous studies only focused on saprolitic layer with one type of relict joint and ignored lateritic joint profile. On this note, development of model that can incorporate all these factors to evaluate suction distribution and flow mechanism in the analysis of slope failure will certainly bridge the vacuum gap. Therefore, this study is conceptualized to tackle this challenge.

1.3 Objectives

The aim of this study is to model a flow mechanism effect on suction distribution in tropical residual soil slope subjected to different rainfall intensity. The objectives of the study are as follows:

i. To study the effect of relict joint set on the saturated permeability (k_{sat}) of residual soil layer (lateritic layer).
ii. To analyse the effect of burrow holes on the saturated permeability (k_{sat}) of residual soil layer (saprolitic layer).
iii. To determine the suction distribution behaviour and flow mechanism on two-layered residual soil with relict joint set and burrow hole subjected to various rainfall intensity and duration.
iv. To model flow mechanism effect on suction distribution in tropical residual soil slope with existing of two set of relict joint in saprolitic layer and burrow holes in lateritic layers subjected to different rainfall intensity

1.4 Scopes of the Study

This study presents the investigation of flow mechanism and suction distribution in a two-layered system of tropical residual soil slope with the presence of relict joint sets in saprolitic layer and burrow hole in lateritic layer. Two research approaches i.e. laboratory physical modeling and numerical modeling were followed to achieve the objectives of this study. Considering the analyses focused on an infinite slope, suction distribution at crest, middle and toe of the slope were considered to be the same. Therefore, the analyses emphasis on suction distribution at middle of the slope.

Soil samples were collected from the Balai Cerap, Universiti Teknologi Malaysia, Skudai area. Their index and engineering properties were determined in the laboratory. The determined soil properties were used in the numerical analysis. Similarly, these soil samples were also used in the laboratory physical model. The laboratory physical modeling was conducted with two layered soil with the incorporation of artificial relict joint and burrow holes artificially incorporated. The laboratory modelling was conducted at Geotechnical Engineering laboratory, School of Civil Engineering, UTM. The slope infiltration model used was of 1000 mm in length, 300 mm in width and 600 mm in height and tilted at slope angle of 18^o. This angle is a typical slope angle used in slope construction. The slope model is instrumented with tensiometers to measure suction distribution during the infiltration test. The experimental program performed was divided into two schemes, i.e. a two-layered soil with two sets of artificial relict joint and a two- layered soil with two set of artificial relict joint and burrow holes.

Numerical analysis was performed to simulate the effect of flow mechanism and suction distribution in tropical residual soil slope under different rainfall intensities. The simulation was carried out using commercial software Seep/W.

1.5 Significance of Study

The findings from this research will be used as improved method of the existing laboratory and numerical analysis in residual soil slope. The benefits that could be derived from this research include the following:

a. Provide knowledge on suction distribution in analyzing slope stability in residual soil with the presence of two relicts joint set subjected to various rainfall intensities.
b. Provide knowledge on suction distribution in analyzing slope stability in residual soil with the presence of burrow holes subjected to various rainfall intensities.
c. To develop a model of flow mechanism in residual soil slope with the consideration of soil of heterogeneity under to different rainfall intensities.

1.6 Thesis Organization

This thesis consists of seven chapters. The thesis starts with Chapter One as Introduction; Chapter Two, Literature Review; Chapter Three, Methodology; Chapter Four, Suction distribution due to one relict joint and two relicts joint; Chapter Five, Laboratory modeling; Chapter Six, Numerical Modelling and the last chapter or Chapter Seven is for Conclusions and Recommendations.

Chapter one presents the background of the study which include problem statement, objectives of the study, scope of the study and significance of the study. The Chapter also described various studies from previous researchers related to this topic.

Chapter two describes the detailed theories and concepts related to this study as outlined by previous researchers. The unsaturated soil theory is the main concept of this study and it should be fully understood. Therefore, after introduction details of unsaturated soil theory were contained. This was followed by explaining rainfall characteristics especially in Malaysia. The macrospores or burrow holes and contribution of this to k_{sat} are detailed in Part 2.5. The phenomenon of capillary barrier which influences the flow of water in residual soil is also contained in this chapter. Lastly, the chapter describes the physical and numerical modeling processes.

Chapter three describes the methodology which includes the material and procedure followed in this study. Basically, the methodology followed to achieve the objectives of this study is divided into two parts; laboratory works and numerical works. The laboratory work is further separated into two parts; testing for soil properties and physical modeling of the study.

The comparison of suction distribution between soil with one relict joint and two relicts joint was discussed in detail in Chapter 4. Results of analysis from pervious study by Lee, *et al*, (2011) stated that the minimum suction value in a residual soil is affected by the rainfall intensity, rainfall duration, and the saturated permeability of the soil. Therefore, the comparison between suction distribution, time to achieve minimum suction and also moisture content are discussed in Chapter 4.

Burrow holes in lateritic soil is another main factor that govern the permeability of soil and hence, affects the flow mechanism in residual soil. Results from permeability test of burrow holes and also two sets of relict are discussed in detail in this chapter. Flow mechanism of two-layer soil with the presence of two relicts joint and burrow holes are included in the Chapter 5.

Numerical modeling is another scope of this study and is explained in Chapter 6. The procedure of determining the best model that can fit the previous field suction distribution data is contained in this chapter. Data from field works are used to verify the results from numerical model. The presence of two relicts joint and burrow holes are included in the numerical analysis. Lastly, the summary of findings, conclusions and recommendations for further study are presented in Chapter 7.

REFERENCES

Agus, S. S., Leong, E.-C., & Rahardjo, H. (2005). Estimating permeability functions of Singapore residual soils. *Engineering Geology*, *78*(1–2), 119–133.

Alaoui, A., Caduff, U., Gerke, H. H., & Weingartner, R. (2011). APreferential Flow Effects on Infiltration and Runoff in Grassland and Forest Soils. *Vadose Zone Journal*, *10*(1), 367.

Arikan, F., & Aydin, N. (2012). Influence of Weathering on the Engineering Properties of Dacites in Northeastern Turkey. *ISRN Soil Science*. 2012, 1.

Aydin, A. (2006). Stability of saprolitic slopes: nature and role of field scale heterogeneities. *Natural Hazards & Earth System Sciences*, (1984), 89–96.

Aydin, A., & Duzgoren-Aydin, N. (2002). Indices for scaling and predicting weathering-induced changes in rock properties. *Environmental & Engineering Geoscience*. 8(2), 121-135

Bastardie, F., Capowiez, Y., De Dreuzy, J. R., & Cluzeau, D. (2003). X-ray tomographic and hydraulic characterization of burrowing by three earthworm species in repacked soil cores. *Applied Soil Ecology*, *24*(1), 3–16.

Beven, K., & Peter Germann. (1982). Macropores and Water Flow in Soils. *Water Resoources Research*, *18*(October), 1311–1325.

Bland, W. and Rolls, D. (1998). *Weathering: An Introduction to the Scientific Principles*. Arnold, Hodder Headline, PLC.

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.

Brand, E. W. 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

Chao, W., Min, L., Cai, H., Jie, H., Dai, F. C., & Long, M. (2013). Combined roles of saturated permeability and rainfall characteristics on surficial failure of homogeneous soil slope, *153*, 105–113.

Chen, H., Lee, C.F. and Law, K.T. (2004). Causative Mechanism of Rainfall-Induced Fill Slopes Failures. *Journal of Geotechnical and Geoenvironmental Engineering*. 130(6) : 593-602

Cho, S. E. (2016a). Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration. *Engineering Geology*, 211, 184–197.

Cho, S. E. (2016b). Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration. *Engineering Geology*. 211, 184-197

Cho, S., & Lee, S. (2001). Instability of unsaturated soil slopes due to infiltration. *Computers and Geotechnics*. 28, 185–208.

Dai, F.C., Lee, C.F. and Wang, S.J. (2003). Characterization of Rainfall-induced Landslides. *International Journal of Remote Sensing*. 24(23), 4817-4834.

Day, R.and Axten, G. (1989). Surficial Stability of Compacted Clay Slopes. *Journal of Geotechnical Engineering*. 115(4), 577-580.

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

Fourie, A.B. (1996). Predicting Rainfall-Induced Slope Instability. *Proceedings of the Instituition of Civil Engineer - Geotechnical Engineering*. 119, 211-218.

Fredlund, D.G. (1995). The Scope of Unsaturated Soil Mechanics: An Overview. *Proceedings of the First International Conference on Unsaturated Soils*. Paris, France: Balkema, Rotterdam, the Netherlands, 1155-1177

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

Fredlund, D.G., Sheng, D. and Zhao, J. (2011). Estimation of Soil Suction from the Soil-Water Characteristics Curve. *Canadian Geotechnical Journal*. 48(2), 186-198.

Gasmo, J., Rahardjo, H., & Leong, E. (2000). Infiltration effects on Stability of a Residual Soil Slope. *Computers and Geotechnics*. 26, 145–165.

Gavin, K. and Xue, J. (2007). A simple method to analyze infiltration into unsaturated soils slopes. *Computer Geotech*. 3(2), 223-230.

GEO-SLOPE International Ltd. (2007). *Seepage Modelling with SEEP/W*. Calgary, Alta., Canada.

Gerscovich, D.M.S., Vargas Jr, E.A. and de Campos, T.M.P. (2006). On the Evaluation of Unsaturated Flow in a Natural Slope in Rio de Janeiro, Brazil. *Engineering Geology*. 88(1-2), 23-40.

Gofar, N., & Lee, L. M. (2008). Response of Suction Distribution to Rainfall Infiltration in Soil Slope Selection of Study Areas. *Electronic Journal of Geotechnical Engineering*, (2008).

Gofar, N., Lee, M., & Kassim, A. (2012). Effect of surface boundary condition on rainfall infiltration. *Jurnal Teknologi*. 44, 63–70.

Gofar, N., & Min Lee, L. (2008). Extreme rainfall characteristics for surface slope stability in the Malaysian Peninsular. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*. 2(2), 65–78.

Gui, M.-W., & Wu, Y.-M. (2014). Failure of soil under water infiltration condition. *Engineering Geology*. 181, 124–141.

Hakro, M. R., & Harahap, I. S. H. (2015). Laboratory experiments on rainfall-induced flowslide from pore pressure and moisture content measurements. *Natural Hazards and Earth System Sciences Discussions*. 3(2), 1575–1613.

Hendrickx, J. M. H., & Flury, M. (2001). Uniform and Preferential Flow Mechanisms in the Vadose Zone. *Conceptual models of flow and transport in the fractured vadose zone*.

Huat, B. B. K., Ali, F. H. J., & Low, T. H. (2006). Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. *Geotechnical and Geological Engineering*. 24(5), 1293–1306.

IAEG (1980). Rock and Soil Description for Engineering Geological Mapping. *International Association of Engineering Geology Bulletin*. 24, 235-274

Ibrahim, A., Mukhlisin, M., & Jaafar, O. (2013). Numerical assessment of rainfall infiltration into soil column for the unsaturated layered residual forest soil. *Jurnal Teknologi (Sciences and Engineering)*. 65(2), 121–127.

Irfan, T. Y. (1998). Structurally controlled landslides in saprolitic soils in Hong Kong. *Geotechnical and Geological Engineering, 16*(3), 215–238.

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

Jamaludin, S., & Hussein, A. N. (2006). Landslide hazard and risk assessment : The Malaysian experience. In *IAEG 2006*, 1–10.

Jarvis, N., Koestel, J., & Larsbo, M. (2016). Understanding Preferential Flow in the Vadose Zone: Recent Advances and Future Prospects. *Vadose Zone Journal*. 15(12).

Kassim, A. (2011). *Modelling the Effect of Heterogeneities on Suction Distribution*

Behaviour in Tropical Residual Soil. Phd Thesis UTM.

Kassim, A., Gofar, N., Lee, L. M., & Rahardjo, H. (2012). Modeling of suction distributions in an unsaturated heterogeneous residual soil slope. *Engineering Geology*. 131–132, 70–82.

Keith, S. R. J. (1992). The Relation of Earthworms to Soil Hydraulic Properties. *Soil Biology Biochemical*. 24(12), 1539–1543.

Kim, Y.-T., & Lee, J.-S. (2013). Slope Stability Characteristic of Unsaturated Weathered Granite Soil in Korea considering Antecedent Rainfall. *Geo-Congress 2013*, 394–401.

Kim, J., Jeong, 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.

Klaus, J., Zehe, E., Elsner, M., Külls, C., & McDonnell, J. J. (2013). Macropore flow of old water revisited: Experimental insights from a tile-drained hillslope. *Hydrology and Earth System Sciences*. 17(1), 103–118.

Krisdani, H., Rahardjo, H., & Leong, E.C. (2006). Experimental study of 1-D Capillary Barrier Model using Geosynthetic material as the Coarse-grained Layer. In *Geotechnical Special Publication*. 1683–1694.

Kung, K.-J. S. (1990). Preferential Flow in a Sandy Vadose Zone: 1. Field observation. *Geoderma*. 46(1–3), 51–58.

Laloui, L., Tombolato, S., Pisoni, G., Munoz, J. J., Rojas, J. C., De Gennaro, V., Tarantino, A. (2011). Benchmark of experimental techniques for measuring and controlling suction. *Géotechnique*. 61(4), 303–312.

Lee, L. M., Kassim, A., & Gofar, N. (2011). Performances of two instrumented laboratory models for the study of rainfall infiltration into unsaturated soils. *Engineering Geology*. 117(1–2), 78–89.

Lee, M.L., Ng, K.Y., Huang, Y.F. and Li, W.C. (2014). Rainfall-Induced Landslides in Hulu Kelang Area, Malaysia. *Natural Hazards*. 70(1), 353-375.

Li, J. H., Du, L., Chen, R., & Zhang, L. M. (2013). Numerical Investigation of the Performance of Covers with Capillary Barrier effects in South China. *Computers and Geotechnics*. 48, 304–315.

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

Liu, C., He, P., & Huang, Q. (2011). Influence of matrix suction on engineering properties of unsaturated soil. *2011 Second International Conference on Mechanic Automation and Control Engineering*. (1), 2250–2253.

Lv, M., Hao, Z., Liu, Z., & Yu, Z. (2013). Conditions for Lateral Downslope Unsaturated Flow and effects of Slope Angle on Soil Moisture Movement. *Journal of Hydrology*. 486, 321–333.

Maail, S., Huat, B., & Jamaludin, S. (2004). Index, Engineering Properties and Classification of Tropical Residual Soils. *Tropical Residual Soils*. 37–55.

Macdonald, A. M., Maurice, L., Dobbs, M. R., Reeves, H. J., & Auton, C. A. (2012). Relating in situ Hydraulic Conductivity, Particle Size and Relative Density of Superficial Deposits in a Heterogeneous Catchment. *Journal of Hydrology*. 434–435, 130–141.

Matsushi, Y., Hattanji, T. and Matsukura, Y. (2006). Mechanism of Shallow Landslides on Soil-Mantled Hillslopes with Permeable and Impermeable Bedrocks in the Boso Peninsula, Japan. *Geomorphology*. 76 (1-2), 92 -108

Mclean, A.C. and Gribble, C.D. (1979). Geology for Civil Engineers. *Publication of Allen (George) and Unwin.*

Md. Noor, M.J. (2011). *Understanding Rainfall-Induced Landslide*. UiTM Press: Universiti Teknologi Mara, Shah Alam, Malaysia.

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

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

Mukhlisin, M., & Taha, M. R. (2012). Numerical model of antecedent rainfall effect on slope stability at a hillslope of weathered granitic soil formation. *Journal of the Geological Society of India*. 79(5), 525–531.

Muller, J.R. and Martel, S.J. (2000). Numerical Models of Translational Landslide Rupture Surface Growth. *Pure and Applied Geophysics* 157: 1009-1038.

Nimmo, J. R., Survey, U. S. G., & Park, M. (2012). Preferential fl ow occurs in unsaturated conditions, 789(September 2011), 786–789.

Novák, V., Šimåunek, J., & Genuchten, M. T. van. (2000). Infiltration of Water into Soil with Cracks. *Journal of Irrigation and Drainage Engineering*.

Oh, W. T., & Vanapalli, k S. (2013). Integrated Slope Stability Analyses of

Wastewater Storage Structure extending the Capillary Barrier Technique. *Geotechnical Special Publication*, (ASCE 2013), 363–372.

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

Rahardjo, H., Aung, K., Leong, E., & Rezaur, R. (2004). Characteristics of residual soils in Singapore as formed by weathering. *Engineering Geology*, *73*(1–2), 157–169.

Rahardjo, H., Aung, K. K., Leong, E. C., & Rezaur, R. B. (2002). Effects of Pore-Size Distribution on Engineering Properties of Residual Soils. *World Engineering*. 70–76.

Rahardjo, H., Leong, E., & Rezaur, R. (2008). Effect of antecedent rainfall on pore-water pressure distribution characteristics in residual soil slopes under tropical rainfall. *Hydrological Processes*. 523(October 2007), 506–523.

Rahardjo, H., Li, X., Toll, D., and Leong, E. (2001). The effect of antecedent rainfall on slope stability. *Unsaturated Soil Concepts and Their Application on Geotechical Practices*. 19, 371-399.

Rahardjo, H., & Lim, T. (1995). Shear-strength characteristics of a residual soil. *Canadian Geotechnical Journal*. 31(1), 60-77

Rahardjo, H., Nio, A. S., Leong, E. C., & Song, N. Y. (2010). Effects of Groundwater Table Position and Soil Properties, (November), 1555–1564.

Rahardjo, H., Santoso, V. A., Leong, E. C., Ng, Y. S., & Hua, C. J. (2012). Performance of an Instrumented Slope Covered by a Capillary Barrier System. *Journal of Geotechnical and Geoenvironmental Engineering*, *138*(4), 481–490.

Rahardjo, H., Satyanaga, A., & Leong, E.C. (2013). Effects of flux boundary conditions on pore-water pressure distribution in slope. *Engineering Geology*, *165*, 133–142. https://doi.org/10.1016/j.enggeo.2012.03.017

Rahardjo, H., Satyanaga, A., Leong, E.-C., Ng, Y. S., & Pang, H. T. C. (2012). Variability of residual soil properties. *Engineering Geology*, *141–142*, 124–140.

Rahman, Z., & Hamzah, U. (2010). Influence of oil contamination on geotechnical properties of basaltic residual soil. *American Journal of Applied Science*, *7*(7), 954–961.

Regmi, R. K., Nakagawa, H., Kawaike, K., & Baba, Y. (2011). Experimental and Numerical Study of Rainfall Induced Slope Failure. *Annuals of Disaster Prevention Resistant Instrumentations, Kyoto Univ*. (54).

Ross, B. (1990). The diversion capacity of capillary barriers. *Water Resources Research*. 26(10), 2625–2629.

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

Singh, H., Huat, B., Sew, G., & Ali, F. (2004). Origin, formation and occurrence of tropical residual soils. *Tropical Residual Soils*. 1–19.

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.

Steenhuis, T.S., Parlange, J. and Kung, K.J.S. (1991). Comment on "The Diversion Capacity of Capillary Barrier." by Benjamin Ross. *Water Resources Research*. 27(8), 2155-2156.

Sun, D., Zang, Y., & Semprich, S. (2015). Effects of Airflow Induced by Rainfall Infiltration on Unsaturated Soil Slope Stability. *Transport in Porous Media*. 107(3), 821–841.

Talib, Z. A., Kassim, A., & Yunusa, G. H. (2016). Influence of Relict Joints on Permeability of Residual Soil. *IOP Conference Series: Materials Science and Engineering*. 136(1), 6–12.

Tami, D., Rahardjo, H., Leong, E.-C., & Fredlund, D. (2004). A Physical Model for Sloping Capillary Barriers. *Geotechnical Testing Journal*. 27(2), 11431.

Taylor, G. and Eggleton, R. A. (2001). *Regolith geology and geomorphology*. John Wiley and Sons, New York.

Trandafir, A.C., Sidle, R.C., Gomi, T. and Kamai, T. (2008). Monitored and Simulated Variations in Matric Suction during Rainfall in a Residual Soil Slope. *Environmental Geology*. 55, 951-961.

Tsaparas, I., Rahardjo, H., Toll, D., & Leong, E. (2002). Controlling parameters for rainfall-induced landslides. *Computers and Geotechnics*. 29(1), 1–27.

Wang, D., Lowery, B., Norman, J. M., & Mc Sweeney, K. (1996). Ant burrow effects on water flow and soil hydraulic properties of Sparta sand. *Soil Tillage Res*. 37, 83–93.

Wang, L., & Liu, C. R. (2012). Analysis of the Influences of Matric Suction of Unsaturated Soil on the Slope Stability. *Applied Mechanics and Materials*, *170–173*, 3186–3189.

Weiler, M. (2005). An infiltration model based on flow variability in macropores:

development, sensitivity analysis and applications. *Journal of Hydrology*. 310, 1–4,

Wu, L. Z., Zhou, Y., Sun, P., Shi, J. S., Liu, G. G., & Bai, L. Y. (2017a). Laboratory characterization of rainfall-induced loess slope failure. *CATENA*. 150, 1–8.

Wu, L. Z., Zhou, Y., Sun, P., Shi, J. S., Liu, G. G., & Bai, L. Y. (2017b). Laboratory characterization of rainfall-induced loess slope failure. *Catena*. 150(September), 1–8.

Yubonchit, S., Chinkulkijniwat, A., Horpibulsuk, S., Jothityangkoon, C., Arulrajah, A., & Suddeepong, A. (2017). Influence Factors Involving Rainfall-Induced Shallow Slope Failure: Numerical Study. *International Journal of Geomechanics*. 17(7).

Zêzere, J.L., Trigo, R.M. and Trigo, I.F. (2005). Shallow and deep landslide induced by Rainfall in the Lisbon Region (Portugal). Assessment of Relationship with the North Atlantic Oscillation. *Natural Hazards and Earth System Science*. 5(3), 331-344.

Zhai, Q., & Rahardjo, H. (2012). Determination of soil–water characteristic curve variables. *Computers and Geotechnics*. 42, 37–43.

Zhan, T., & Ng, C. (2004). Analytical analysis of rainfall infiltration mechanism in unsaturated soils. *International Journal of Geomechanics*. (December), 273–284.

Zhang, J., Jiao, J. J., & Yang, J. (2000). In situ rainfall infiltration studies at a hillside in Hubei Province, China. *Engineering Geology*. 57(1–2), 31–38.

Zhang, L.L., Zhang, J., Zhang, L.M. and Tang, W.H. (2011). Stability Analysis of Rainfall-Induced Slope Failure. *Proceedings of the Institution of Civil Engineering - Geotechnical Engineering*. 164(GE5), 299-316.

Zhang, X., Zhu, Y., & Fang, C. (2009). The Role Fore Air Flow in Soil Slope Stability Analysis. *Journal of Hydrodynamics, Ser. B*. 21(5), 640–646.