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TAJUK PROJEK : Mechanics of Rainfall Infiltration through Soil Slope

Saya ASSOC. PROF. DR. NURLY GOFAR

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# MECHANICS OF RAINFALL INFILTRATION THROUGH SOIL SLOPE

# (MEKANIK PENYUSUPAN AIR HUJAN DALAM TANAH CERUN)

**NURLY GOFAR**
**AZMAN BIN KASSIM**

**FAKULTI KEJURUTERAAN AWAM**
**UNIVERSITI TEKNOLOGI MALAYSIA**

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# ABSTRACT

A sloping layered soil model consisting of a fine sandy silt layer over a coarse 'jointed' silty gravel was constructed inside a specially designed apparatus to study the mechanisms associated with capillary barrier effect for a two-layered soil system. In this study, simulated rainfalls of different intensities and durations representative of tropical climatic conditions were applied uniformly across the top surface of a tilting infiltration box of 2000mm in length, 1000mm in height and 100mm in width. The experimental result shows that the two-layer system under the influence of a high precipitation rate is primarily governed by the water retention capacity of the fine soil. At the interface along down slope, infiltration water retained in the upper layer of sandy silt and only constantly infiltrates into the lower layer after pore-water pressure increases to -8kPa. However, the observation of breakthrough at lower pore-water pressure corroborates the existence of a partial breakthrough region identified along the interface.

# ABSTRAK

Satu model cerun tanah berlapis yang terdiri daripada lapisan tanah sandy silt (berbutiran halus) menutupi lapisan tanah silty gravel ’jointed’ (berbutiran kasar) telah dibina dalam satu aparatus khas untuk mengkaji mekanisme capillary barrier dalam sistem tanah berlapisan dua. Dalam kajian ini, hujan rekaan yang berlainan keamatan dan tempoh masa (mewakili keadaan cuaca tropikal) ditabur secara seragam di atas permukaan kotak penyusupan yang berdimensi 2000mm panjang, 1000mm tinggi dan 100mm lebar. Keputusan eksperimen menunjukkan dalam keadaan hujan berkeamatan tunggi, sistem tanah berlapisan dua adalah dipengaruhi oleh kapasiti penakungan air tanah berbutiran halus. Pada permukaan di sepanjang bawah cerun, air penyusupan bertakung dalam lapisan atas (sandy silt) dan menyusup secara malar kedalam lapisan bawah setelah tekanan udara liang mencapai -8kpa. Namun, pada tekanan udara liang yang lebih rendah menunjukkan kewujudan zon breakthrough separa di sepanjang permukaan tertentu.

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| | | |
|---|---|---|
| $\sigma'$ | - | Effective normal stress |
| $\sigma$ | - | Total normal stress |
| $\tau_{ff}$ | - | Shear stress at failure |
| $(u_a - u_w)$ | - | Matric suction |
| $A_{ev}$ | - | Air entry value |
| $k$ | - | Water coefficient of permeability |
| $k_{sat}$ | - | Saturated permeability |
| $m_w$ | - | Slope of soil water characteristic curve (SWCC) |
| $u_a$ | - | Pore-air pressure |
| $u_w$ | - | Pore-water pressure |
| $\phi'$ | - | Effective friction angle |
| $\phi^b$ | - | Unsaturated friction angle |
| $\theta$ | - | Volumetric water content |
| $\psi$ | - | Suction |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

At present, a growing body of literature discusses significantly different mode of traditional slope failure (Lumb, 1975, Rahardjo et al., 1995 and Vaughan, 1985). This mode of relatively shallow failures develop parallel to soil slope commonly occur in tropical climate sucah as Malaysia. There is also sufficient evidence in literatures (i.e., Rahardjo & Fredlund, 1995, Fourie, 1996 and de Campos et al., 1991) that these failures associated with periods of prolonged or heavy rainfall.

Tropical residual soil has an apparent vertical soil section that presents a common feature of tropical or subtropical climates that experience periods of intense and prolonged rainfall. The soil profile consists of several layers and the boundaries between layers formed more or less parallel to the ground surface. The profile also has a weathering aspect that give rise to a vertical weathering profile that has a critical aspect from engineering perspective. The entire weathering profile generally indicates a gradual change from fresh rock to a completely weathered rock at the ground surface (Fookes, 1997; Dearman et al, 1978; Anon 1981a).

The weathering process involved in the formation of residual soil results in variation within the soil. Most distinctive is the microstructure in which the gradation changes with depth. The permeability of residual soils is considerably affected by the variation in grain size, void ratio, mineralogy, degree of fissuring and the characteristics of the fissures. It is also strongly controlled by the structural discontinuities of the material where the flow takes place along relict joint, quartz veins, termite or other bio channels (Garga & Blight, 1987).

The presence of relict structure in a sloping layered soil formation leads to the variation in the permeability of the soil. This result in an inconsistency in the saturation profiles developed for a homogenous soil. The permeation profiles in sloping layered soil is influenced by capillary effect which limits water's downward movement and causes temporary water storage in the soil layers which may lead to pore-water pressure build-ups at the interfaces between soil layers (Ross, 1990; Stormont & Anderson, 1999, Rahardjo et al, 2004; Yang et al, 2006). This phenomenon is referred to as capillary barrier effect.

The mechanism of capillary barrier effect in layered soil has been studied by means of analytical solution (Ross, 1990; Steenhuis et al., 1991; Stormont, 1995), numerical modeling (Oldenburg & Pruess, 1993; Webb, 1997; Morris & Stormont, 1999), field tests (Hakonson et al., 1994; Barth & Wohnlich, 1999) and laboratory experiment (Baker & Hillel, 1990; Stormont & Anderson, 1999; Tami et al., 2004).

Due to the complexities of the problem associated with infiltration in a layered soil (e.g., geometry and nonlinearity of the soil parameters), an analytical solution is actually difficult to obtain. Although the infiltration in a layered soil can be studied using a suitable numerical modeling for saturated-unsaturated flow, it is important to verify that the mechanisms used in the numerical model are physically correct. Alternatively, a laboratory study is a convenient and practical approach to verify the results from numerical modeling. Furthermore, laboratory study offers an advantage that all related conditions and soil properties can be carefully controlled when compared with field tests.

In this report, an instrumented physical laboratory model of a sloping layered soil for infiltration study is described. The performance of the physical model of two-layer system of a 'jointed' coarse silty gravel underlying a fine sandy silt is also presented.

## 1.2 Objectives

The study was carried out in fulfillment of the following objectives:

i. To investigate the engineering properties of typical residual soil slope

ii. To investigate the mechanics of rainfall flow through the geological discontinuities of the slope

iii. To study the mechanism of rainfall-induced failure on the slope

## 1.3 Scope of the Study

The research focuses on a residual soil derived from granite weathering that represents the type of soil slope. The pilot study is selected at a sloping area in UTM, Skudai whereby soil samples were collected for study. The mechanism of water flows through the soil was studied through a fabricated slope model in laboratory.

The results of the analysis were used to identify rainwater flow through the geological discontinuity of the residual soil.

## 1.4 Significance of the Study

With regards to the importance of this research, the findings may be viewed as a fundamental research. The benefits that would be gained from the study include the understanding of the water flow mechanism in the layered residual soils coupled with geological discontinuities.

# CHAPTER 2

# LITERATURE STUDY

## 2.1 Introduction

This chapter provides the basic and clinical researches on the topic of residual soil slopes and relict joints. Considerable literatures relevant to the topic are available. Most of the literatures were directed towards determining the properties of residual soils, formation of relict joints and their effects on the stability of slope.

## 2.2 Residual Soils

Ideally, there is no universally accepted definition of residual soils. Different researchers gave different definitions. However, the common phenomenon in all such definitions is that the residual soil is a material formed in situ by weathering of rocks and remained at the place where it was formed. For example, MacCarthy (1993) suggested that residual soils are those form from rock or accumulation of organic material and remain at the place where they were formed. The Public Works Institute of Malaysia (1996) defined it as ‘a soil which has been formed in situ by decomposition of parent material and which has not been transported any significant distance’ and residual soil as “a soil formed in situ under tropical weathering conditions". The tropical residual soils are formed in tropical areas, physically defined as the zone contained between $20^o$ N (Tropic of Cancer) and $20^o$ S (Tropic of Capricorn) of the equator, which includes Malaysia.

### 2.2.1 Thickness of Residual Soils in Malaysia

The thickness of residual soil layer varies from place to place depending upon the factors (Table 2.1) responsible for weathering like, rainfall, temperature chemicals present, compositions of parent rocks, etc. and the extent to which the weathering process has advanced (Bergman and McKnight, 2000).

**Table 2.1**: Weathering agencies and their description

| Factors | Description |
|---|---|
| Climate | Refers to the effect on the surface by temperature and precipitation. |
| Geologic | Refers to the parent material (bedrock or loose rock fragments) that provide the bulk of most soils. |
| Geomorphic / Topographic | Refers to the configuration of the surface and is manifested primarily by aspects of slope and drainage. |
| Biotic | Consists of living plants and animals, as well as dead organic material incorporated into the soil. |
| Chronological | Refers to the length of time over which the other four factors interact in the formation of the particular soil. |

### 2.2.2 Weathering Profiles

A typical weathering profile is a vertical section of the soil layers or soil horizons that reflects progressive stages of transformation from fresh bedrock through weathered material to ground surface. In Malaysia, tropical residual deposits are found in abundance and because the climate is hot and humid the formations are intense with a predominance of chemical weathering over other processes of weathering, thus resulting in deep weathering profiles and soil mantles often exceeding 30 m (Tan, 2004). Table 2.1 gives the proposed classification of weathering profile over metamorphic rock (Clastic Metasediment) in Peninsular Malaysia (Komoo and Mogana, 1988).

### 2.2.3 Shear Strength Properties of Residual Soil

The residual soils are generally found in unsaturated condition. The shear strength of unsaturated soils can be represented by the so-called extended Mohr-Coulomb criterion (Fredlund, 1978).

$$\tau_{ff} = c' + ( \sigma - \mu_a ) \tan\phi' + ( u_a - u_w )\tan\phi^b \qquad (2.1)$$

Where, $\tau_{ff}$ = shear stress on the failure plane at failure

$c'$ = effective cohesion

$\sigma$ = normal stress

$u_a$ = pore-air pressure

$u_w$ = pore-water pressure

$(\sigma - u_a)$ = net normal stress

$\phi'$ = effective angle of shear resistance

$(u_a - u_w)$ = matric suction

$\phi^b$ = angle indicating the rate of increase in shear strength relative to matric suction.

As the soil approaches saturation, the pore-water pressure ($u_w$) approaches the pore-air pressure ($u_a$) and Equation (2.1) can be rewritten as:

$$\tau_{ff} = c' + (\sigma - \mu_w)\tan\phi' \qquad (2.2)$$

In which it is the Mohr-Coulomb strength criterion for saturated soils. By applying Equation (2.1) to unsaturated soils, the shear strength component due to matric suction, i. e. $(u_a - u_w)\tan\phi^b$, is masked as the cohesion intercept, $c = c' + (u_a - u_w)\tan\phi^b$. Therefore, the cohesion intercept ($c$), in residual soils appear to vary widely (Rahardjo *et al.*, 2003).

### 2.2.4 Hydraulic Properties of Residual Soil

The hydraulic properties of residual soil can be attributed to water retention characteristic (soil water characteristic curve) and water coefficient of permeability (hydraulic conductivity function).

#### 2.2.4.1 Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve (SWCC), also referred to as soil moisture retention curve, depicts the relationship between soil water content and soil water pressure potential. A typical SWCC is shown in Figure 2.1.

**Table 2.2:** Classification of weathering profile over metamorphic rock (Clastic Metasediment) in Peninsular Malaysia

| Term | Zone | Description |
| --- | --- | --- |
| Residual Soil | VI | All rock material is converted to soil. The mass structure and the material fabric (texture) are completely destroyed. The material is generally silty or clayey and shows homogenous color. |
| Completely Weathered | V | All material rock is decomposed to soil. Material partially preserved. The material is sandy and is friable if soaked in water or squeezed by hand. |
| Highly weathered | IV | The rock material is in the transitional stage to form soil. Material condition is either rock or soil. Material s completely discolored but the fabric is completely preserved. Mass structure partially present. |
| Moderately Weathered | III | The rock material shows partial discoloration. The mass structure and material structure is completely preserved. Discontinuity is commonly filled by iron-rich material. Material fragment or block corner can be chipped by hand. |
| Slightly Weathered | II | Discoloration along discontinuity and may be part of rock material texture are completely preserved. The material is generally weaker but fragment corners cannot be chipped by hand. |
| Fresh Rock | I | No visible sign of rock material weathering. Some discoloration on major discontinuity surfaces. |

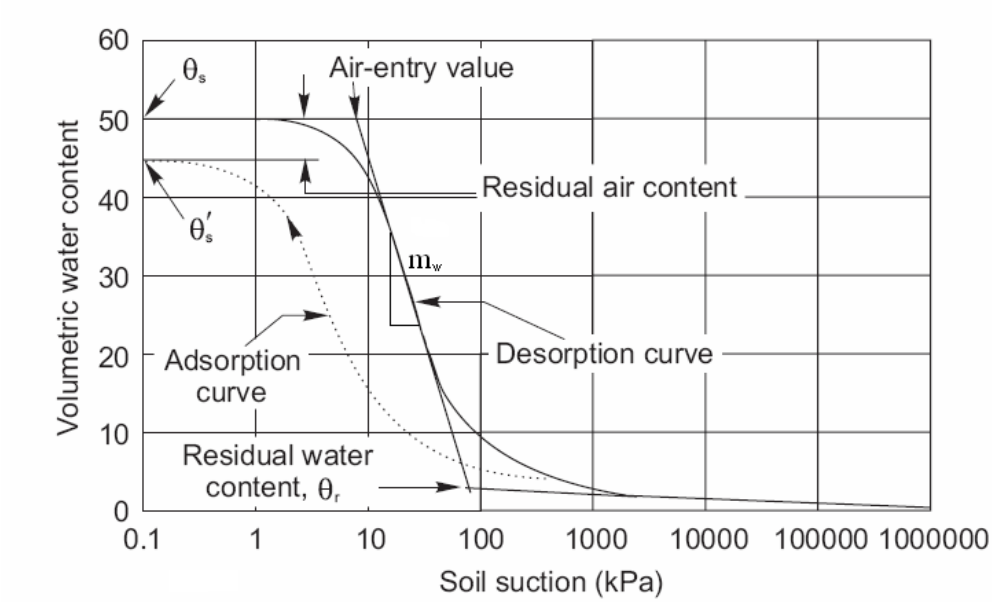


**Figure 2.1** Typical absorption and desorption SWCC (Zhan and Ng, 2004)

As observed in Figure 2.1, the volumetric water content at saturation of desorption curve ($\theta_s$) is greater than that of absorption curve ($\theta'_s$). The difference between $\theta_s$ and $\theta'_s$, defined as the residual air content, is caused by the entrapped air in the soil during absorption process. There are two characteristic points in a SWCC, namely air entry value ($A_{ev}$) and residual water content ($\theta_r$) (Zhan and Ng, 2004). The $A_{ev}$ indicates the maximum suction required to dissipate the entrapped air from the soil. Before the suction exceeds $A_{ev}$, the soil is saturated or nearly saturated, hence the behaviour of the soil is similar to that of saturated soil with a compressible fluid due to the existence of occluded air bubbles. On the other end of the curve, very little water exists in the soil when the soil suction is greater than $\theta_r$. The effect of water content on the behaviour of soil is thus negligible. As the result, the soil at these two unsaturated stages is not the main concern for the behaviour of unsaturated soil (Bao *et al.*, 1998). What is of greater concern is the SWCC between $A_{ev}$ and $\theta_r$, in which both air and water phases are continuous or partially continuous, and the soil properties are strongly related to its water content or negative pore-water pressure (Zhan and Ng, 2004). The rate of changes in negative pore-water pressure corresponding to volumetric water content is represented by the slope of SWCC ($m_w$).

A wide-array of methods can be used to obtain the SWCC, depending on the desired path (absorption or desorption) and the range of matric suction. Laboratory SWCC test can be conducted by using pressure plate test (for suction less than 1500 kPa), salt solution method (for suction greater than 1500 kPa), and capillary rise open tube method (for absorption SWCC), while field SWCC can be obtained by taking the field measurements of water content and suction by moisture probe and tensiometer, simultaneously. Alternatively, the SWCC can be predicted by using empirical relationships, as proposed by several researchers included Fredlund and Xing (1994), Agus *et al*. (2001) and Gitirana and Fredlund (2004).

#### 2.2.4.2 Hydraulic Conductivity Function

The water coefficient of permeability ($k$) represents the soil's ability to transmit and drain water. This, in turn, indicates the ability of the soil to change matric suction as a result of environmental changes (Fredlund and Rahardjo, 1993). Water coefficient of permeability of saturated soil is a function of void ratio ($e$) only. For unsaturated soil, the water coefficient of permeability is a function of void ratio ($e$) and volumetric water content ($\theta$). This relationship is commonly expressed by a suction-dependent hydraulic conductivity function, as illustrated in Figure 2.2.

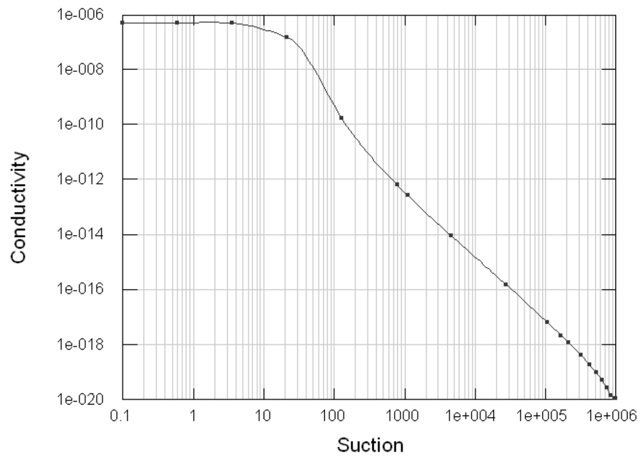


**Figure 2.2** Typical suction-dependent hydraulic conductivity function

The hydraulic conductivity function of unsaturated soil can be obtained through direct or indirect measurement. The direct measurement of unsaturated flow behaviour that commonly conducted by using Instantaneous Profile Method (IPM) is not encouraged in practice since the test requires elaborate equipment and qualified personnel, which proves time consuming and expensive (Brisson *et al.*, 2002). The duration of the test increases as the water content in the soil decreases (Leong and Rahardjo, 1997).

The indirect prediction methods for hydraulic conductivity function have been proposed by several researchers. Van Genuchten (1980) developed a close form equation to estimate unsaturated hydraulic conductivity through three independent parameters obtained by fitting the proposed soil water retention model to experimental data. The unsaturated hydraulic conductivity was predicted well in four out of five study cases. Fredlund *et al.* (1994) and Gribb *et al.* (2004) suggested that hydraulic conductivity function can be estimated through saturated permeability and SWCC by using fitting method. Leong and Rahardjo (1997) compared the hydraulic conductivity function estimated from several empirical equations, macroscopic models and statistical models. They concluded that the use of newly developed empirical equations could give a good fit to the experimental data. In conclusion, methods of predicting hydraulic conductivity function indirectly can be used with confidence when no experimental data are feasible.

## 2.3 Relict joints

Macro-structural features such as joints inherited from the parent rock are preserved, particularly in igneous saprolites. Although these relict joints undergo a weakening process during weathering, their location, orientation, continuity and role as preferential weakness planes essentially remain unchanged. Main weathering induced changes in joint properties are mineralogical (wall alteration and filling/ coating material) and geometrical (decrease in roughness and aperture through grain alteration and healing upon softening of asperities, increasing curvature of planes through creep and mass deformation). The detection, sampling and testing of relict joints therefore becomes increasingly difficult as material decomposition increases.

A large proportion of landslides in saprolites are associated with relict joints (Cowland and Carbray, 1988; Chigira, 2001; Wen and Aydin, 2003). Fookes (1997) suggested that relict joints represent a significant and uncertain hazard in the formation of temporary and permanent slopes. This is because relict joints are difficult to detect with the aid of routine site investigation procedures, and their potential occurrences are ignored until their control on mass shear strength becomes apparent by movements or failures along them (Deere and Patton, 1971; Sandroni, 1985; Blight, 1989).

Relict joints often participate in slope failures as a combination of a near vertical release surface and an extensive basal slip plane. Complex failure surfaces may form when several discontinuities join or lie within a close distance. In the latter case, the intervening intact weathered rock blocks are sheared along certain segments of such surfaces. Often, toppling failures in saprolites is in the form of rotation of blocks within a creeping saprolitic mass. An increase in matrix-to-block proportions accelerates the rate of renewal of slope failure events.

Relict joints with black seams are common in saprolites (Figures 2.3 and 2.4). Chemical analyses of black seams show that they generally contain fine-grained weathering products coated with Fe-Mn oxides and a humic substance leached from the upper horizons. Slickensides frequently observed on relict joints of this type are likely caused by repeated volumetric changes during saturation-drying cycles, particularly in sloping terrains where creep, gradual stress relief due to erosion and sudden removal of confining material during landslides can be expected. Relict joints with slickensided black seams have been found to have a much lower friction angle than other relict joints.

The likelihood that relict joints may form part of a potential failure surface depends on their geometrical distribution parameters, including their orientation, spacing and persistence. These also determine the likelihood of their intersecting with other joints and forming a network within saprolites. However, generally limited site data and possible changes in structural domains of nearby exposures and cuts require a sound structural framework of the area to be established to guide extrapolation and grouping of data into sets. The resulting distribution parameters can be used either in a probabilistic or deterministic manner to assess the stability of slopes in saprolites developed over jointed rock masses.

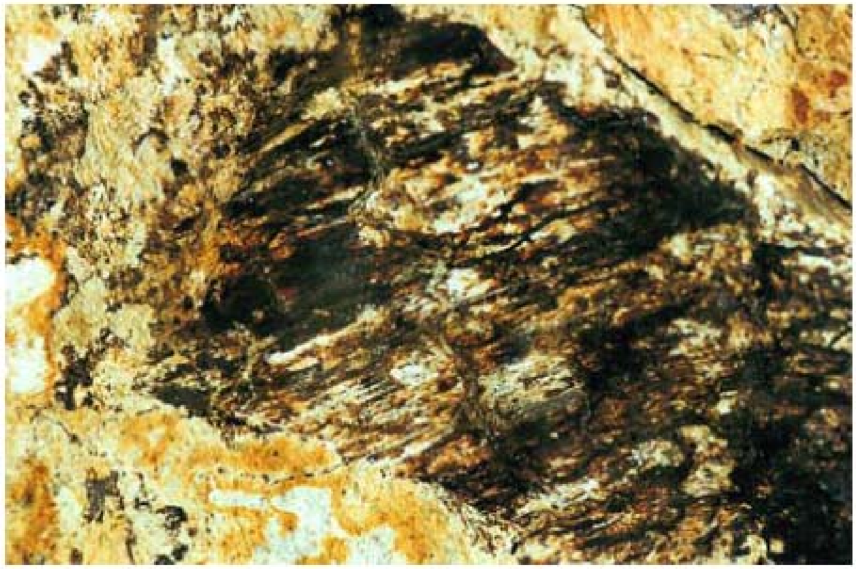

**Figure 2.3** Slickensided black seam on the surface of a relict joint plane.

**Figure 2.4** Black seams sandwiched within a white clay vein formed along a deformed relict joint plane showing irregular waviness.

## 2.4 Concluding Remarks

From the foregoing literatures, it is evidenced that residual soils formed in large portions of Malaysia soil strata. The engineering properties of residual soils have been studied extensively by numerous researchers. However, the mechanics of water flow through residual soil is still unclear. The soil seepage induced by rainfall infiltration has caused severe landslides in Malaysia. It is the problem such as this that provoked the present study to be carried out.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

The main objective of this research is to investigate the mechanics of rainfall flow through the geological discontinuities of the layered residual soil slope. To achieve these objectives, five phases of research activities were undertaken, i.e. research initialization, preliminary preparation, experiments, analysis, and generalization. Figure 3.1 shows the flow chart of the research activities.

The study was initiated by critically reviewing published works related to the topic of slope failure of residual soil in order to develop a strong background of the research. The knowledge on the state of the art of the research topic was gained through consultation with several well-known experts such as Professor Harianto Rahardjo from Nanyang Technological University Singapore, Dr. David Toll from University of Durham, Professor Faisal Ali from University of Malaya, Professor Roslan Zainal Abidin from University Technology Mara, and Mr. Law Tien Huat from Mohd. Asby Consultant Sdn. Bhd. Problem statement and hypothesis were formed based on the literature reviews and the professional opinions from experts.

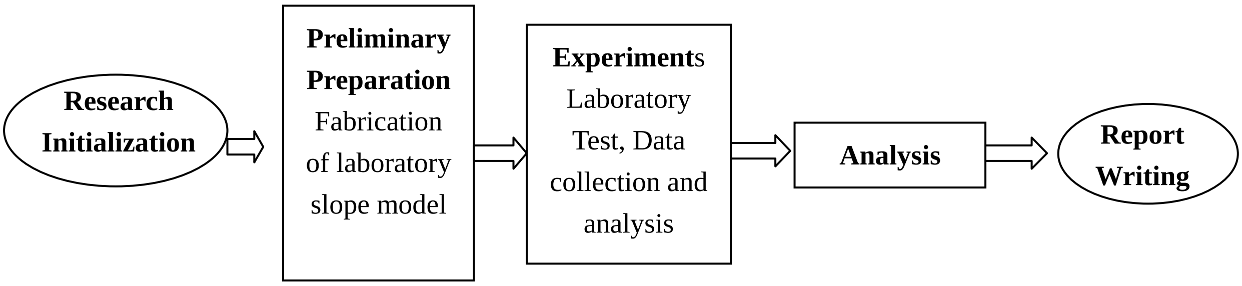


**Figure 3.1** Research framework

The second stage of the research involves the preliminary preparation of experimental apparatus. Numerical analysis was performed to facilitate the preliminary design of the laboratory model.

Investigations on the engineering properties of the residual soils were carried out prior to the experiments. A series of laboratory experiments on a physical slope model were then performed to investigate the mechanics of water flow in the soil.

In the analysis stage, the data obtained from the laboratory tests were analyzed. Subsequently, discussions were made to explain the mechanism of water flow through geological discontinuity.

The last stage of the study was report writing and documentation of research findings.

## 3.2 Description of the Model

The geometry of the fabricated laboratory model is illustrated in Figure 3.2. The sloping layered soil model consists of four main parts: an infiltration box, a water flow system, instrumentations, and data acquisition systems. Figure 3.3 shows the general arrangement of the apparatus for the infiltration study.

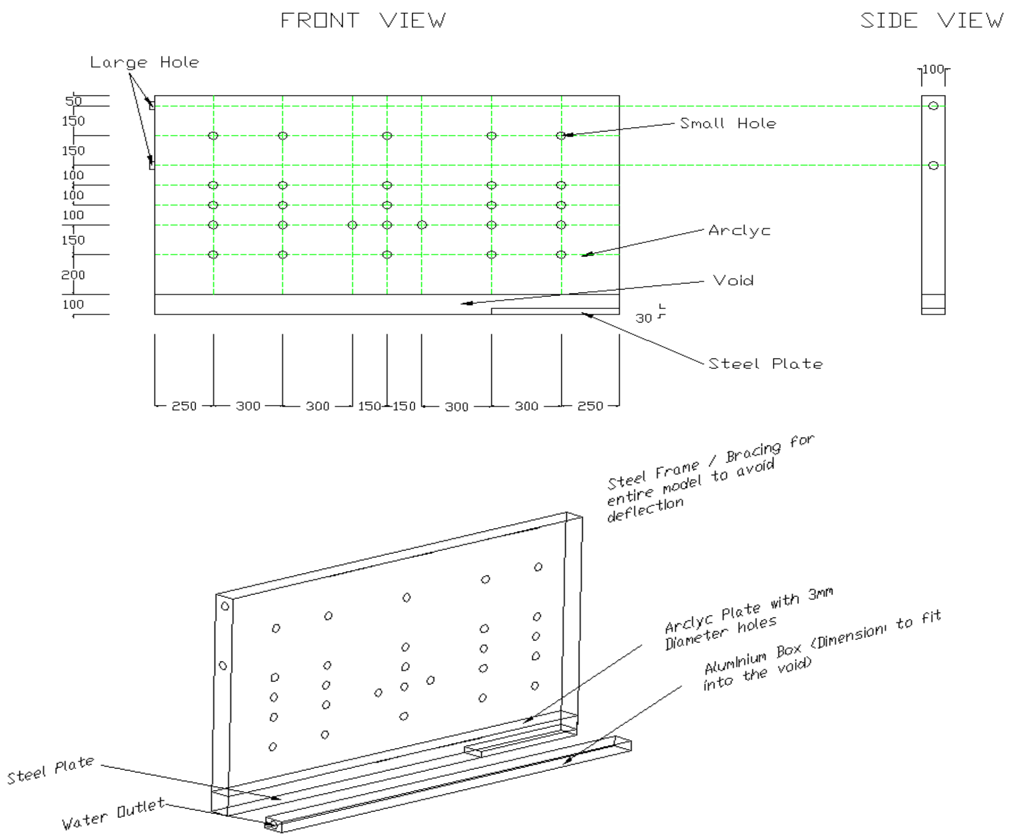


**Figure 3.2** The infiltration box

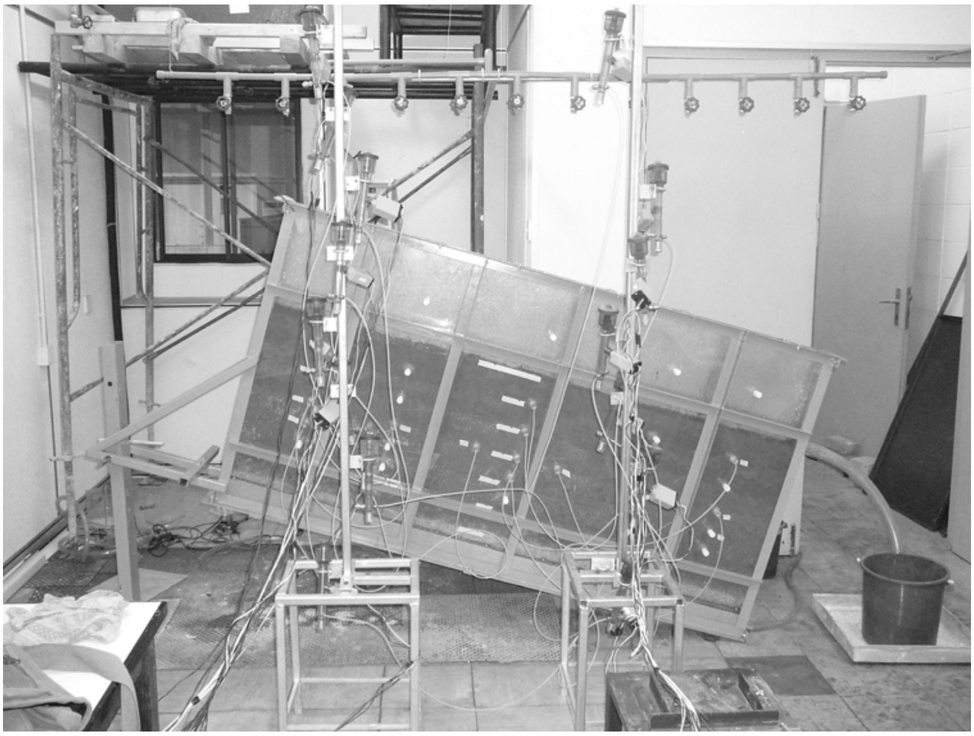

**Figure 3.3** The general laboratory model setup

The infiltration box is 2000mm in length, 1000mm in height and 100mm in width (Figure 3.2). The watertight infiltration box was designed and constructed with deflection limit considerations in order to avoid leakages. The frame of the infiltration box was made of steel, and the sidewalls were made of acrylic sheets of 5mm thickness.

A total number of 27 special threaded holes were drilled at various spacing along one sidewall for installing the connecters of the instrumentations. Some perforated holes of 3mm were drilled at the base of the infiltration box to facilitate percolation discharge. In addition, two additional holes were drilled along the sidewall at top end of the infiltration box for run-off collection purposes.

Since the sloping angle was considered as one of controlling parameters in slope stability, the model was designed for slope angles of $0^o$, $18^o$ and $27^o$ by setting the left side of the box at different hook at an adjacent steel column.

The water flow system of the infiltration study comprises three parts, i.e. rainfall control, runoff discharge, and percolation discharge. The rainfall control consisted of a water storage tank, a constant head tank, a flow regulator, and a rainfall simulator.

The water storage tank with storage capacity of 216L was placed 2.8m above the floor to provide continuous water flow into the constant head tank. The constant head tank was placed immediately below the water storage tank with a constant head of 0.3m. Water in the storage tank flowed into the constant head tank through a control valve. An overflow outlet was placed at the same level with the inlet flow of the constant head tank to create a constant head condition throughout the test.

A rainfall simulator (Figure 3.4) was installed 1m above the infiltration box to generate typical high precipitation rate of tropical climate conditions. Uniform rainfall precipitation was created through 12 sprayer units with punching needle hole distributed at 150mm spacing. The rainfall intensity was controlled using flow regulators.

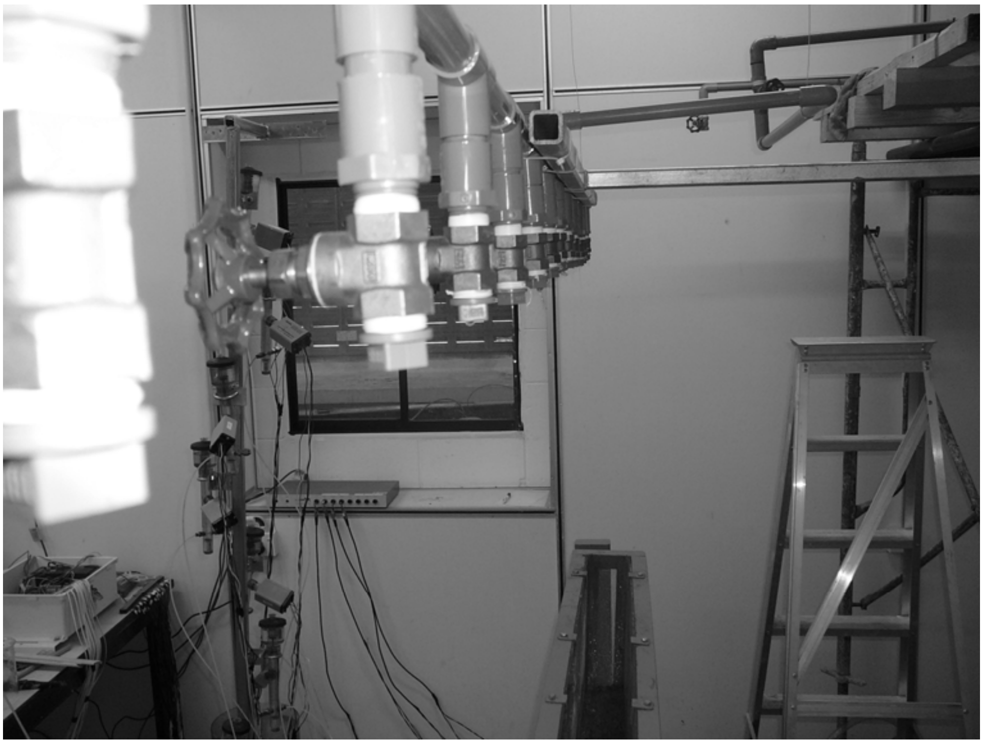

**Figure 3.4** The rainfall simulator

The overflow-discharge system was used to create the no-ponding upper boundary condition for the infiltration box. The overflow was drained as runoff through the outlet located at the soil surface. Alternatively, the ponding condition can be created by sealing the runoff outlet with a threaded plug.

The last component of the water flow system is the outlet for the discharge of percolated flow. 50mm thick of gravels with an average size of 5mm was placed on the perforated bottom of the infiltration box to avoid turbulent flow.

Tensiometers were installed along the sidewall of the infiltration box. The tensiometer (Soil Moisture Corp. Model 2100F) is equipped with pressure transducer (Soil Moisture Corp. Model 5301-B1) that is capable of measuring soil suction at low pressure range of 0kPa to 70kPa. Figure 3.5 shows an assembled tensiometer-transducer used in this study.

A ceramic cup was installed into the infiltration box through a predrilled hole after compaction was completed. The method offers the advantages of protecting the ceramic cup from damage during soil compaction, but care should be taken to ensure that the ceramic cup was closely contacted with the soil particles. Several holes with threaded housing were fabricated to mount the ceramic cup and the tube assembly on the sidewall of the infiltration box,. A specially designed connector that fit well into the threaded housing, “O” ring, and sealing tape were used to form a good seal at the connection. The details of the connector are shown in Figure 3.6.

**Figure 3.5** An assembled tensiometer-transducer

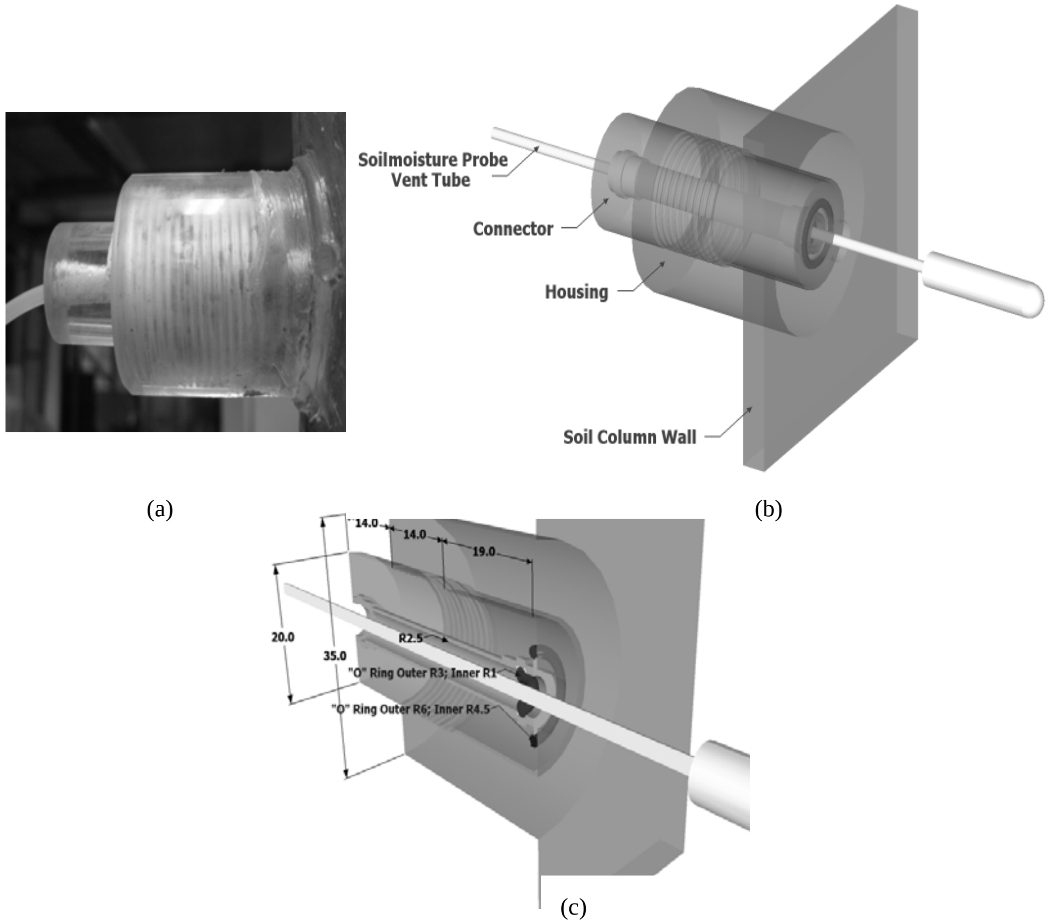


**Figure 3.6** (a) Photo, (b) Three-dimensional sketch, and (c) Cross-sectional view of the tensiometer connector

## 3.3 Data Acquisition System

The data acquisition system used in the study comprises a unit data logger, a solid state relay, an external power supply, and a personal computer. The tensiometers was connected to the Campbell Scientific Data Logger, model CR10x (Campbell Scientific Inc.). The CR10x data logger consists of one unit of 32 single-ended channels multiplexer (model MUX AM416). A program was written to set up communication between the data logger and instruments for data collection. In addition, a controlling-software (PC208W version 2.3) was installed in the personal computer for executing the data.

The CR10x data logger was powered up by an internal 12 V battery but the optimum power requirement for the tensiometer transducer system was 24V. Therefore, the tensiometer transducer system was connected to an external 24V power supply via a solid state relay. The functions of the solid state relay are to protect the data logger circuit and to switch on the power only when the triggering signal from data logger was received. These functions are essential to protect the tensiometer transducer system from over-heated due to long operating durations.

The data from the data logger units were transferred to the personal computer periodically through several serial ports. The data stored in the personal computer were normally set in a format of pressure versus real time at 5min interval.

# CHAPTER 4

# DATA AND DISCUSSIONS

## 4.1 Introduction

This chapter presents the results of slope infiltration tests carried out in the laboratory. The slope model was subjected to different durations and intensities of rainfall.

## 4.2 Soil Materials

Two types of soil were employed in the study, i.e. silty gravel, sandy silt. The coarser grained silty gravel was placed below the sandy silt layer in the infiltration box. Joints were created in the silty gravel layer to resemble actual discontinuity in residual soil. Figures 4.1, 4.2 and 4.3 show the particle size distribution (PSD), permeability function and soil water characteristic curve (SWCC) of the soils, respectively.

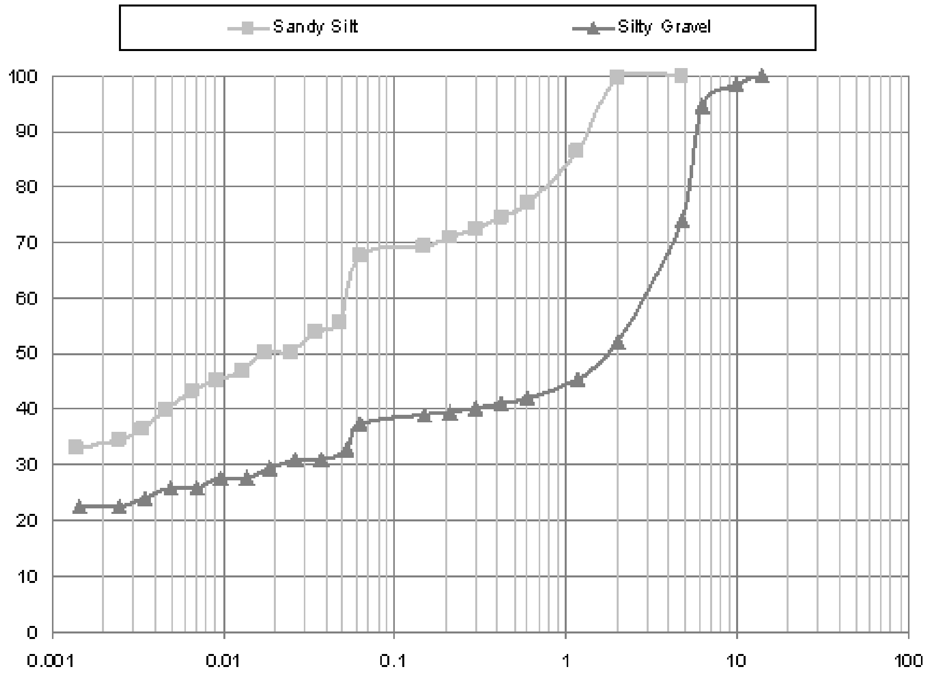


**Figure 4.1** Particle size distributions of the soils


**Figure 4.2** Coefficient of permeability (m/s) vs. matric suction (kPa)

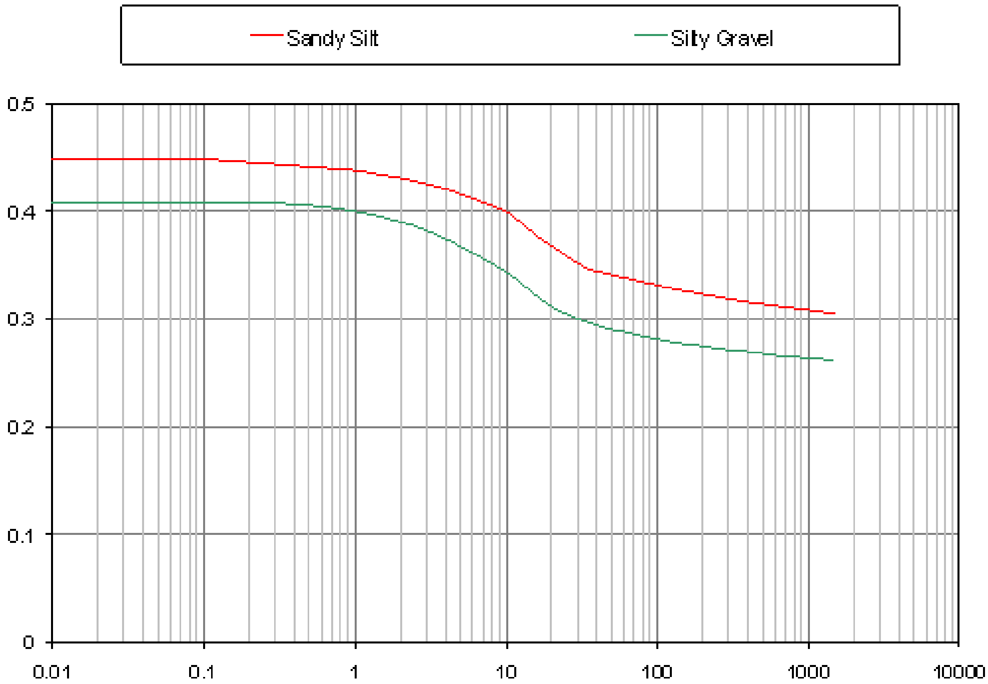


**Figure 4.3** Soil water characteristic curve (SWCC) – volumetric water content vs. matric suction (kPa)

The physical properties of the soils are tabulated in Table 4.1. From Table 4.1, it is found the permeability of silty gravel was one order of magnitude higher than the permeability of silty sand.

## 4.3 Testing Program

The experiment was conducted to study the mechanism and behaviour, i.e. pore-water pressure changes of a two layer system under different precipitation rates. The experiment involved two-layer system placed at a 18$^{o}$ slope angle of a 'jointed' coarse silty gravel underlying a fine sandy silt – each was 300mm in thickness. The joints or artificial relict structures in silty gravel were formed by inserting thin steel sheets during the placement of coarse silty gravel. The steel sheet were pulled out after compaction process was completed. Figure 4.4 shows that artificial relict structure created in silty gravel layer.

**Table 4.1:** Physical properties of the soils

| | Silty Gravel | Sandy Silt |
|---|---|---|
| **Composition** | | |
| Gravel (%) | 48 | 0 |
| Sand (%) | 15 | 33 |
| Silt (%) | 20 | 34 |
| Clay (%) | 17 | 33 |
| LL (%) | 53.2 | 59.3 |
| PL (%) | 35.5 | 31.9 |
| PI | 17.7 | 27.4 |
| BS | GMH | MHS |
| $G_s$ | 2.65 | 2.63 |
| $\rho_b$ (kg/m$^3$) | 1805 | - |
| $\rho_d$ (kg/m$^3$) | 1366 | - |
| MDD (kg/m$^3$) | - | 1415 |
| OMC (%) | - | 31.0 |
| $K_{sat}$ (m/s) | 3.7 x $10^{-6}$ | 5.0 x $10^{-7}$ |
| c' (kPa) | 3.3 | 7.6 |
| $\phi'$($^o$) | 39.5 | 32.1 |
| $\theta_s$ | 0.41 | 0.45 |
| AEV (kPa) | 3.5 | 7 |
| $\theta_r$ | 0.28 | 0.34 |

In order to control the density of the soil in-situ, the moisture content of soils to be placed in the infiltration box were initially controlled to targeted residual volumetric water content, $\theta_r$.

**Figure 4.4** The artificial relict structure

The initial condition for the test was set at $\theta_r = 0.28$ and 0.34 obtained from Figure 4.3 for silty gravel and sandy silt, respectively. An antecedent rainfall intensity of 2.1ml/min ($1.7694 \times 10^{-6}$ m/s) was applied for an hour prior commencing the test for achieving the natural suction profile as observed in field work. Subsequently, a 24hour simulation was conducted by applying rainfall intensity of 20.6ml/min ($1.7196 \times 10^{-5}$ m/s) with the purpose of studying the effect of 1day rainfall on the two-layer system.

### 4.4 Suction Distributions

Figure 4.5 presents the suction distributions along the sidewall of infiltration box at distance of (a) 250mm (upstream), (b) 1000mm, (c) 1350mm and (d) 1650mm (downstream). Figure 4.5(a) and (b) show the pore-water pressure distributions achieve a unit gradient below the interface (at -0.3m) after 4 to 8hour lapse. However, the pore-water pressures in Figure 4.5(b) move towards a nearly saturated condition at the top portion after 4hour. Similar patterns are also initially observed in Figure 4.5(c) and (d) but the total suction profiles decrease to nearly saturation condition after 4hours.

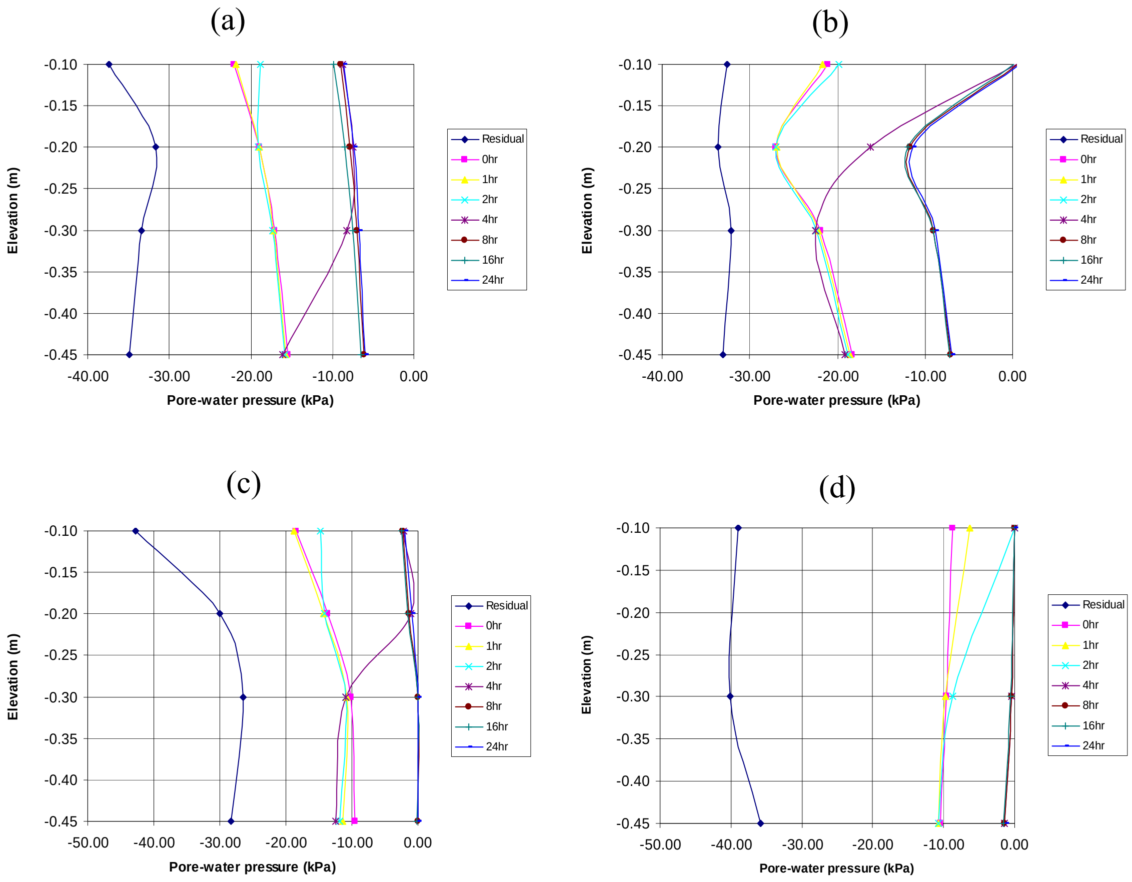


**Figure 4.5** Suction distributions (a) 250mm, (b) 1000mm, (c) 1350mm and (d) 1650mm

It is also found that the downstream side is very much wetter when compared to the upstream side. This could be due to flow impedance effects of the downstream boundary.

Most of the infiltration tends to be retained in sandy silt (upper) layer hence, the suction decreases gradually with time. Little infiltration into the lower layer was observed at the early stage of the experiment. The water only starts to infiltrate into the lower layer four hour after infiltration resulted in increase in pore-water pressure thus, increase in volumetric water content at the interface at the downslope. The negative pore water pressure basically remained low in the silty gravel (lower) layer until the water started to flow across the interface. A unit gradient occurred at pore water pressure of -8kPa. It will be referred to as total breakthrough suction value (Ross, 1990).

Figure 4.5 shows the vertical movement of water into the coarse layer or breakthrough took place once the suction decreased to a high enough pore-water pressure, i.e. at total breakthrough value. However in the sloped experiment the breakthrough also occurs at suction of higher than total breakthrough value. Figure 4.5 demonstrates the suction changes below the interface but does not achieve a unit gradient to suggest the present of a partial breakthrough along the interface. These effects of two-layer system have been demonstrated and researched by many others as the capillary barrier effect (Hillel & Baker, 1988).

# CHAPTER 5

# CONCLUSIONS AND SUGGESTIONS

## 5.1 Introduction

A study on the mechanics of water flow through geological discontinuity of residual soil slope is reported in this thesis. The specific objectives of the study were stated in the Chapter 1, as the ultimate goal of the study is to investigate the effect of geological discontinuity on the suction distribution of residual soil slope. In this Chapter, the conclusions of the study are presented after which the recommendations for further research are presented.

## 5.2 Conclusions

In conclusion, the developed sloping layered soil model can be used to study the mechanisms associated with capillary barrier effect for a two-layered soil system. The experimental results shows that the two-layer system of a ‘jointed’ coarse silty gravel underlying a fine sandy silt under the influence of a high precipitation rate is primarily governed by the fine soil of sandy silt. It is found that infiltration water retains in the upper layer of sandy silt and only infiltrates into the lower layer after pore-water pressure at the interface increases along down slope.

This study also demonstrated breakthrough regions under laboratory condition. In this experiment, total breakthrough occurs at pore-water pressure of -8kPa. However, the observation of breakthrough at lower pore-water pressure corroborates the existence of a partial breakthrough region identified along the interface.

## 5.3 Suggestions for Future Researches

In light of the limitations of the present study, a few areas were identified where further research were required:

i. **The study on a full scale model constructed under natural environment.** From the field measurement, it was found that the changes in ambient environment (i.e. solar radiation, humidity, temperature etc.) could also alter the soil suction. It would enhance the findings from the present study by accounting more surface boundary conditions.

ii. **The improvement on the laboratory modeling technique, particularly for the rainfall simulator.** An advanced rainfall simulator should be used to enable the simulation of low rainfall intensity for longer duration of antecedent rainfall. Besides, the installation of Time-Domain Reflectometry (TDR) probe that provides the measurement of volumetric water content would allow the inferences of the suction measurements from tensiometer.

iii. **The study on the mitigation measures of rainfall-induced slope failure.** The mechanisms of the rainfall-induced slope failure for different types of soil have been identified in this study. The further study may look into the possible mitigation measures.

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