EFFECT OF TRANSPORT LAYER SYSTEM ON SUCTION DISTRIBUTION FOR TROPICAL RESIDUAL SOIL SLOPES

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2015

I recognise and appreciate the life-long influences of my parent, my teachers, my wife, my children, my family and my friends, whom have been the source of inspiration in my life. This thesis is dedicated to all of them.

ACKNOWLEDGEMENTS

All praise is due to Allah, the lord of the worlds. With HIS will, guidance and blessings this thesis was successfully completed. May HIS peace and blessing be upon our noble Prophet Muhammad (S.A.W).

At this juncture, I wish to express my utmost gratitude, indebtedness and appreciation to all who contributed towards the success of this research. First and foremost is my main supervisor, Associate Professor Ir. Dr. Azman bin Kassim for his dedications, patience, encouragements, critics and fatherly advice throughout the course of the research. The same goes to my external co-supervisor, Dr. Nurly Gofar of School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.

I equally extend my appreciation to all the Staff and Technicians of the Department of Geotechnics and Transportations, Faculty of Civil Engineering, Universiti Teknologi Malaysia, my colleagues in the Department of Civil Engineering, Bayero University Kano and Assoc. Prof. Dr Muhammad Mukhlisin of University Kebangsaan Malaysia for assisting me to use his pressure plate equipment during my laboratory testing. The management of Bayero University Kano and Tertiary Education Trust Fund (TETFund) Nigeria needs to be acknowledged for extending a financial support through the TETFund grants. I warmly thank my wife (Zainab Umar) and children (A'ishah, Maryam and Muhammad) for their love, patience and encouragement during the trial moments. Lastly, to all my friends, research colleagues, brothers and sisters, unfortunately your names are too many to be mention in this limited space; however, I deeply acknowledged and appreciate all your effort.

ABSTRACT

Substantial surficial deposits of many tropical climate regions are covered by tropical residual soils. The weathering process forms a layered sloping soil of Grade VI and Grade V soil mantle with variable hydraulic conductivities, k_{sat} which creates capillary barrier effect at the interface of Grade VI and Grade V soil layers. Although the capillary barrier effect impedes downward water infiltration, the water diversion capacity is limited and the moisture content increases at the interface that can lead to potential slope failure. Hence, this study investigates the effects of employing transport layer to increase the diversion capacity at the interface of Grade VI and Grade V soil layers via laboratory experiments, field monitoring and numerical modelling. A laboratory physical slope model was developed to perform infiltration tests with five (5) configuration schemes of Grade V and Grade VI soils sandwiched by four (4) different types of transport layer, i.e. Gravel, Drainage Cell (DC)+Gravel, Sand and DC+Sand, and without transport layer. A total of thirty two (32) infiltration tests were performed in this study. Three research plots i.e. a control plot without transport layer and two (2) plots with sand transport layer as well as with gravel transport layer were constructed and instrumented to monitor rainfall, runoff, amount of diverted water and matric suction distribution. The monitoring was performed during wet period from September 2014 to January 2015 where the soil experienced high water content but low matric suction. Subsequently, the two-layered slope with and without the transport layers was numerically simulated using a finite element method to validate the field data and to determine the best modelling scheme to represent the residual soil slope model with transport layers. The results of the laboratory experiments clearly shows that the transport layer sandwiched between the Grade VI and Grade V soil layers was capable of diverting the infiltrating water above the interface. There was a significant increase of matric suction measured at the interface of soil layers with DC + Gravel transport layer as compared to that without the transport layer especially for 2-hr and 24-hr rainfall intensities while the effect was insignificant for 7-day rainfall intensity. Field monitoring also indicates that the initial matric suction value in the control plot responded to the infiltration and reached a matric suction value that corresponds to the breakthrough suction of 5.0 kPa after series of rainfalls. However, the initial matric suction values were relatively maintained in the plots with transport layers to indicate that the transport layer played the role of increasing the amount of diverted water at the interface. The finding was supported by the results of amount of diverted water collected at the research plots. Continuum model is capable of modelling the effects of employing transport layer at the interface by subdividing the layer into multiple isolated zones with different average k_{sat}. The results of the analysis demonstrated that the capability of transport layer to maintain the matric suction and to divert water was governed by the contrast in the k_{sat} where the higher k_{sat} of gravel shows a better performance as compared to sand. A combination of initial suction at 30 kPa, 0.5 m thickness of sandy silt (Grade VI), 0.3 m thickness of gravel transport layer and 21° slope angle resulted in a diversion length of more than 15 m. However, the lower initial suction value due to rainfall infiltration during wet period yielded a shorter diversion length.

ABSTRAK

Kebanyakan endapan permukaan bagi kawasan iklim tropika adalah diliputi tanah baki tropika. Proses luluhawa membentuk satu lapisan tanah bercerun dari Gred VI dan Gred V dengan keberaliran hidraulik tepu, k_{sat} berbeza yang menyebabkan berlakunya kesan halangan rerambut di antara muka lapisan Gred VI dan Gred V. Walaupun kesan halangan rerambut ini menghalang penyusupan air lebih dalam, namun kesan ini akan hilang akibat saliran yang kurang baik dan berupaya mengagalkan cerun kerana tanah kandungan lembapan meningkat di antara muka. Oleh itu, kajian ini menyiasat kesan penggunaan lapisan pengangkut untuk meningkatkan kapasiti lencongan air di antara muka lapisan Gred VI dan Gred V melalui eksperimen makmal, pemantauan tapak dan pemodelan berangka. Satu model fizikal cerun telah dibangunkan dalam makmal untuk ujian penyusupan di mana lima (5) skema konfigurasi lapisan Gred VI dan Gred V mengapit empat (4) jenis lapisan pengangkut iaitu Kelikir, Sel Saliran (DC)+Kelikir, Pasir dan DC+Pasir, dan tanpa lapisan pengangkut. Sejumlah tiga puluh dua (32) ujian penyusupan telah dilakukan bagi kajian ini. Tiga plot kajian iaitu satu plot kawalan tanpa lapisan pengangkut dan dua plot mempunyai satu lapisan pengangkut pasir dan satu lapisan pengangkut kelikir telah dibina bagi merekodkan kadar hujan, air larian, jumlah air lencongan dan taburan sedutan matrik. Pemantauan tapak dijalankan dalam musim hujan bermula dari bulan September 2014 hingga Januari 2015 ketika tanah mengandungi kandungan air yang tinggi tetapi sedutan matrik yang rendah. Seterusnya, cerun dua lapisan tanah ini yang mempunyai lapisan pengangkut dan tanpa lapisan pengangkut telah disimulasi secara pemodelan berangka menggunakan kaedah unsur terhingga bagi mengesahkan data lapangan dan untuk mengenalpasti pemodelan berangka yang terbaik bagi mewakili model cerun tanah baki yang mengandungi lapisan pengangkut. Keputusan eksperimen makmal jelas menunjukkan lapisan pengangkut yang diapit antara lapisan Gred V dan Gred VI mampu melencong air yang menyusup di atas permukaan. Terdapat peningkatan yang ketara pada sedutan matrik yang diukur pada di antara muka bagi lapisan tanah dengan DC+lapisan pengangkut kerikil berbanding tanpa lapisan pengangkut untuk keamatan hujan 2 jam dan 24 jam, tetapi hanya sedikit perubahan bagi keamatan hujan 7 hari. Pemantauan tapak pula menunjukkan bahawa nilai sedutan matrik awal berubah dalam plot kawalan akibat tindak balas terhadap penyusupan air hujan dan mencapai nilai akhir yang sama dengan sedutan matrik pada keadaan bulus iaitu 5.0 kPa selepas beberapa siri hujan. Namun, nilai sedutan matrik awal adalah relatif dengan nilai akhir bagi plot dengan lapisan pengangkut menunjukkan keberkesanan keupayaan lapisan pengangkut untuk meningkatkan kapasiti lencongan air di antara muka tanah. Hasil keputusan ini disokong dengan jumlah air yang dilencongkan meningkat di plot tapak kajian tersebut. Model selanjar berkebolehan memodelkan kesan penggunaan lapisan pengangkut di antara muka tanah ini dengan kaedah membahagikan lapisan tanah kepada berbilang zon terasing yang mempunyai berlainan purata k_{sat}. Keputusan analisis model ini menunjukkan bahawa keupayaan lapisan pengangkut untuk mengekalkan sedutan matrik dan jumlah air yang dilencongkan dipengaruhi oleh k_{sat} di mana nilai k_{sat} bagi kerikil yang lebih tinggi menunjukkan prestasi yang lebih baik berbanding dengan pasir. Gabungan sedutan matrik permulaan pada 30 kPa, ketebalan 0.5 m bagi tanah sandy silt (Gred VI) dan 0.3 m bagi lapisan pengangkut kerikil serta sudut cerun 21° mampu menghasilkan panjang lencongan sehingga 15 m. Bagaimanapun dengan nilai sedutan matrik permulaan yang lebih rendah akibat penyusupan air semasa musim hujan menghasilkan panjang lencongan lebih pendek.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Several triggering factors on the failure of unsaturated residual soil slopes have been identified and discussed in many literatures. These factors include climatic conditions, geological features, earthquake shaking, topography, vegetation, construction activities or combination of these factors (Keefer *et al.*, 1987; Cho and Lee, 2001; Dai *et al.*, 2002; Ost *et al.*, 2003; Basile *et al.*, 2003; Rahardjo *et al.*, 2005; Rahardjo *et al.*, 2014). Some of these factors such as construction activities (excavation and filling of slopes) and changes in the slope's topography can be avoided. However, other factors such as climatic condition, earthquake and geological factors are inevitable and peculiar to geographical locations.

In most of the tropical regions like Malaysia where the residual soil slope frequently exist in unsaturated condition with deep groundwater table, slope failures usually occur due to rainfall infiltration. Many literatures, have shown that rainfall infiltration is the most significant triggering factor to slope instability in tropical regions (e.g. Brand, 1984; Anderson and Sitar, 1995; Lim *et al.*, 1996; Toll *et al.*, 1999; Tsaparas *et al.*, 2002; Chen *et al.*, 2004; Collins and Znidarcic, 2004; Rahardjo *et al.*, 2007c; Tu *et al.*, 2009; Zhang *et al.*, 2014; Dou *et al.*, 2015). Rainfall infiltration certainly affects both hydraulic properties and shear strength properties of unsaturated soils, which invariably affect the stability of the soil slope. It eliminates the shear strength of the soil, especially during monsoon seasons when the soil is subjected to prolonged or intense rainfall events

(Zhang *et al.*, 2005). Thus, rainfall infiltration makes rainfall-induced slope failure a major persistent and devastating natural disaster. It results in loss of lives, various form of severe injuries, destruction of public infrastructures and considerable loss of properties in several tropical climate countries.

In tropical regions which experienced period of intense or prolonged rainfall events, heavy rainfalls along with hot temperature and other humid climatic conditions result in the formation of deep residual soil profile. This residual soil commonly exists in unsaturated conditions, with presence of negative pore-water pressure or matric suction. The negative pore-water pressure contributes additional shear strength to the unsaturated residual soil. This additional shear strength normally ceases or reduces considerably enough to trigger slope failure due to loss of matric suction as wetting front progresses from the ground surface (Fredlund and Rahardjo, 1993; Rahardjo *et al.*, 1995a; Rahardjo, *et al.*, 2005; Md.Noor, 2011; Fredlund *et al.*, 2012).

Residual soil which can be defined as soils that formed in-situ as a result of weathering process, and which have not been subjected to any movement or transportation is found to be in abundance and covers substantial surficial deposits in many tropical regions (Taha *et al.*, 1997; Agus *et al.*, 2001; Huat and Toll, 2012). Residual soil is normally considered as the uppermost layer (Grade VI) of the soil profile according to the six-fold weathering classification system of International Society for Rock Mechanics (ISRM, 1981) and it is considered as true or mature residual soils (or as lateritic soils) which exist over saprolite. The saprolite refers to that portion of the weathering profile where the soil mostly preserves the microfabric and volume of its parent rock (Aydin *et al.*, 2000). Thus, residual soil consists of materials that are predominantly decomposed to Grade IV and Grade V of the weathering profile. The mature and the saprolitic soils together are often referred to as the tropical residual soils (Bland and Rolls, 1998; Taylor and Eggleton, 2001; Aydin, 2006).

One of the common inherent features of tropical residual soil mantle is heterogeneity, which occurs due to weathering process. For instance, weathering of parent rocks create heterogeneity in the weathering profile which forms zones of material with variable hydraulic conductivities and which are commonly aligned parallel to natural surface (Chigira, 2001). Heterogeneity in residual soil causes variations in particle sizes, porosity and mineralogy, which in turn causes variations in hydraulic conductivity and storage capacity. Thus, it controls water flow through the residual soil profile. The water flow is found to govern the distribution and variation of negative pore-water pressure in unsaturated residual soils (Zhan and Ng, 2004).

Some common form of heterogeneity in tropical residual soil mantle such as the relict discontinuities are found in saprolitic soil i.e. in Completely Weathered - Highly Weathered (CW - HW) soils and they significantly affects the permeability of the soil mass and often control the mechanisms and locations of slope failure (Novák *et al.*, 2000, Aydin, 2006). The soil permeability generally increases with depth in the residual soil mantle in different orders of magnitude. For instance, Agus *et al.* (2005) reported a variation of saturated hydraulic conductivity of Bukit Timah residual soil mantle in Singapore to be within two orders of magnitude. Hence, a contrast in hydraulic conductivity between soil layers can facilitates infiltration and movement of water in the soil mass, which greatly affects suction distribution in tropical residual soil mantle (Pradel and Raad, 1993; Tsaparas, *et al.*, 2002; Cai and Ugai, 2004; Kassim, 2011).

The contrast in the hydraulic conductivity plays a significant role in suction distribution and water flow in tropical residual soil mantle. (Reid, 1997) illustrated that small contrasts in hydraulic conductivity in layered residual soil slope materials can greatly modify suction distribution, effective stress field, and the stability within a slope. According to Reid (1997), small contrast in hydraulic conductivity of soil impedes downslope water flow, which can create unstable areas with locally elevated pore-water pressures. This can result in negative pore-water pressure elimination and subsequently precede a slope failure. Similarly, Deere and Patton, (1971) concluded that when a lower permeability layer overlain a higher permeability layer parallel to a slope surface, it results in development of excess pore-water pressure in the weathered slopes which can precede a slope failure.

The typical arrangement of Grade VI over Grade V soil layers according to weathering profile, results in fine-grained soil material close to the ground surface compared to soil at greater depth. Thus, fine material content decreases with increase in depth (Tuncer and Lohnes, 1977; Rahardjo *et al.*, 2004a). Most of the rainfall-induced slope failures occur as shallow slope failure and often within the Grade VI lateritic residual soil layer. This is due to the contrast in the hydraulic conductivity between the upper Grade VI residual soil and the lower Grade V layer that impedes downward movement of water and creates an unstable area with locally elevated pore-water pressure. Rahardjo *et al.* (2001) analyses 20 rainfall-induced slope failures that occurred in Nanyang Technological University, Singapore and found that 15 out of the 20 occurred within the grade VI residual soil layer, while the remaining occurred at the interface between Grade VI and Grade V. Therefore, the depth to the interface from ground surface has a great influence on stability of slope as it determines the depth of failure of the slope. The top grade VI residual soil usually slides along the interface of the two layers when the interface lies near the slope surface (Rahardjo *et al.*, 2001).

In summary, the typical arrangement of Grade V and Grade VI soil layers and the inherent feature of heterogeneity in Grade V layer results in contrast in hydraulic conductivity between the soil layers. This in turn forms a system of soil with natural capillary barrier effect, which relies on variation of hydraulic conductivity as function of matric suction potential and creates a capillary break at the interface of grade V and grade VI soil. The capillary break restricts downward movement of water and facilitates lateral flow of water above the interface of the soil layers (Morris and Stormont, 1997; Li *et al.*, 2013).

A capillary barrier system is an earthen cover which comprises of fine-grained soil layer overlying a coarse-grained soil layer (Ross, 1990; Stormont, 1996; Yang *et al.*, 2004a) and can occur naturally in layered heterogeneous systems or can be an engineered using selected soil material (Oldenburg and Pruess, 1993; Walter *et al.*, 2000; Lu and Likos, 2004; Lu and Godt, 2013). The contrast in particle sizes of the two soil results in different unsaturated hydraulic properties (i.e. soil water characteristic curve (SWCC) and hydraulic conductivity) in the system (Fredlund and Rahardjo, 1993). With a low pore-water pressure at the soil interface under unsaturated conditions, the coarse-grained soil layer usually has low potential pressure compared to fine-grained soil layer. The low potential pressure of the coarse-grained soil layer therefore limits the downward movement of water. Rainwater that infiltrates the upper fine-grained soil layer is temporarily retained in that soil layer by capillary forces, until it is ultimately removed by evaporation, evapotranspiration, lateral drainage or percolation (i.e. breakthrough into the coarse-grained soil layer). Once breakthrough occurs, then the system no longer forms a barrier to the downward water movement (Yang, *et al.*, 2004a).

The concept of capillary barrier effect have been studied and widely applied in geoenvironmental engineering applications as a soil cover for landfills and mining waste to reduce water infiltration into protected waste materials (e.g. (Ross, 1990; Yanful *et al.*, 1993; Morris and Stormont, 1997; Khire *et al.*, 1997, 1999, 2000). However, recent studies (e.g. (Tami *et al.*, 2004a; Tami *et al.*, 2004b; Rahardjo *et al.*, 2012; Rahardjo *et al.*, 2013; Li *et al.*, 2013; Harnas *et al.*, 2014; Zhan *et al.*, 2014; Ng *et al.*, 2015) have demonstrated the effectiveness of capillary barrier system in minimizing rainfall infiltration by diverting it above the interface of unsaturated residual soil slope. Thus, maintaining the negative pore-water pressure and invariably the shear strength of the unsaturated soil. However, when the amount of infiltrating water is greater than the storage capacity of the fine-grained soil, then the fine-grained soil approaches saturation and breakthrough into the coarse-grained layer will eventually occur (Morris and Stormont, 1997; Morris and Stormont, 1998). In a capillary barrier system, saturation may occur due to poor drainage along the interface. Once breakthrough occurs, the system becomes ineffective as rainwater will continue to penetrate into deeper depth and eliminates the soil matric suction.

One of the measures of improving the performance of capillary barrier system is the use of transport layer (or unsaturated drainage layer) (Stormont and Morris, 1997; Morris and Stormont, 1999). A transport layer is an intermediate layer of different soil material of relatively high permeability compared to other soil layers and constructed at the finer/coarser interface so that the infiltrating water can flow above and within this layer due to the sloping surface. The difference in particle sizes between the fine-grained soil layer and the transport layer maximizes lateral water diversion in the system (Ross, 1990; Steenhuis *et al.*, 1991; Stormont, 1995; Smesrud and Selker, 2001). A system with capillary barrier effects was found to be more effective with transport layer by preventing the development of positive pore-water pressure in response to rainfall infiltration (Morris and Stormont, 1997; Zhan *et al.*, 2014). The material to be used as transport layer should have sufficient moisture to be conductive enough to laterally divert downward moving water and yet remain unsaturated to preserve capillary break within the underlying coarser material (Stormont and Morris, 1997).

At present, no much attention was given to the natural capillary barrier phenomena that exist in tropical residual soil mantle, which is quite abundance in tropical regions. Poor drainage in residual soil, renders the capillary barrier phenomena ineffective due to development of positive pore-water pressure in response to rainfall infiltration. The development of positive pore-water pressure results in slope failure that is shallow in nature. Therefore, the poor drainage characteristics of the residual soil mantle can be improved significantly by introducing a transport layer.

1.2 Problem Statement

Rainfall-induced slope failure is a common geotechnical problem in many tropical climate countries. Matric suction or negative pore-water pressure which play a significant role in the stability of unsaturated residual soil slope is greatly affected by rainfall infiltration which results in reduction of additional shear strength provided by matric suction and trigger slope failure. Despite several attempts to mitigate the occurrence of this type of problem, several literatures have demonstrated its occurrence in many countries particularly during monsoon seasons where intense or prolonged rainfall infiltrations are anticipated. Therefore, previous methods for alleviating this type of failure such as horizontal drains and surface covers are less effective because horizontal drains only lower the groundwater table while surface cover can fail with time.

The use of capillary barrier concept for slope stabilization appeared to be an effective method. However, it may not be implemented in countries like Malaysia due to abundance of rainfall especially during monsoon season when the soil is initially wet with low matric suction. Moreover, capillary barrier effect that form due to natural soil arrangement as a result of weathering process was not given proper attention. This is due to possible positive pore-water pressure development at the interface, in response to rainfall infiltration, and can precede a slope failure. Nevertheless, previous findings have shown that an unsaturated drainage layer system (i.e. transport layer system) can be used to improve the performance of capillary barrier system in landfill system for containment of buried wastes. However, the use of transport layer system for the improvement of capillary barrier effect for slope stabilization is yet to be explored.

Although the use of capillary barrier effect for slope stabilization have been explored in many countries such as Singapore, China, Japan, Canada etc., its application in Malaysia is still not fully investigated. Therefore, this study focused on possible ways of improving the performance and effectiveness of capillary barrier effect that exist naturally in tropical residual soil mantle by incorporating various types of transport layer system under different climatic conditions.

1.3 Research Objectives

The aim of this study is to propose a transport layer system for diverting infiltrating rainwater in a layered tropical residual soil slope based on mechanism of suction distribution and water flow behaviour. Hence, to achieve the overall objective of the study, the following specific objectives are set forth.

i) To determine the effect of local rainfall condition on performance of capillary barrier effect in a two-layered residual soil instrumented slope with and without transport layer systems.

ii) To analyse the suction distribution in a two-layered residual soil slope, with and without the transport layer subjected to various rainfall patterns using laboratory physical slope model.

iii) To analyze the effect of different materials as transport layer material in a two-layered residual soil slope.

iv) To propose material and configuration for transport layer system based on measured suction distribution and diversion capacity.

1.4 Scope of the Study

The disparity in the hydraulic conductivity due to weathering process in tropical residual soil mantle was investigated in this study. This disparity forms a natural capillary barrier system. Various types of transport layers are incorporated at the interface of a two-layered residual soil slope to alleviate the problem of localize pore-water pressure development due to poor drainage. The transport layers were incorporated to increase the lateral diversion and delay the breakthrough occurrence in the residual soil mantle. Two different materials (i.e. sand and gravel) parted into four various combinations of transport layers (i.e. Gravel; Drainage Cell (DC) + Gravel; Sand and DC + Sand) were tested in the laboratory. However, the determined suction distribution from the laboratory modelling experiments have strongly demonstrated the potential of using sand and gravel alone as transport layer material. Therefore, only these materials are used as transport layers in the field monitoring work. The study focused on a two-layered system (Grade V and Grade VI) of tropical residual soil slope with and without transport layer at their interface. Three research approaches that include laboratory modelling, field monitoring and numerical simulations were followed in this study.

Soil samples were collected from the study area located at Block P18 in the Faculty of Electrical Engineering. The site is a sloping site located within the premises of Universiti Teknologi Malaysia, Johor Bahru campus. These samples were subjected to different tests in order to determine the properties of each layer. The determined properties are used as input parameters for the laboratory modelling experiments and numerical simulations works. Furthermore, Atlantis Drainage Cell System, gravel from crushed granite and sand were also obtained and used as transport layer materials. Relevant laboratory properties of these materials were also determined.

The laboratory modelling experiments were performed in a specially fabricated two dimensional laboratory slope model, which was made from 5 mm acrylic sheet and stainless steel frame. The length, height and width of the slope model are 2000 mm, 1100 mm and 100 mm, respectively. The slope model was tilted at two slope angles of 18° and 27°. These relatively gentle slope angles are chosen because they represent the typical slope angle found in natural residual soil slope. The study mainly focused on infiltration and diversion capacity behaviours in unsaturated residual soils; hence, the slope was not tested for failure. Monitoring instruments with automated data acquisition system were installed in the laboratory slope model to allow for continuous negative pore-water pressure (matric suction) measurements throughout the selected testing period. The simulated rainfall intensity were applied through a rainfall simulator which was part of the laboratory set up. These rainfall intensities were obtained from statistical extreme rainfall analysis on rainfall data of Johor Bahru, Malaysia.

The selected sloping site at P18 in the Faculty of Electrical Engineering, Universiti Teknologi Malaysia was used for the field monitoring work. Three research plots are constructed and instrumented with tensiometers, rain gauge, run-off collectors and percolated water collectors.

The numerical simulations were performed with commercial software SEEP/W (Geo-slope International, 2007). The geometry of the slope at P18 was modelled in the numerical simulation work. Four months rainfall data recorded during the field monitoring work were used in the numerical simulations. Moreover, the hydraulic properties of the tested residual soil and that of transport layer materials are also used in the numerical simulation work. Finally, the numerical simulation was also used and proposed the design parameters of the transport layer.

However, due to the difficulties of sampling representative volumes of heterogeneous residual soil, the laboratory modelling experiment was subjected to the following assumptions:

i) The typical soil arrangement in the laboratory slope model is assumed to be representative of the soil arrangement at the site.

ii) The soil materials used in each layer of the laboratory slope model are assumed to be homogeneous.

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

iv) The infiltration rate in the experiments was obtained from the difference between rainfall and runoff rate. Other surface losses from evaporation and other processes were assumed to be very negligible.

1.5 Limitations of the Study

Despite the fact that multiple methodologies were employed in this study, it is subjected to the following limitations.

i) Both the laboratory physical slope model and field slope model are not tested for failure. Therefore stability is not the main concern.
ii) Only suction distribution behaviour was measured in the laboratory modelling experiments.

iii) The simulated rainfall intensity in the laboratory modelling experiment were estimated and applied through the rainfall simulator using trial and error method.

iv) The suction, runoff, and diverted water measurements in the field were performed manually.

v) The long term performance of the instrumented slope with transport layer was not investigated.

1.6 Significance of the Study

The outcome of this study can be utilized as an improved method of using the natural capillary barrier effect which normally exist in an unsaturated residual soil mantle as a result of weathering process. This improved method can be use as slope stabilization method to curtail the problem of rainfall infiltration that results in rainfall-induced slope failure in unsaturated residual soils. The best configuration of transport layer in the capillary barrier system was also provided. The benefits that could be gained from this study may include the following.

i) Understanding the behaviour of natural capillary barrier effect that exist in unsaturated residual soil slope due to weathering process under critical rainfall patterns.

ii) Development of an improved capillary barrier system with transport layer at the interface using different materials, so as to alleviate the problem of localize pore-water pressure development in the layered slope.

1.7 Thesis Organisation

This thesis consists of seven chapters. The first chapter is an introductory chapter that provides an overview on the research topic and describes the background of the problem of rainfall-induced slope failure in tropical residual soils and the concept of capillary barrier and transport layer. Statement of problem, objectives, scope and limitation as well as the significance of the research were also highlighted in the chapter.

Chapter 2 provides an extensive review of previous literatures related to the research topic. Relevant published literatures on rainfall-induced slope failures, tropical residual soil, unsaturated soil behaviour and capillary barrier principle are provided in this chapter. Similarly, the methodology and techniques adopted by previous researches related to this thesis are also reviewed and presented herein.

Chapter 3 discusses the research methodology adopted in this study. Apart from discussing the methods of basic data collection, chapter 3 also explains the methodologies followed in achieving the objectives of this study. The methods adopted in the laboratory modelling experiments, field monitoring works and numerical simulations are well explained under this chapter. Other methods that are not covered in published standards are carefully explained and validated.

Chapter 4 presents and discusses preliminary results obtained from the tests described in chapter 3. These results consist that of soil and transport layer characterization, engineering properties, mineralogical properties and the hydraulic properties of the materials. Moreover, the statistical analyses of historical rainfall data for determining the appropriate rainfall intensities and duration for laboratory modelling experiments were also presented. The chapter was concluded with preliminary results of field monitoring work performed in this study.

Chapter 5 presents the results of laboratory modelling experiments. The discussions mainly focuses on the results of laboratory experiments considering the effect of natural capillary barrier system which forms in tropical residual soil as a result of weathering process. The laboratory experiments also focused on the effect of transport layer on suction distribution in a capillary barrier system.

Chapter 6 presents the results of numerical modelling performed to model the effects of transport layers on mechanism of rainfall infiltration and suction distribution in residual soil slope. Several modelling approaches were followed to determine the appropriate modelling scheme, which perfectly modelled the transport layer. The best modelling scheme determined was finally utilised and proposed a design components of transport layer.

Lastly, Chapter 7 is the final chapter of this thesis and covers conclusions drawn from the present study and recommendations for further researches on the subject.

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