WATER INFILTRATION STUDY ON SLOPES

by

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Dedicated

to

My wife

Aemy Lee Wai Ming

&

My Daughter and Son

Low Lydia
&
Low Kinson

For

THE LIFETIME OF LOVE, SUPPORT, INSPIRATION AND KINDNESS

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ABSTRACT

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Rainfall has been considered the major cause of the majority of slope failures and landslides in regions experiencing high seasonal rainfalls. It is well known that infiltration impair slope stability, but since it cannot be measured directly from the field, its assessment often relies on vague correlation among rainfall, runoff and infiltration, correlation between rainfall and infiltration, thus slope stability involves a large number of factors. Some of these factors, such as rain duration and intensity, surface cover and degree of saturation are extremely difficult to evaluate. The factors affecting water infiltration on slope such as surface cover, weathering grades, slope angle were studied and the results are presented and discussed.

In tropical humid areas such as Malaysia, residual soils forming processes are very active. Residual soils are products of the insitu weathering of igneous, sedimentary and metamorphic rocks. The process of weathering varies with the depth of the soils or exposure of the soils. Because the weathering proceeds from the surface down and inwards from joint surface and other percolation paths, the intensity of the weathering generally reduces with increasing depth. Most of the cut residual soil slopes in Malaysia will normally expose the various weathered grades of the soils. Due to the complexity of the weathering grades of residual soils (includes differences of particle size, density, mineral contents, cohesion, void ratio etc.), infiltration into slopes also varies from point to point down the slope. In this study water infiltration study was carried out in the field using infiltrometer and in the laboratory using "sprinkler model". Studies on infiltration have always been part of hydrology and Irrigation engineering. Infiltration forms the link between surface and subsurface hydrology. Infiltrated water must be quantified and subtracted from the surface runoff in flood prediction studies and surface water management. Numerous researchers have actually incorporated infiltration into the slope stability analysis of the residual soils, e.g., Othman (1990), Affendi et. al.(1992, 1996) and Suhaimi and Abdul Rahman (1997). In most analysis of slope stability, the infiltration rate of the slopes is assumed uniform throughout the slope. The soil is also assumed homogeneous except some layered bedding problem. Anderson et. al. (1985, 1988) in the United Kingdom, described the development of a combined soil-water slope stability model which incorporates infiltration in slope stability analysis.

In tropical regions, most of the soils are residual soils and indirectly the slopes will normally cut through the residual soils and exposed all the difference weathering grades materials. The effects of the weathering grades on the infiltration rate are also discussed in detail.

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CHAPTER 1

INTRODUCTION

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1.0 INTRODUCTION

Slope stability problems in residual soil are attracting increasing attention. Some slope failure events in recent years have proven fatal; the Highland Towers collapse in 1993 claimed 57 lives whilst the Genting Highlands tragedy in 1996 resulted in 22 fatalities. In addition to these two major events, several other landslides and slope failures have had fatal consequences and the annual cost of landslide and slope remedial measures are in the order of hundreds of millions of Ringgit.

Rainfall has been considered the major cause of the majority of slope failures and landslides that happened in regions experiencing high seasonal rainfalls (Brand 1984). Basically, it is well known that infiltration impair slope stability, but since it cannot be measured directly from the field, its assessment often relies on vague correlation with rainfalls and runoff, correlation between rainfall and infiltration, thus slope stability involves a large number of factors. Some of these factors, such as rainfall duration and intensity, slope surface cover and degree of saturation are extremely difficult to evaluate.

In tropical humid areas such as Malaysia, residual soils forming processes are very active. Residual soils are products of the insitu weathering of igneous, sedimentary and metamorphic rocks. The process of weathering varies with the depth or exposure of the soils. Because weathering proceeds from the surface down and inwards from joint surfaces and other percolation paths, the intensity of the weathering generally reduces with increasing depth. Most of the cut residual soil slopes in Malaysia will expose the various weathering grades of the soils. Due to the complexity of the weathering grades of the residual soils (which includes differences of particle size, density, mineral contents, cohesion, void ratio etc.), infiltration into slopes also varies form point to point down the slope.

Conventionally, infiltration of water is not included in slope stability analysis. Many of the steep slopes were designed based on experiences. Recently, attempts have been made to include rainwater infiltration and partial saturation in slope stability analysis. Most of the slopes failure and landslides occurred after prolonged heavy rainfall or antecedent rainfall. The mechanism of the failures was mainly due to the lost of matric suction of soils by rainwater. When the rainwater infiltrates into the slopes, it will start to saturate the soil, i.e., reduce the matric suction. The wetting front of the rainwater will continue to move into the soil even after the rain stopped. Movement of the wetting front stops when equilibrium condition is achieved.

Matric suction is one of the main stress variables in unsaturated soil theory. The existence of matric suction will increase the strength of the soil. A deep ground water table condition is normal in hilly area. In this case, the negative pore water pressure or matric suction plays an important role in controlling the soil shear strength and consequently the stability of many steep slopes. Shallow landslides often occur in steep residual soil slopes after heavy and prolonged rainfall. When water starts to infiltrate into the soil, the matric suction especially near the ground surface will slowly reduce and become zero as the soil approaches saturated condition. The significant reduction in matric suction causes a decrease in the soil shear strength that subsequently produces shallow landslides.

Studies on water infiltration have always been part of hydrology. Water infiltration forms the link between surface and subsurface hydrology. Infiltrated water must be quantified and subtracted from the surface runoff in flood prediction studies and surface water management. Numerous researchers have actually incorporated infiltration into the slope stability analysis of the residual soil, e.g., Othman (1989), Affendi et. al. (1994, 1996) and Suhaimi et. al. (1994,1997). In most of the analysis of slope stability, the infiltration rate of the water into soil is assumed uniform throughout the slope. The soil is also assumed homogeneous except in some layered bedding problem. Anderson et. al. (1985, 1987,1988) in the United Kingdom, described the development of a combined soil-water slope stability model which incorporates infiltration in slope stability analysis.

In tropical regions, most of the soils are residual soils and indirectly the slopes will normally cut through the residual soils and exposed material of different weathering grades. The effects of the weathering grades on the infiltration rate will be discussed in details in this study.

1.1 OBJECTIVES

The main objective of this research is to investigate some of the factors affecting the infiltration on cut slope of tropical residual soils. The factors considered are: -

a) Slope surface cover - grass and artificial geotextiles.

b) Angle of slopes

c) Weathering grade of soils

f) Changes of soil properties, i.e., density, void ratio, particle sizes etc.

g) Perched water table.

All the factors mentioned above if considered during the analysis of slopes will result in a better understanding of the slope failure mechanism especially that caused by perched water table and prolonged heavy rainfall.

1.2 SCOPE OF STUDIES

Before a meaningful investigation could be conducted, a working knowledge of the behavior of residual soils as well as the infiltration characteristics is required. A comprehensive literature survey was conducted to understand the behavior of residual soils in saturated and unsaturated conditions, infiltration in both the saturated and unsaturated zones and all factors affecting infiltration on slopes. Secondly, a hydrological slope model was designed in order to study some of these factors, i.e., angle of slopes, surface cover, etc., which affect the infiltration rate. The model is equipped with a sprinkler system and a hydraulic jack (to vary the slope angles). The design of the model will be elaborated in detail in Chapter 3, “Materials and Methodology”.

In addition to the model, infiltration tests were carried out at sites by using an Infiltrometer P-88 (by Geonor, Norway). Two sites were chosen and are from two different types of residual soil. One of the cut slopes is in a weathered granitic residual soil and the other is in a weathered sedimentary residual soil. At the sites, infiltration tests were carried out on different weathering grades. In addition, tests were also conducted to study the effects of grass covers on infiltration rates.

The scopes of the investigation were divided into four phases. Phase I, consists of literature review that include the theory of infiltration in both saturated and unsaturated residual soils, is reported in Chapter 2, “Literature Review.” Phase II covers the development and evaluation of laboratory equipments, slope model, computer analysis, methods and procedures to execute the investigation. These studies are reported in Chapter 3, “Materials and Methodology”. Following the successful implementation of phase I and phase II, laboratory and field tests were carried out and the data were analyzed. Phase III comprised of data compilation and analyses and the results are reported in Chapter 4 “Test Results and Analysis of Data.” Phase IV consists of discussion and conclusions that were obtained from the study and suggestions for further research are mentioned in Chapter 5, “Discussion,” and Chapter 6, “Conclusions and Recommendations”, respectively.

CHAPTER 2

LITERATURE REVIEW

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LITERATURE REVIEW

2.1 INTRODUCTION

In the first part of this chapter, literature review was carried out on the characteristics of residual soils, the theory of infiltration and the existing methods for determining the soil infiltration. This chapter deals with numerous practical infiltration equations presented by previous researchers and previous works on water infiltration. The advantages and disadvantages of the methods are discussed briefly. At the end of this section, the need for objective method in determining the infiltration characteristics is established.

2.2 RESIDUAL SOILS

Residual soils are products of in-situ weathering of igneous, sedimentary and metamorphic rocks. They occur in most countries of the world but are extensively found in tropical humid areas such as Malaysia. Warm temperatures and abundant moisture in the tropical region provides an optimum environment for rapid weathering processes, in particular chemical weathering. In this region, the residual soil forming processes are very active.

The process of weathering varies with soil depth or exposure. Because weathering proceeds from the surface down and inwards from joint surface and other percolation paths, the intensity of the weathering generally reduces with increasing depth. Figure 2.1 illustrates a typical residual soil profile that can be subdivided into several zones depending on the extent of weathering. The properties and mechanical behavior of residual soils can be quantified with respect to flux boundary conditions (i.e., infiltration and evaporation) and groundwater fluctuations. However, the effect of climate is seldom incorporated into geotechnical designs because of difficulties in the assessment of the unsaturated soil zone above the water table.

2.2.1 STAGES OF WEATHERING OF BEDROCK MASS

The distribution pattern of the different stages of weathering of bedrock material within the weathering profile is very distinctive and allow the recognition of a number of morphological horizons, each of which is characterized by variable amounts of different stages of weathering of bedrock material. Basically, from the geological point of view, the weathering grades can be subdivided into 6 stages, i.e., stage 1 - 6 according to the rock mass weathering grades applied by Irfan and Dearman (1978) and Baynes (1978).

The weathering grades could be described as below:-

a) Grade 6 - a) All rock material converted to soil.

b) Mass structure and material fabric destroyed

c) Significant change in volume.

b) Grade 5 - a) All rock material decomposed and disintegrated to soil.

b) Original mass structure still largely intact

c) Grade 4 - a) More than 50% of rock material decomposed and disintegrated to soil.

b) Fresh / discolored rock present as discontinuous framework or core stones

d) Grade 3 - a) Less than 50% rock material decomposed and disintegrated to soil

b) Fresh / discolored rock present as continuous framework or core stones

e) Grade 2 - a) Discolouration indicates weathering of rock material and discontinuity surfaces.

b) All rock material may be discolored by weathering and may be weaker than in its fresh condition.

f) Grade 1 - a) No visible signs rock material weathering.

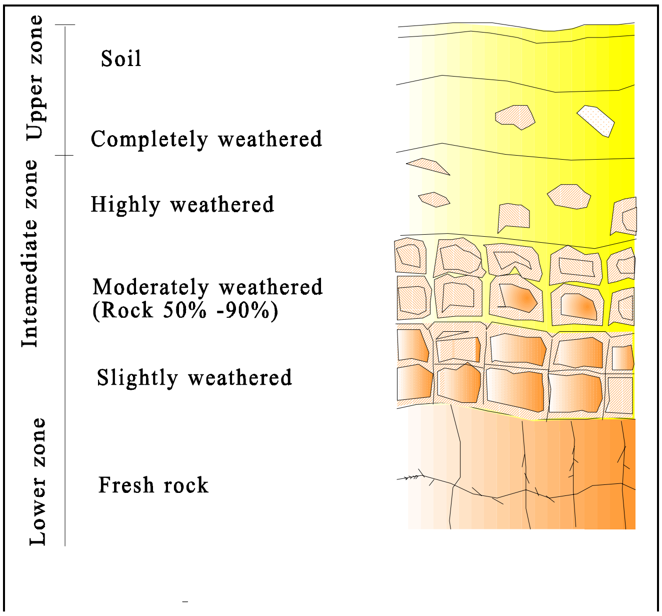

Figure 2.1 Schematic diagram showing a typical tropical residual soil profile

Movement of water into the soil is controlled by gravity, capillary action, and soil porosity. Of these factors, soil porosity is most important. The porosity of soil is controlled by its texture, structure and organic content. Coarse textured soils have larger pores and fissures than fine-grained soils and therefore allow for more water flow. Pores and fissures found in soils can be made larger through a number of factors that enhance internal soil structure. For example, the burrowing of worms and other organisms and penetration of plant roots can increase the size and the number of macro and micro-channels within the soil. The amount of decayed organic matter found at the soil surface can also enhance infiltration. Organic matter is generally more porous than mineral soil particles and can hold much greater quantities of water.

Above-mentioned soil characteristics that affecting infiltration could be found in weathered residual soil from grade 1 to grade 6.

2.3 INFILTRATION

The research on water infiltration into the soil was first discussed by E. Buckingham in 1907 and followed by other researchers. Infiltration is the process by which water enters the surface strata of the soil and moves downward towards the water table. This water first replenishes the soil moisture deficiency and any excess water moves downward, where it is trapped in the voids and become groundwater. The maximum rate at which a soil in any given condition is capable of absorbing water is called its ***infiltration capacity (f)***. It is evident from the above discussion that the groundwater stored, depends mainly upon the number of voids present in the soil, which, in turn, does not depend upon the size the soil particles but rather upon the arrangement, sorting, shape and degree of compaction. Therefore, different soils will have different number of voids and hence different ***infiltration capacity.***

It is evident that rainwater will penetrate the soil at full capacity rates only during the periods when rainfall rates exceed the ***infiltration capacity (f)***. When the rain intensity is less than the infiltration capacity, the prevailing infiltration rate is approximately equal to the rainfall rate. Hence, the actual prevailing rate may be equal to or less than the infiltration capacity. The actual prevailing rate at which the water is entering the given soil at any time is known as ***infiltration rate (i)***.

If the rainfall intensity exceeds the ***infiltration capacity (f)***, the difference is called as the ***rainfall excess rate (p).*** The excess water is, first of all, accumulated on the ground as ***surface detention (D)*** or flows over land into the streams as ***surface runoff (r)***.

The rate of infiltration normally declined rapidly during the early part of a rainstorm event and reached a constant value after several hours of rainfall. A number of factors are responsible for these phenomena, including: -

a) The filling of fine soil pores with water reduces capillary forces.

b) As the soil moistens, clay particles swell and reduce size of pores.

c) Raindrops impacts breaks up soil clumps, splashing fine particles into pores and reduce the number of pores and its sizes.

Infiltration impairs slope stability in three different ways: Firstly, it induces subsurface underflow; secondly, it changes the moisture content of the soils (or reduce soil suction) and lastly it changes the groundwater storage within the soil mantle. It is estimated that over the period of rainstorm, most of the infiltration will be retained locally, altering the soil suction and local groundwater table. This is considered to be the most important cause of rapid landslide.

2.3.1 MECHANISMS OF INFILTRATION OF WATER THROUGH SOIL

When water falls on a soil surface, a small part of it is absorbed by the thin top layer of soil thereby creating moisture gradient or potential where the top layer is wetter than the bottom layer. This will force the water to flow downwards toward the drier zone of the soil profile. When water is in excess, it will fill the interstitial spaces at the top thin layer forming saturated soil column. When this occurs, the rate of flow increases since the saturated column will provide the extra head thereby increases the moisture gradient.

When there is a constant supply of water at the soil surface, such as rainfall, the excess water moves downward through the unsaturated zone toward the water table below. The downward flow of water through the partially saturated zone toward the water table is known as percolation.

Infiltration of water through soil occur due to the following reasons: -

a) Capillary effects of the existing soil pores in the soil profile.

b) Gravitational effect on the infiltrating water.

c) Differences of the soil moisture gradient of the upper and lower layers.

2.4 INFILTRATION EQUATIONS AND MODELS

Infiltration is affected by a number of factors, which can be grouped as surface characteristics, soil characteristics, precipitation characteristics, fluid characteristic and the antecedent moisture content (AMC) conditions. There are presently several models available and is used in hydrological analysis. These models, in general can be divided into two types, i.e. empirical models and conceptual models.

Empirical models are derived from the field data. They do not rely on the physics of flow through porous media. All empirical models tend to express infiltration capacity or infiltration rates as function of time.

As for the conceptual models, they rely on physics of flow through porous media. Most of these models are based either explicitly or implicitly on Darcy's law. Principal characteristic of these models is that they incorporate parameters, which are determined from physically measurable properties of the soil-water system.

Chapter 2 LITERATURE REVIEW

Early attempts to quantify the infiltration process were, for the most part, formulas, which were obtained empirically or derived from limited physical basis. The formula of Green and Ampt (1911) was derived from a simplified model of the infiltration process. These authors assumed that the saturation profile propagates as a distinct waterfront, behind which the saturation distribution was uniform at the maximum value obtainable in the process. Basically the model implicitly assumed:-

a) The soil surface is covered by a negligible thickness of ponding water.

b) There is a clearly defined wetting front as water infiltrates into the soil.

c) The wetting front separates the soil into fully saturated and unsaturated layers.

d) The moisture content in saturated layer remain constant during the infiltration process.

e) There is a negative pore pressure just below wetting front.

It was assumed that the saturation of the porous material at points ahead of the advancing waterfront remained at a uniform initial saturation. Combining Darcy's law and the continuity equation for these particular cumulative infiltration model results in a simple equation as function of time which can be expressed as follows: -

$$(Q/C) - \{[h_t\varphi\,(S_0 - S_1)]/\,C\}\ln\,\{1 + [Q/(h_t\,\varphi(S_0\text{-}S_1)\,\} = t \quad \text{..........eq. 2.1}$$

Where Q = cumulative infiltration,

φ = porosity,

h_t = total head,

S_0 = maximum saturation obtained on the imbibition's cycle,

S_1 = initial saturation,

C = hydraulic conductivity at S_0

t = time

The total head h_t is the sum of the capillary pressure head at the waterfront and the depth of ponded water on the surface of the soil.

Another equation on infiltration rates is the formula of Horton (1940), which is as presented as below:

$$f = f_e + (f_0 - f_e)\, e^{-\alpha t} \quad \text{……………………………………eq. 2.2}$$

Where f = infiltration rate at time t

f_0 = initial infiltration rate

f_e = limiting value of the infiltration rate

α = a constant with little or no physical interpretation

Childs (1969) reported that infiltration equation (eq. 2.2) can best be regarded as an intuitive formula.

The above formula are examples of algebraic equations derived from limited physical concepts. These equations are most often used by adjusting the parameters to fit a given set of data. In some cases, some physical significance of the various parameters are entirely lost; parameters such as the entrapment of air in the soil and the built pressure ahead of the wetting front in soil.

Another infiltration formula commonly used is that proposed by Philip (1957) which is as presented below (eq. 2.3) :

$$q_0 = (S/2)\, t^{-1/2} + B \quad \text{……………………..…………………………eq. 2.3}$$

Where ,

q_0	=	infiltration rate
t	=	time
S and B	=	constants which can be adjusted to give the best fit to measured infiltration rates.

Skaags (1969) also suggested an equation (eq. 2.4) on infiltration rate in the form of: -

$$F = at + bt \quad \ldots\ldots \text{eq. 2.4}$$

Where,

F = cumulative depth (in/cm)

t = time (seconds)

a = a constant close to the hydraulic conductivity value at the surface at t = 0.

b = absorptive value obtained from the rate of penetration of the wetting front.

The first factor, **a,** is generally thought to represent conductivity flow under gravity by unimpeded laminar flow through network of large pores. The other factor **b**, is the diffusion term representing the filling up of the smaller pores by diffusion from one pore space to the next.

Dixon (1976), taking into account the factors affecting the infiltration characteristics of soil such as the entrapment of air and the build up of the pressure head of the wetting front, concluded that an empirical equation known as the Kostiakov's equation is more convenient to use than the Green and Ampt (eq. 2.1) equation because it expresses the infiltration rate, I, as a function of the wetting front depth. Dixon's conclusions were supported by the work of Schwartzendruber and Huberty (1958) and Skaags et al (1969). The Kostiakov's equation is as presented below (eq 2.5) : -

$$Iv = at^b \quad \text{……………………………………………………..eq. 2.5}$$

Where Iv = cumulative infiltration volume

t = elapsed time after incipient ponding

a,b = constants

Parameter, *a*, is the infiltration volume Iv during the first unit of elapsed time t after the onset of ponding and *b* is the ratio of *a* and the current infiltration volume.

The Kostiakov's equation predicts that the infiltration rate will approach zero at large times. A modification has been proposed by Schwartzendruber and Huberty (1958) to allow for a certain minimum rate that is as represented below in eq. 2.6 (notice the similarity in Kostiakov's equation): -

$$Iv = c + at^b \quad \text{......eq. 2.6}$$

Where

c = minimum infiltration rate at $t = \infty$

In 1931, Richards published a mathematical model of the capillary conduction of water in soil. This equation, known as the Richards Equation, has remained the basis for most of the work concerning infiltration since then.

Richards combined Darcy's law and the equation of mass conservation for the water to obtain the following equation (eq. 2.7): -

$$\partial / \partial z \left(C \ \partial h / \partial z \right) - \partial C / \partial z = \partial \theta / \partial t \quad \text{......eq. 2.7}$$

Where C = hydraulic conductivity

θ = volumetric moisture content

h = capillary suction head

z and t = are the space and time coordinates respectively

The Richards equation has been made more amenable to solution by converting it to an equation with θ as the only dependant variable or to a form with h as the only dependant variable. The former is known as the "diffusivity" or water content form, and the latter are called the pressure head form. The conversion to either water content or pressure head form is accomplished by the use of the functional relationships among C, θ and h. The pressure head form is somewhat more general than the diffusivity form because it can be applied in both saturated and unsaturated domains. The diffusivity form yields no information in saturated regions because the relationship between h and θ is not single valued.

A series of papers by Philip (1957 - 1959) remains today as the classical analysis of infiltration. Philip obtained an approximate solution to the Richards equation under the boundary condition of constant water content at the upper surface and for a ponded water boundary condition. The initial condition treated by Philip was uniform water content. The equation for infiltration rate (refer to eq. 2.8), which was derived from this analysis, is as presented below: -

$$q_0 = (S/2)\, t^{-1/2} + (C_n + B) + (3/2)Dt^{1/2} + 2Et^{3/2} + G \quad \text{.....eq. 2.8}$$

Where,

S,B,D,E, G	=	coefficients which can be calculated using a series of ordinary differential equations
C_n	=	hydraulic conductivity associated with the initial water content

2.5 FACTORS AFFECTING INFILTRATION RATE AND CAPACITY

Infiltration capacities of most soils are characterized by extreme variability. The actual value at any particular time at a location is the combined results of the interaction of many factors. Some factors cause the infiltration capacity to differ from one location to another, whereas others produce variations from time to time at any location. The infiltration rate in soil is influenced by various factors such as the ones listed in the following sections: -

2.5.1 THICKNESS OF THE SATURATED LAYER AND THE DEPTH OF SURFACE RETENTION

The principal force that causes water to enter the soil is gravity as the layer of soil near the surface has its interstitial spaces saturated. If the thickness of this saturated soil at any given time and at any given section is ***l***, then the water will flow through a series of tiny capillary tubes of length ***l***, as shown in Figure 2.2.

At the top of each capillary tube, the pressure head is equal to **D** (i.e., equal to the surface detention) and the total pressure head causing discharge is **D** + ***l*****.** On the other hand, the resistance to the flow by the soil is proportional to ***l*** **.** If ***l*** is large compared to **D,** changes of ***l*** will have nearly equal effect on the force and the resistance, and the rate of infiltration will be nearly constant.

However, at the beginning of rain, **D** and ***l*** may be of the same order of magnitude. Under such a condition, force is large compare to the resistance, and water will enter the soil rapidly. However, with the passage of time, ***l*** will become much greater than **D**, and therefore, there will not be significant difference between the values of force and resistance and hence, the rate of infiltration falls reduces.

The effect of surface detention on infiltration of slopes is not very important. Most of the rainwater does not detain on slopes but drain as surface runoff.

2.5.2 **SOIL MOISTURE**

There are two important effects of soil moisture on infiltration rate. The soil-moisture content at the beginning of the rain had a greater effect upon the rate of infiltration during the first 20 minutes than other factor. The amount of soil moisture has an important effect on the infiltration rate. Water infiltration is higher in dry soil compared with wet soil. When rain falls on dry soil, the upper surface becomes wetter than the lower layers. Thus, there exists a large difference of capillary potential between the top portion of the soil and the portion below.

Due to this difference in the suction head, the downward force will act on the water which will be in addition to the normal force of gravity which to act on the moisture. As time passes, the lower portion will become wet, hence this difference in suction head will decrease, and therefore the infiltration rate will reduce as the moisture content increases. The second effect of the soil moisture on infiltration rate is the reverse of the first. Linsley, Kohler and Paulhus (1949) stated that when the soil becomes wet, the colloids present in the soil swell immediately and reduce the pore size of the soil and hence, reduce the infiltration capacity during the initial period of rainfall.

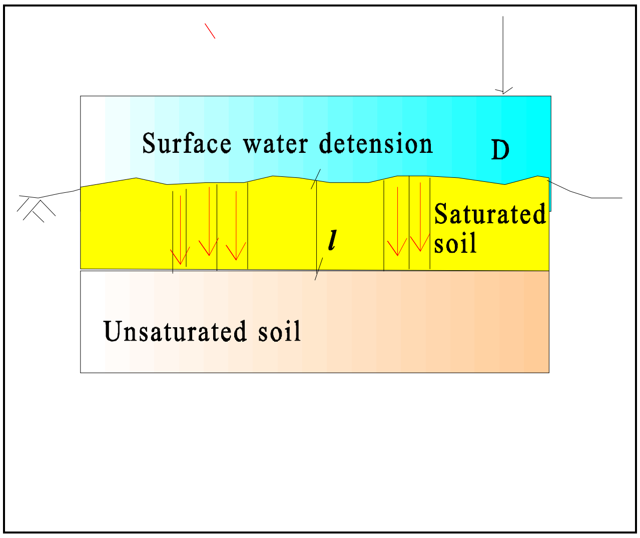

Figure 2.2 Effect of the saturated layer and the depth of surface detention on infiltration.

2.5.3 RAINFALL CHARACTERISTICS

There are two important rain characteristics, which will influence the infiltration rate in soil, and they are as follows:

2.5.3.1 DURATION OF RAINFALL

As long as there is a supply of water at the surface, the infiltration process will continue. This process will continue from a transient condition until it reaches a steady state. In other words, the infiltration rate through the soil will reach a constant after a certain time.

2.5.3.2 INTENSITY OF RAINFALL

The higher the intensity of rainfall, the higher the initial infiltration rate through the soil. However, the infiltration rate through a soil sample is limited by the infiltration capacity of the soil. Any excess of rainwater would be washed away as surface runoff.

2.5.3.3 SURFACE CRUSTING

Rainfall can form a crust formation on the surface by the sorting action of raindrops.

In some cases, even sandy soil will become impermeable. When rain falls, it breaks down the topsoil structure into fine particles and deposited them in the voids, thus reducing the infiltration rate through the soil (Bresler and Kremler 1970).

2.5.3.4 RAINDROP IMPACT

Mechanical compaction caused by raindrops greatly reduces the infiltration capacity in soils of fine texture. The surface of exposed clay soils can be worked into a virtually impermeable condition in this manner, whereas the infiltration capacity of a clean sandy soil is affected by rain compaction. Besides, the impact of the rain will also tend to break crumbs and detach material on the surface. Protection by vegetation cover can reduce or practically eliminate this effect, even in finely textured soils. This is another factor, which will be discussed in detail later.

2.5.3.5 WASHING OF FINES

When a soil becomes very dry, the surface often contains many fine particles. When the rain falls and infiltration begin, these fines are taken down into the soil and are deposited in the voids, thus reducing the infiltration capacity. This factor also reduces infiltration capacity during a period of rain.

2.5.4 COMPACTION OF THE SOIL DUE TO MAN AND ANIMALS ACTIVITIES

Where heavy humankind activities occur on a soil, the surface in rendered relatively impervious. Examples of types of area that have low infiltration capacities as the results of this factor are overgrazed pastures, playgrounds, and dirt road. Even though this factor does not play an important role in the study of slope infiltration, the compaction of the heavy vehicles, e.g., excavators and trucks during slope cutting should be considered.

There is also other type soil compaction which influences the infiltration rate through soil. Richard, et. al. (1967), investigated the effect of soil compaction on the infiltration rate in various land uses as shown in Table 1.

2.5.5 THE PARTICLE / PORE SIZES OF THE SOIL

The soil porosity is expected to have a close relationship with the hydraulic conductivity of the soil. This hydraulic conductivity is one of the flow parameters in the infiltration analysis. In general, the bigger the pore sizes, the higher the infiltration rate.

Kirby (1976) showed that grain size has influence on infiltration rates in soil as summarized in Table 2.

TABLE 1: INFILTRATION RATES RESULTS FOR SOILS IN THE BRISTOL AREA (Kirby 1976)

SOIL SERIES	SITE CHARACTERISTICS	INFILTRATION CAPACITY (mm/hr)
WORCESTER	-bare ground, compaction by vehicle -	9
	part bare, compaction by vehicle	29
NIBLEY	-vegetated, compaction by cattle	11
	- light pasture	115
VESHAM	-heavy pasture, compaction by cattle	164
CHARLTON	-heavy pasture	55
	-light pasture	366

TABLE 2: EFFECT OF GRAIN SIZE ON INFILTRATION RATES ON SOIL WITHOUT VEGETATION COVER

GRAIN SIZE	INFILTRATIONS RATE (cm/hr)
CLAY	0 - 4
SILTS	2 - 8
SANDS	3 –12

2.5.6 VEGETATIVE OR SYNTHETIC SLOPE COVER

This factor is related to many of the factors described above, but it is the most important factor and it will not be unwise to discuss its effects under a separate heading.

The presence of a dense vegetation cover over a soil increases the infiltration capacity of that soil to a considerable extent. With the existence of vegetation cover, the rain will not be able to compact the soil, and it provides a layer of decaying organic matter, which promotes the biological activity of burrowing insects, and animals that in turn produces permeable soil structure. The vegetation roots system also breaks down soil particles and increase the granulation and porosity that encourages more rapid passage of infiltrating water. Dense vegetation or any synthetic cover would increase the infiltration rate of a soil sample with considerable extent in comparison with bare soil. The presence of vegetation or synthetic cover reduces the velocity of runoff and increase the surface detention, thus, allowing more time for the water to infiltrate the soil.

Kirby (1976) showed that the soil surface covers have influence on infiltration rates, as summarized in the table below: -

TABLE 3: INFLUENCE OF GROUND COVER FOR CECIL, MEDISON AND DUNHAN SOILS ON INFILTRATION RATES

GROUND COVER	INFILTRATION RATE (mm/hr)
1.Old permanent pasture	57
2.Old permanent pasture (moderately grazed)	19
3.Old permanent pasture (heavily grazed)	13
4.Weed and grain	9
5.Clean tilled	7
6 .Bare ground	6

Further, transpiration by vegetation removes soil moisture and increases the difference of suction potential between upper layer and lower layer of soils and thus tends to increase infiltration rate during initial periods of rain.

2.5.7 SLOPE CHARACTERISTICS

Slope characteristics are important factors in determining the amount of infiltration and runoff. With an increasing slope gradient, water detention will be reduced due to increase in water runoff. The length of the slope also plays an important role in infiltration rate. The longer the slope, the greater the time that is allowed for the water to infiltrate into the soil.

2.5.8 TEMPERATURE EFFECT

The viscosity of water changes with temperature. Since the flow in the interstitial spaces of soil is nearly always laminar, the rate of infiltration will also change with viscosity. Hence, infiltration capacity will change with temperature. In tropical regions, the effect of temperature is not crucial as temperature changes are not extreme.

2.5.9 ENTRAPPED AIR

When infiltration occurs at nearly uniform rates over a large area, the air in the soil spaces may be trapped temporarily. The downward movement of the sheet of water (wetting front) entering the soil then compresses the air. The effect is particularly noticeable in areas where the ground is nearly horizontal. The compression of the air in the ground forces air out through wells. However, some of the entrapped air does tend to retard infiltration and is one of the factors that cause a reduction in infiltration capacity as the storm progresses.

2.6 METHODS OF DETERMINING INFILTRATION

Butler (1959)mentioned that due to the great number of variables involved in the infiltration process, the measurements of infiltration rates and capacities cannot be predicted with much accuracy unless predictions are based on field measurements under various conditions.

Various methods have been used in an attempt to quantify infiltration. These methods differ in accordance with the different purpose for which they are established and according to available facilities available. Two experimental methods are generally used to determine infiltration capacity.

1. Infiltrometers
2. Rain simulator method.

Since soil structure controls the rate of infiltration, measurements are usually conducted on soil in place. Laboratory or other determinations of infiltration of soils of modified structure usually provided results differing widely from those that occur in the field (in this study, infiltration rates was determined using infiltration sprinkler model in the laboratory to investigate the effects of surface covers, slope angle and length of slope. As for the field, Infiltrometer was used). Among the various methods used to obtain comparative results are listed by Sherman and Musgrave (1949), as follows:

1. Measurement of the rate of water intake in areas defined by concentric rings of various sizes.
2. Measurement of the rate of water intake in areas defined by tubes with different techniques.
3. Measurement of the rate of intake of water defined by irrigation practices, particularly flooding.
4. Measurement of runoff of water applied to small samples areas by rainfall simulators of various kinds.

Landon (1984) summarized that the methods of measuring infiltration based on the flooded basin infiltration in the field. This involved the use of basins with area between 3 and 10 m^2. The soil surface is prepared in a manner similar to that used when the land is developed, and a number of graduated measuring staffs are located within the basin.

After the construction of a bund of suitable height around the basin, water is introduced and the rate of intake into the soil is calculated from readings on the measuring staffs.

In some circumstances, it may be desirable to maintain a constant head of water in which case the infiltration rate is obtained by relating the rate of water inflow to the surface area of the plot.

Before describing the methods, it is important to first differentiate between two important terms, namely, (i) Small watersheds (ii) large watersheds.

i) Small Watershed

Small watersheds are those drainage basins, which are small to such an extent that the rain intensity may be considered as being uniform over the entire basin. The area of such a basin may range from a few hectares to perhaps 2500 hectares. Such a basin will also respond quickly to rainfall, and hence, each period of intense rainfall is likely to produce a separate peak in the runoff hydrograph. Such basins are generally encountered in the design of culverts, storm sewers, small bridges, etc.

ii) Large Watersheds.

The large drainage basins are the basins of long dimensions and thus, larger than those for which the rain intensity may be considered as being uniform over the entire basin. They generally involve the construction of flood protection (such as dams and etc.), irrigation, water supply works, etc.

2.6.1 DETERMINATION OF INFILTRATION CAPACITY BY USING INFILTROMETERS

There are various kinds of infiltrometer which are used to measure infiltration rate. The simplest method is the cylinder or ring infiltration. This method of measuring infiltration rate uses either a single ring infiltrometer (refer to Figure 2.3) or a double ring Infiltrometer (refer to Figure 2.4), but the later are preferred because it reduces the error due to the effects of the edges of the inner ring. The measurement is usually performed in triplicate at any given site and the three stations not less 10 meters apart, should be located according to a described soil profile. At each pre-wetted station, a large and a small diameter steel cylinder were hammered concentrically into the ground to a depth of 15 cm and leveled. Each ring is filled to equal height of water in the inner ring and allowed to fall 5 - 15 cm between refills up to its original level, and the height of water in the outer ring was adjusted throughout to follow these changes. Rates of flow are established from water levels at predetermined time intervals. In practice, the rate of inflow becomes constant normally after 3 to 5 hours of infiltration, depending on the soil.

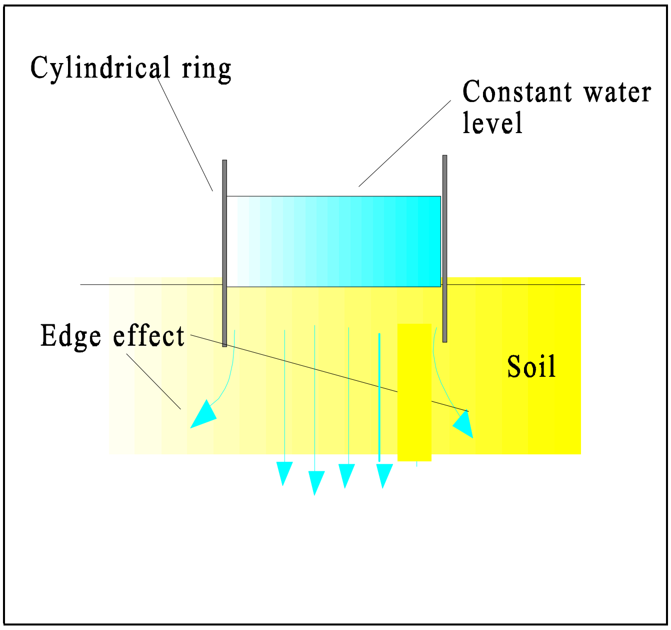

Figure 2.3 Single Ring Infiltrometer

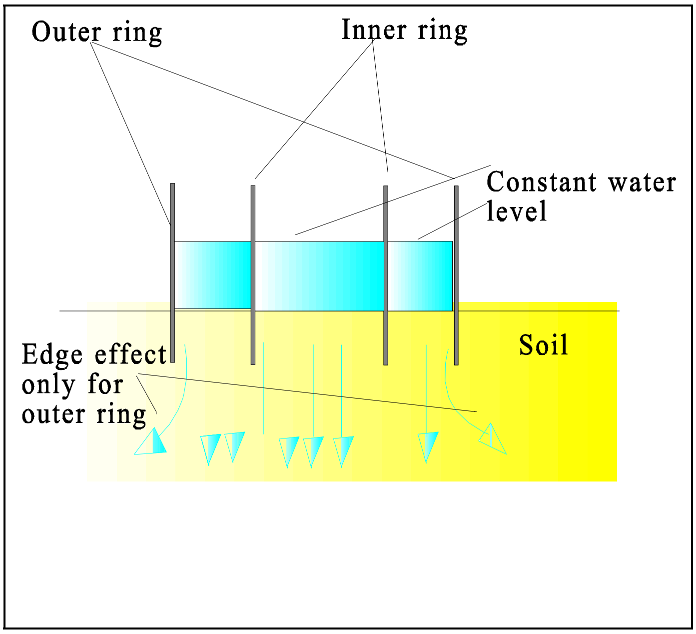

Figure 2.4 Double Ring Infiltrometer

There are various kind of infiltrometers, for this study, Infiltrometer P-88 from GEONOR was used and will be discussed in details in Chapter 3 " Material and Methodology".

2.6.2 RAIN SIMULATOR METHODS

The infiltration rate may also be determined by passing water down a furrow of known length and wetted cross sections and measuring the inflow and outflow (Chow 1967). In describing this, he stated that the flow rates may be obtained empirically or by the use of " V " notch of rectangular weir sections associated with standard formulae.

The use of rainfall simulators in determining infiltration rate has been widely known. Chow (1967) stated that rainfall simulators have been used to determine infiltration rates on sample areas lying within and representing larger areas for which information is desired. Artificial rainfall is supplied under standardized procedures. The rate of runoff and rainfall is then determined and analyzed.

Lutz and Chandler (1957) stated that the methods to determine infiltration rates can be categorized into two: -

1. Infiltration is regarded as equivalent to the water applied when runoff is prevented.

2. Infiltration is regarded as equivalent to the difference between water applied and runoff when the latter are permitted (in this study, the infiltration rate was obtained according to this category).

Even though there are many methods to determine infiltration rates, there seem to be a general acceptance of a problem associated with it. The problem of determining infiltration rates is well summarized by Miller (1977). He stated that it is not possible to predict infiltration rates from knowledge of the physical properties of the soil even though notable progress is being made.

The use of artificial rainfall by means of various kinds of rainfall simulators to determine the infiltration rates has so far been accepted because of its efficiency in representing natural rainfall. In this study, artificial rainfall is simulated by using the sprinkler system to model the effect of natural rainfall.

Many types of infiltrometers and rain simulator methods have been used and unquestionably still more will be developed. Their use has not been standardized and so it cannot be said that any particular type is the best. The objections to the use of ring and tube infiltrometers apply also to the sprinkling type, although to the lesser degree. It has been quite definitely established that the results obtained by infiltrometers are qualitative and not quantitative (Wilm 1941). In other words, with infiltrometers, it is possible to determine the relative effect of any change in land use or of any other controllable physical characteristics. It is not possible, however, to determine satisfactorily the runoff from a drainage basin by the direct use of infiltration capacities as determined by infiltrometers. This is because of the factors stated above and because infiltration capacity for a large basin in which there is subsurface storm flow, as determined by infiltrometers would in all probability give grossly misleading results.

2.7 WATER MOVEMENT IN UNSATURATED ZONE.

As mentioned earlier, the movement of water in soil is governed by both the gravity and capillary forces. The total potential at any point is the sum of the two and water moves from areas of high to low potential. As gravity may not be the dominant force, water can move in any direction, although usually in a vertical direction, either upward or downward.

As the name implies, the unsaturated zone contains air or water vapour as well as water. The unsaturated hydraulic conductivity, often referred to as capillary conductivity, is a function of moisture content. The lower the moisture, the smaller the capillary conductivity value, while maximum values are attained at near saturation.

When rain water fall on dry soil, initially the capillary force (matric suction) is dominant, but the influence of gravity increases with time. The distribution of moisture in the soil profile as water move downwards is divided into four zones (Bodman 1943): -

1) Saturation zone

2) Transmission zone

3) Wetting zone

4) Wetting front

The saturation zone is a thin surface layer (about 15mm thick) that is saturated with water. It passes down with a marked decline in moisture content. The wetting zone lies below the transmission zone, the lower boundary being referred to as the wetting front. The moisture gradient in the wetting zone is steep.

If infiltration continues, the wetting front moves downwards and the transmission zone becomes larger. When infiltration stops, water is redistributed in the profile. The upper zones begin to drain and water continues to move down until all the zones reach field capacity.

Infiltration rates are influenced by two factors:- storage capacity in the near surface layers and the rate that water can move downwards through the unsaturated zone. The limiting factor may be a thin relatively impermeable layer such as clay band and hardpan. If infiltration continues for long periods, "p***erched***" water tables can develop above such impeding layers.

When rainfall ceases, evaporation begins to dry out the surface layer and water rises in the soil profile when capillary forces exceed gravitational forces.

Lateral movement of water through the soil layer is referred to as t***hrough flow*** by Kirby and Chorley (1967). Permeability of soil zones tends to reduce with depth, which places a limit upon the amount of deep infiltration. Through flow occurs above the level of reduced permeability. Soil moisture content increases down a hill- slope but only approaches saturation in a zone adjacent to the stream channels. During the course of a rain storm the saturation area extends further up the hill slope, but overland flow only occurs over the lower parts of the hill slope where the soil is saturated.

The rate of advancement of the saturated zone can be estimated by wetting band theory proposed by Lumb (1975):-

$$v = kt / (S_f - S_o)n \qquad \text{eq. 2.9}$$

Where,

v	=	wetting band
t	=	rainfall duration
k	=	soil permeability
S_f and S_o	=	initial and final degree of saturation and
n	=	porosity.

2.7.1 SOIL MOISTURE

Soil moisture is a term applied to the water held in the soil by means of molecular attraction. It forms a film around the soil particles, fills the small wedge-like spaces between soil particles and may completely fill the smaller interstitial spaces. This moisture is held so tightly that it strongly resists any forces tending to displace it. The degree of its resistance to movement is expressed by its capillary tension or the synonymous term capillary potential, which is measure of the force required to remove this moisture from the soil. It is most conveniently expressed in terms of depth of water having an equivalent pressure. Its value is negative with respect to atmospheric pressure. This negative pore pressure is also known as soil matric suction by Fredlund (1972).

The review panel for the soil mechanics symposium " Moisture Equilibrium and

Moisture Changes In Soils ", adopted the subdivision of soil suction and the definitions as shown below which was quoted by the International Society of Soil Sciences:-

1. *Matric suction is the negative gauge pressure relative to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water.*

2. *Osmotic suction is the negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane with a pool containing a solution identical in composition with the soil water.*

3. *Total suction is the negative gauge pressure relative to the external gas pressure on the soil water to which a pool of pore water must be subjected in order to be in equilibrium through a semi-permeable membrane with the soil water. Total suction is thus equal to the sum of matric suction and osmotic suction.*

In this study, only matric suction was measured because the influence of osmotic suction is relatively small compared to matric suction and it is difficult to measure or monitor osmotic suction.

2.7.2 MATRIC SUCTION

Infiltration capacity is governed by soil capillary potential (soil matric suction). It is important to understand what is soil suction as this quantity will also be determined to monitor the depth of infiltration during laboratory sprinkler model tests in the study. As mentioned earlier, soil suction arises from the act of surface tension from the water in the soil pores. Thus, soil suction is actually the negative pore water pressure of the soil. It has the tendency to absorb water and if it absorbed water, the degree of the suction head decreases. The magnitude of this suction depends on the radius of curvature of the water meniscus between the soil particles. As moisture content in the soil increases, the radius of curvature of the meniscus also increases and this account for the reduction of suction in the soil. When the soil becomes saturated, this suction force diminishes.

2.7.3 SOIL-MOISTURE CHARACTERISTICS

The relationship of soil moisture and matric suction characteristics is ***not unique***. It is in the form of hysterisis prior to the process of wetting and drying. Soil - moisture characteristic is the relation between matric suction (kPa) of the soil and its moisture content (%). The soil moisture characteristics are important in the infiltration study especially during the monitoring of the wetting front in the soil.

2.7.4 MEASUREMENT OF SOIL SUCTION

Methods of measuring the soil suction are as follows:

1. *Suction plate* (Croney 1952) - The sample of soil is in close contact with the flat upper surface of a sintered-glass disc of fine size. Moisture equilibrium is established with water at known applied suction beneath the disc, the soil being weighed when it has reached equilibrium. The test can be repeated for various fixed suction to give the relationship between suction and moisture content. The rate of which the sample of soil reaches equilibrium in this test can be related to a coefficient of consolidation for the soil.

2. *Continuous Flow* (Croney 1952) - This method is a varition of the suction plate in which the flow of moisture to or from the suction plate in which the flow of moisture to or from the sample is metered continuous by means of a glass capillary tube. Handling of soft or fragile samples of soil is thereby eliminated. The chamber containing the soil is immersed in a constant temperature bath to avoid dilatometer effects.

3. *Rapid Method* (Croney 1952) - The rapid method permits the measurement of the suction

existing in a small sample of soil taken, for example, in field studies. It is a variation of the continuous flow method, and the suction applied at the end of the capillary tube is adjusted so that there is no change in the moisture content of the sample during the test. The suction applied to the flow tube to maintain the water meniscus in state of equilibrium is equal to the suction of the soil.

4. *Field Tensiometer* (Black 1958) - The all glass tensiometer employed for the field studies uses the same type of porous disc as the suction plate equipment. The mercury manometer embodied in the instrument provides a continuous record of negative pore water pressures in the soil at depth down to 9 ft. An alternative form employing copper capillary tube and using a bourdon type pressure gauge is used for studies beneath structures where a protruding manometer would not be permissible. In the research of Affendi (1996), tensiometers with pressure transducers were used to monitor soil suction in the field.

5. *Pressure plate* - This is a variation of the suction plate in which the specimen rests, the water beneath the disc remaining at atmospheric pressure.

6. *Pressure Membrane* (Croney 1958) - This device extends the range of the pressure plate to higher pressure, resulting in greater equilibrium suction in the soil sample. A cellulose

membrane on which the soil rests is supported by a sintered bronze disc containing water at atmospheric pressure. The suction produced in the soil when drainage is completed is equal to the applied air pressure.

7. *Oedometer* (Croney 1958) - The standard oedometer can be used to produce a known suction in samples of saturated compressible soils. Wall friction and only partial mobilization of lateral pressure result in less complete drainage than that obtained when other methods are used to prepare samples to a nominal value of suction.

8. *Centrifuge* (Croney 1958) - The centrifuge method depends on applying a high constant gravitational field to soil supported on a column of porous stone that has a fixed water table at its base. The suction obtainable is a square root function of the speed of rotation so that very high speeds are necessary to obtain suction values in excess of about pF 4.4 (pF: the logarithm to base ten of the suction expressed in centimeters of water equal to pF value).

9. Freezing Point Depression Method (Croney 1952) - The suction of any sample of soil having a freezing point of t ^{o}C can be deduced as the following formulae:

$$pF = 4.1 + \log_{10} t \qquad \text{..eq. } 2.10$$

The method causes the suction to rise to the highest value compatible with the existing moisture content. This restricts the value of the method, which is normally also affected by super cooling of the soil water.

Although there are various instruments and methods to measure soil suction, small tip tensiometers with an attached porous ceramic cup at its tip are used in the hydrological sprinkler models in this study to determine the soil suction and indirectly to monitor the movement of water in the soil.

2.8 ROLE OF SUCTION IN SLOPE STABILITY

The principle of effective stress for unsaturated soil was first used by Terzaghi (1923) and was in the first International Conference on Soil mechanics in 1936. Numerous researchers have carried out work since then in order to confirm the principle. Following an extensive research program on unsaturated soil conducted in Imperial College the shear strength of partially saturated soil was hypothesized (Bishop, 1959) to be a function of an effective stress defined as in eq. 2.11. But the validity of this principle for use in unsaturated soil mechanics has been questioned by Jennings and Burland (1962).

$$\sigma' = (\sigma - u_a) + \chi\,(u_a - u_w) \qquad \text{eq.2.11}$$

where σ' and σ are the effective and total stresses respectively, u_a is the pore air pressure and u_w is the pore water pressure. χ is a function that depends on the saturation with value 1 at 100% saturation and 0 for completely dry soil.

Fredlund and Morgentern (1987) showed from stress analysis that any two combination of the three possible stress variables $(\sigma - u_a)$, $(\sigma - u_w)$ and $(u_a - u_w)$ can be used to define unsaturated soil. The equation for unsaturated shear strength τ is written in terms of the stress state variables for an unsaturated soil and is an extension of the form of equation used for saturated soils

$$\tau = c' + (\sigma - u_a)\tan\phi + (u_a - u_w)\tan\phi^{b} \qquad \text{eq. 2.12}$$

where ,

c'	= effective cohesion
σ	= total stress
u_a	= pore air pressure
u_w	= pore water pressure
ϕ'	= effective angle of friction
$(u_a - u_w)$	= matric suction

ϕ^b = gradient with respect to changes in (u_a-u_w) when $(\sigma - u_a)$ is held constant.

The factor of safety for slope stability analysis using method of slices can be derived using shear strength equation 2.12 above. The shear force mobilized at the base of slice can be written as: -

$S_m = \beta/F \ \{c' + (\sigma - u_a) \tan\phi + (u_a-u_w) \tan\phi^b\}$……………………………..….eq. 2.13

Where

S_m = the shear force mobilized on the base of each slice.

F = the safety factor

β = the sliding surface angle of the slice.

C

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MATERIALS
&
METHODOLOGY

CHAPTER 3

TEST MATERIALS AND METHODOLOGY

3.0 INTRODUCTION

Chapter 3 describes the location of sites, the experimental set-up, methods and technique adopted in this study. The basic parameters measured are the water infiltration rate and capacity in the field and laboratory. The summary of the tests is shown Figure3.1 below and will be discussed in details in this chapter: -

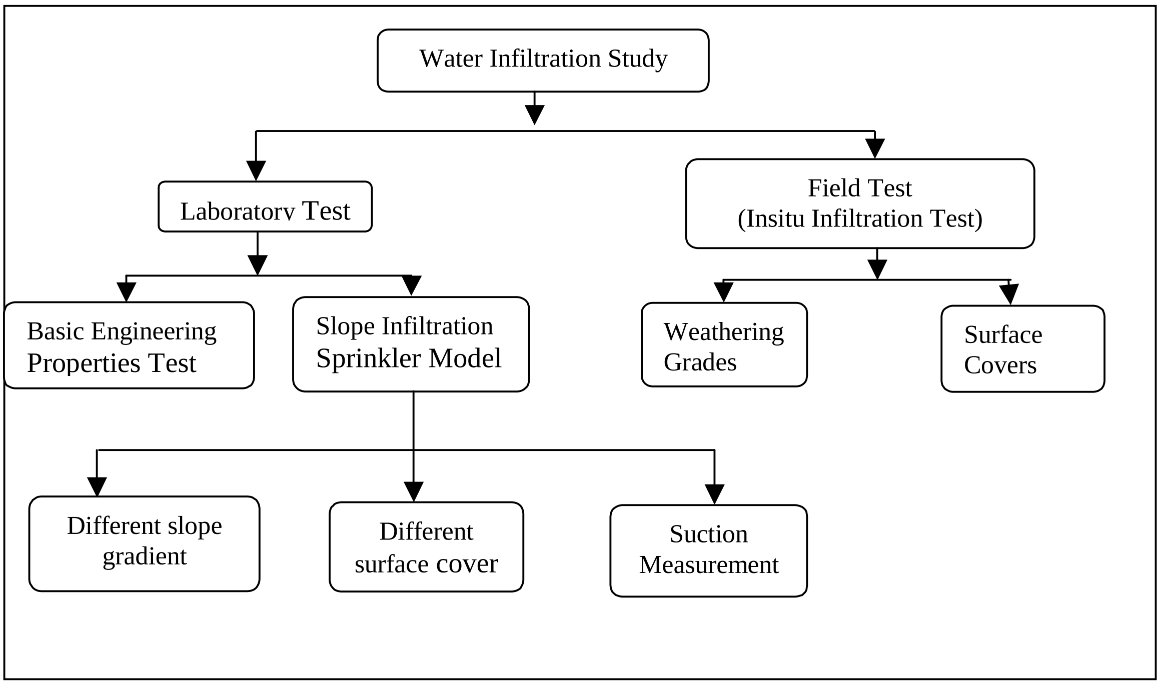

Figure 3.1: - Summary of the Slope Infiltration Study

Chapter 3 TEST MATERIALS AND METHODOLOGY

Field infiltration test and laboratory infiltration model tests were carried out to investigate the infiltration characteristics with respect to the factors mentioned earlier.

In order to determine the infiltration rates in this study, two methods were used. At the site, the infiltration rate was determined by using the GEONOR Infiltrometer P- 88 and for the laboratory; infiltration study was carried out by using Hydrological Sprinkler Model.

For field tests, the influence of weathering grades of residual soils and slope covers on the infiltration rate were studied. As for the laboratory infiltration test, modelling was carried out based on the factors such as slope angle and surface cover. All the tests mentioned above are discussed in detail in this chapter.

3.1 STUDY SITES

There were two sites chosen for the study. One of the sites chosen was a residual soil developed over the more commonly outcropping Perm-Triassic Mesozonal Granite. The study site was a road cut at 31.0km along the Kuala Lumpur - Karak Highway. The cross-section of the slope under study is shown in Figure 3.2. The weathering grades shown in Figure 3.2 are described in detail in Section 2.2.1 “Stages of Weathering of Bedrock Mass”.

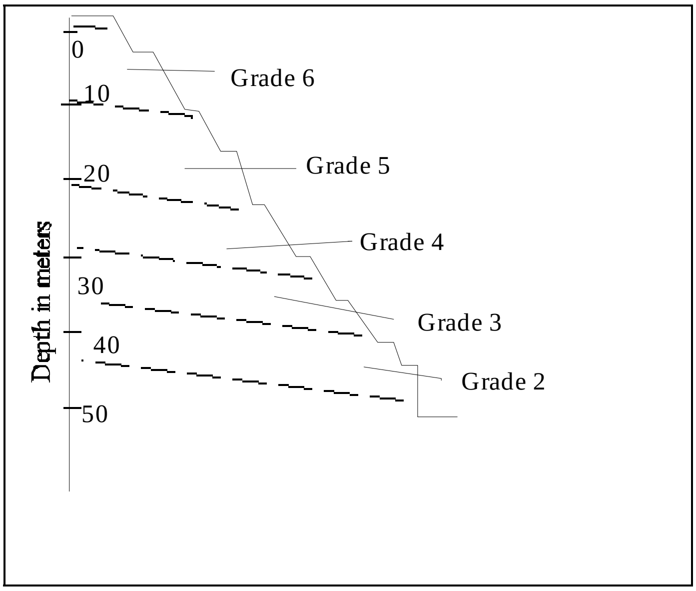

Figure 3.2 Various Morphological Horizons of The Slope Under Study

For this test site, field infiltration tests were carried out at the different weathering grades. Another type of soil used for this study was residual soil from a slope along Mukim Labu Kuala Lumpur International Airport (KLIA) Quarters Link Road. The slope consists of two difference types of weathered sedimentary residual soil, i.e., weathered shale and sandstone. The properties of the soil are shown in more detail in Chapter 4. The soil sample was collected from the weathered sandstone bed for the laboratory Sprinkler Model. The main purpose of choosing this sample was that the soil was collected during the slope cutting and thus this would not disturb the stability of the slope. Soil samples were collected at the 3rd. Berm (from top), which were grade three materials.

3.2 SOIL ENGINEERING PROPERTIES TESTS

The following tests were carried out: -

1. In-situ Density Test
2. Standard Compaction Test.
3. Particle Size Distribution Tests.
4. X-ray Diffraction Test.

3.2.1 IN-SITU DENSITY TEST

In-situ density tests using the sand replacement method was carried out at the field to find out the in-situ density of the soils in order to obtain the relationship between infiltration rate and density of soils. The insitu density tests in this study were carried out by contractors appointed by JKR for the KLIA Quarters Link Road Project. The values of in-situ bulk density were also used in the soil compaction for the infiltration sprinkler model in the laboratory to simulate the field condition. The tests were conducted according to the BS1377: Part 9: 1990.

3.2.2 STANDARD COMPACTION TEST

This test, which is also called as the Standard Proctor Test, was carried out to obtain the required moisture content of the particular field density for compaction of the soil used in the infiltration sprinkler model. The compaction was done in accordance to BS1377: Part 4: 1990: 3.7.

In this test not only the optimum moisture content was determined but also the corresponding moisture content to the in-situ density.

3.2.3 PARTICLE SIZE DISTRIBUTION TEST

The determination of the particle size distribution consists of two major tests. For particle size greater than 63 μm, wet sieving method specified in BS1377: 1990 part 2, clause 9.2 - 9.26 was used. Hydrometer tests were conducted for particles less than 63 μm according to BS1377: 1990, part 2, clause 9.5 - 9.5.8.

3.2.4 X - RAY DIFFRACTION TEST

Study of the clay mineralogy was conducted by using X- ray Diffraction method. The Shimadsu X-ray Diffractometer with CuKα radiation was used in this study. In the X- Ray

Diffraction Test, the spacing of the atom forming the crystallographic lattices of the minerals was studied, as these provide a unique way of identifying minerals.

In the theory of X-Ray Diffraction, the basal or “d spacing” is related to the diffraction angle θ. Discriminating between samples is necessary in mineral analysis based on their basal spacing, and to do this, all the diffraction peaks must be recorded. All the characteristic reflections of a mineral are recorded with an instrument, and subdividing the different classes of clay minerals is thus possible. For practical reasons, measuring the angle 2θ is more convenient and this is displayed as the X-axis in the X-ray diffraction traces (diffractograms), while the intensity peaks are slightly affected by the rate of scanning, but this is usually of little consequence provided the rate is standardised.

For each sample, three scans were performed on the Untreated (air dried), glygolated and heated (in furnace for $550^{o}C$) samples. The three scans were then superimposed on each other to obtain a compound diffractograms from which the qualitative determination of the clay minerals could be carried out. The results will be shown in Chapter 4 “Test Results and Analysis”.

3.3 FIELD WATER INFILTRATION TEST

At the site, infiltrometer was used to determine the infiltration rate with respect to the factors such as weathering grades and surface cover (grass).

The Geonor P-88 infiltrometer was used to measure the saturated hydraulic conductivity of soils above ground water level. The saturated hydraulic conductivity of soil could only be determined at the end of the test. Between the tests, the infiltration characteristics were observed and determined.

The required equipment for the making an infiltration test is shown in Figure 3.3. The water level was kept constant in the test pit with cross sectional area of 25 x 25cm. Water infiltrates into the soil through the walls and the bottom of the pit. Normally the rate of the infiltrating flow will decrease during the test, until a steady state was achieved. This steady state flow was used to calculate the saturated hydraulic conductivity of the soil (K).

The water level in the test pit was monitored by a level sensor, and the water supply from the tank was regulated by a valve to keep the water level constant. The water level in the tank was measured by another sensor. The flow rate was measured continuously. A readout display on the infiltrometer showed the measured flow during the test, and the time required for refilling the tank.

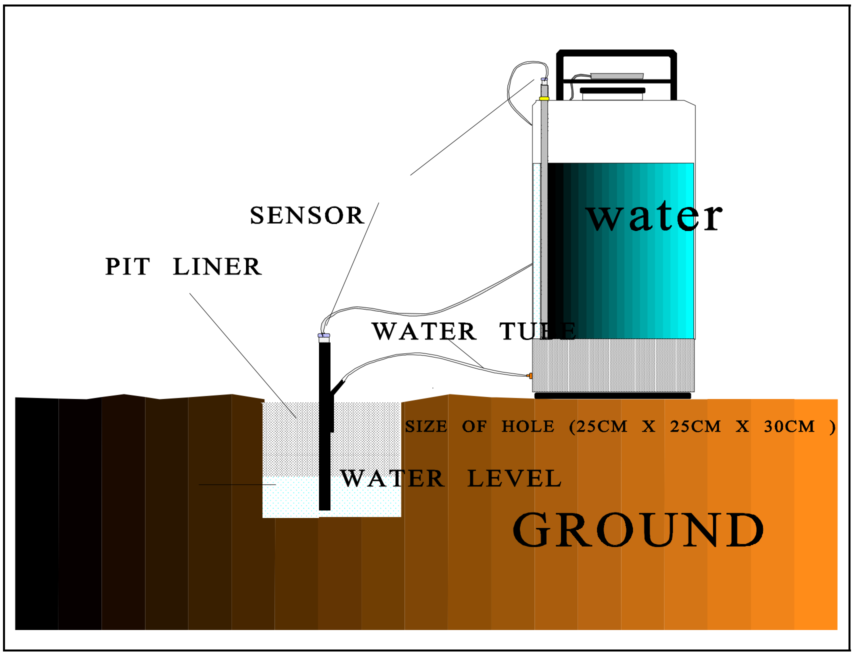

Figure 3.3 Infiltration Test Without Consider Surface Cover

When the infiltration test has gone through a wetting period of 30 minutes, the criterion for test completion was check continuously. The microprocessor checked if the infiltrating flow has reached the steady state (< 5% deviation more than 5 minutes). When steady flow was recorded, the test was terminated and the hydraulic conductivity (K) was then calculated automatically by an approximated formula (Porchet formula).

If the flow did not reached a steady state when the ending criterion was first checked, the infiltration test will need to be continue until a steady state is achieved. After 60 minutes of infiltration, without reaching a steady state, the test will end automatically. The steady state flow would then be calculated from the measured flow from the first 60 minutes. In such cases, K was calculated from the predicted flow value.

It took between 35 to 60 minutes from the start of the infiltration test until the result was ready.

3.3.1 TEST PROCEDURES

In addition to the infiltrometer equipment, a spade was used to dig a test pit for infiltration test. The amount of water used depend on the soil type, and is normally between 20 to 60 litres. The tank volume is 25litres, refilling of water therefore normally has to be done during a test. The following procedure has been recommended before starting a test: -

i) A hole with vertical wall was dug with cross sectional area of 25 x 25cm (refer to Plate 1.0 and Plate 2.0). The depth was about 30cm. The test hole digging was carried out carefully to avoid disturbance to the soil profile. Disturbance may alter the infiltration characteristics of the soils.

ii) A pit liner (Spongy type) was placed in the test hole with the tube's perforation pointing upwards to avoid the wall from collapse.

iii) The infiltrometer was placed near the hole. The infiltrometer was positioned vertically (to make sure that the water level measurement in the tank is correct).

iv) The main tube (with the little side tube) was installed into the pit liner perforation to ensure the bend on the side tube was at the same level as the top of the pit-liner.

v) Sensors was connected to the top of the pit liner tube and into the hole the upper left corner of the tank.

vi) The tank was filled with water and the Infiltrometer was ready to start the infiltration test (refer to Plate 3.0, Plate 4.0 and Plate 5.0).

3.3.2 CALCULATING THE HYDRAULIC CONDUCTIVITY

K is the hydraulic conductivity of the soil immediately adjacent to the test hole and was calculated from the following formula (Porchets Formula): -

$K = Q_s / (a * (a + 4*h))$……………………………eq. 3.1

Where,

Q_s = flow after steady state is reached.

a = length of the side walls of the test pit (standard = 25cm)

h = water level in the test hole (standard = 10cm)

If the criterion of ending the test is not attained within one hour, the test will end automatically and a steady flow, Q_e,can be calculated from the following formula: -

$$Q_e = 2 * (3*Q_{60} - Q_{20}) \qquad \text{eq. 3.2}$$

Where,

Q_e = Calculated steady state

Q_{60} = Flow after 60 minutes

Q_{20} = Flow after 20 minutes

The hydraulic conductivity of the soil, K is then calculated from Q_e by substituting Q_e as Q_s in eq. 3.1.

3.3.3 INFILTRATION STUDY WITH SURFACE COVER

In this study, the infiltration rates of soils with surface covers were also determined at the sites. The Geonor Infiltrometer P-88 was used with minor modification.

In the infiltration study with surface cover, the method used was different from the infiltration study for soils alone. Since the influence of surface cover (grass) was considered in the infiltration study, a casing was used instead of digging test pit for the normal infiltration test. This modification actually could be considered similar to the method of Single Ring Infiltrometer Test. As mentioned in Chapter 2, Single Ring Infiltration Test is not as good as double ring method due to the boundary or edge effect that involved water spreading in the ground. Therefore, in the study of infiltration rates with surface cover, two tests were carried out by the casing method for both the soil with and without surface cover to look into the influence of the surface cover onto the infiltration rate only.

Before the infiltration test was carried out, a casing was hammered carefully into the ground for more than 75mm depth. Sufficient depth of the embedded length is required to ensure water do not come out from the edge of the casing due to seepage flow. To ease the installation process, a steel plate with indication of a centre point was fabricated to cover the top of the casing during the installation. After the casing was installed, moulding clay was used to seal the inner edges of the casing to prevent any abnormal water passage at the edge of the casing (for details, refer to Figure 3.4).

Calculation of the infiltration rates also was corrected due to the infiltration contact area of the soil reduced. The calculations are as below: -

$K = Q_s / a^2$ …………………………………………..eq. 3.3

Where,

Q_s = flow after steady state is reached.

a = length of the side walls of the test hole (standard = 25cm)

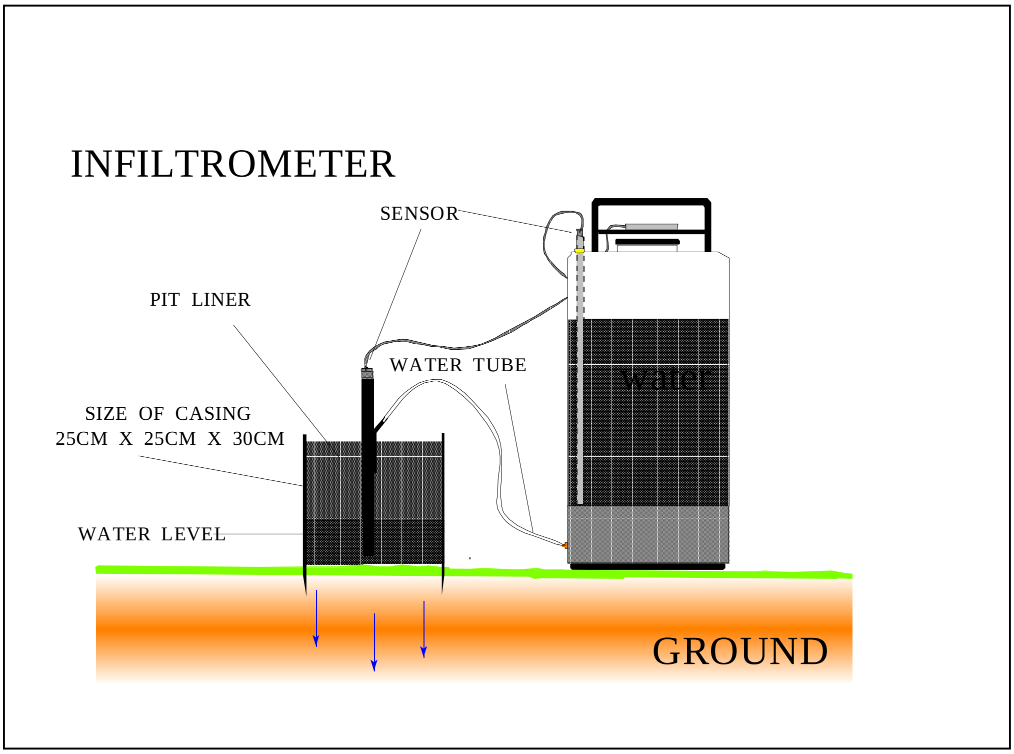

Figure 3.4 Infiltration Test with Surface Cover - Grass

3.4 LABORATORY WATER INFILTRATION TEST

In the laboratory, soil samples from the KLIA slope was used because the soil sample could be obtained easily during the cutting of the slope. Thus, it did not actually disturb the slope during sampling. As for Karak Highway soil sample, taking large amount of sample from the slope was prohibited by the authorities due to the similar reason.

A infiltration sprinkler model was designed and fabricated in order to study the infiltration rate with respect to slope angle, surface cover and slope length. The infiltration sprinkler model is as shown in Figure 3.5 and Plate 15.0.

The sprinkler model was equipped with a hydraulic jack system (refer to Plate9.0). During the infiltration test, the model could be jacked up to a required angle. Two flow meters were used in the model. One of the flow meters was attached to the inflow piping to measure the inflow quantity, and the other was fixed at the outflow pipe of the collection tank to measure the surface runoff.

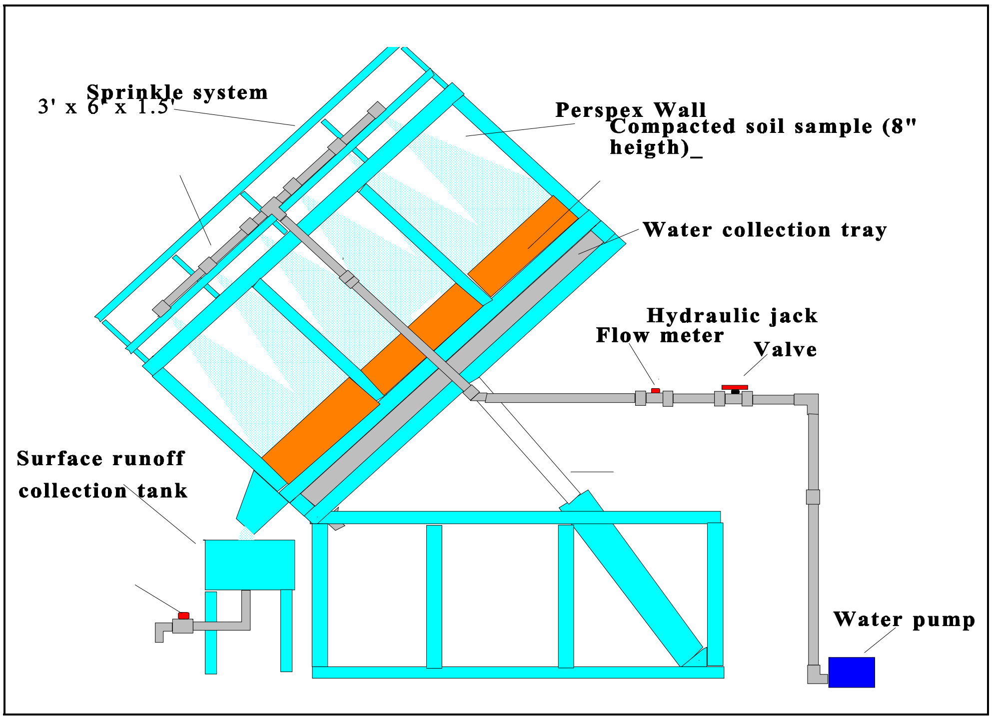

Figure 3.5 Slope Infiltration Sprinkler Model

Five small tip tensiometers were used to measure soil matric suction during the test. The small tip tensiometers were installed at various depths in order to determine the wetting front. The installation and the locations of the tensiometers will be discussed in detail later.

The walls of the model were fabricated using Perspex to ease the wetting front observation and to make sure that the soil is well compacted.

3.4.1 TEST PROCEDURES

In this investigation, infiltration sprinkler model was used to measure the infiltration rate of water into the soil sample in relation to its slope angle of 0^0, 15^0, 30^0 and 45^0; and in relation to different types of soil surface covers. The procedures in preparing the infiltration sprinkler model for the infiltration test are given in the following stages:

STAGE ONE: COMPACTION OF THE SOIL SAMPLE IN THE INFILTRATION MODEL

Before the soil was placed in the model, a layer of gravel was compacted at the bottom of the model. This gravel layer provides drainage to avoid the build up of water table in the model. The base of the chamber in the model was also fabricated with wire mesh to allow proper drainage.

As discussed in Chapter 3, Part 3.2.2.2, the changes of moisture content vs. the dry density of the soil was obtained according to BS1377/48 using a proctor compaction machine at standard proctor energy. The soil was added with required water content in order to achieve insitu density and then thoroughly mixed using a mixer.

The soil, with its required moisture content, was then compacted thoroughly using a vibration hammer to a thickness of eight inches in the model (as shown in Plate 6.0 and Plate7.0). The eight-inch thickness of soil is chosen to shorten the test duration. Before the vibration hammer is used, calibration needs to be carried out. There are a few methods available to calibrate the vibration hammer. One of the easiest methods is to make comparison with the standard compaction test. During the calibration, a few trials were carried out with different levels of human effect (forces that presses the vibration hammer), thickness, and compaction duration to compare with the standard compaction test. The trial that was closest to the standard compaction test was used.

After thorough compaction, the rugged/uneven (as shown in Plate 8.0), was levelled using scrappers and split level. This is to make sure that the soil surface is horizontal and there was no ponding of water on any part of the soil surface during the infiltration test.

STAGE 2: INSTALLATION OF SMALL TIP TENSIOMETER INTO THE SOIL

After the soil surface has been levelled horizontally, the soil tip tensiometers, with its porous ceramic tips, were installed into the soil. Before installation, a hole needs to be cored according to the position and depth of the tensiometers in the model. The size of the hole needs to be accurate because an intimate contact with the soil is necessary in order for the small tip tensiometer to function properly. The preparation procedure and the installation of the small tip tensiometer will be discussed in details later.

STAGE 3: INSTALLATION OF SPRINKLERS

The sprinkler system, which was attached to a water storage tank and a flow meter through pipes, was installed above the soil surface on the model's frame. The pointing position of the sprinkler head needs to be adjusted so that the water could be sprayed evenly on the surface of the soil. Water was pumped from the storage tank using a water pump. The valve of inflow needs to be calibrated in order to obtain a reasonable flow.

STAGE 4 : PREPARATION OF THE SURFACE RUNOFF TANK

In this stage, the surface runoff collection tank was prepared (as shown in Plate 10.0). A plastic sheet was used to lead the runoff directly into the collection tank. A 2 mm rectangular wire mesh in the size of the collection tank, was placed in the tank. This is to ensure that those runoff particles, which have a size of more than 2 mm, does not affect the readings and ruin the flow meter connected to the base of the surface runoff collection tank. For the soil particles smaller then 2mm diameter, after passing the out flow pipe, all the water (with the soil particles) would pass through a 63μm sieve in order to estimate the soil lost during the infiltration test (refer to Plate 14.0). After the four stages mentioned, the infiltration sprinkler model was ready for test. During the test, the level of the water in the runoff tank needs to be maintained by controlling the valve. A level mark was marked in the tank for reference.

After model preparation, the model was jacked to the required angle. Then the water storage tank was completely filled with water. The base of the tank was connected to a pipe leading to a water pump. The pump was switched on and the water from the water storage tank was then pumped to the sprinklers. The pumped water leads to the sprinklers through a flow meter. This flow meter will be called the intake flow meter throughout this study.

After passing through the intake flow meter, the water then leads to the sprinkler where it is sprinkled evenly onto the soil surface.

The water sprinkled on the surface of the soil then infiltrates through the soil. The excess water that does not infiltrate through the soil will flow as surface runoff. This runoff will be collected in the surface runoff collection tank and eventually will be passing through a flow meter to measure the rate of the surface runoff. This flow meter will be called the runoff flow meter throughout this study.

All the five small tip tensiometers were monitored closely during the test to obtained the pattern of the wetting front during the infiltration test.

3.4.2 INFILTRATION RATE COMPUTATION

In order to calculate the infiltration rate of water through this soil sample, two readings are needed; firstly, water intakes (measured in litres), which is obtained from the intake flow meter and secondly, the volume of runoff (also measured in litres), which is obtained from the runoff flow meter. The difference between the two readings is the volume of water infiltrates into the soil sample. The infiltration rate is calculated at every interval to study the pattern of the water infiltration.

The infiltration test was carried out until the soil suction readings stabilized. During this test, the readings for the volume of water obtained from the intake flow meter and the runoff flow meter were taken every 10 minutes.

For every 10 minutes, the infiltration rate was calculated by subtracting the runoff rate from the intake rate. The calculation for the infiltration for a period of 10 minutes is as given in the Table 3.1.

TABLE 3.1: EXAMPLE OF TYPICAL READING OBTAINED

Time (min)	Intakes Flow (litre)	Runoff Flow (litre)
0	0	0
10	200	150

Intake rate = (Current intake volume - initial intake volume) time

= (200 - 0) / 10 = 18 l/min

Runoff rate = (Current runoff volume - initial runoff volume) time

= (150 - 0) / 10

= 15 l/min

The volumetric infiltration rate is as follows:

Volumetric Infiltration Rate = Intake rate - Runoff rate

= 20 - 15

= 5 l/min

To obtain the infiltration rate, the volumetric infiltration rate is then multiplied with the area of the soil surface (2m x 1m) in the model to give the infiltration rate in mm/s.

The above example gives the infiltration rate through the soil only for 10 minutes sprinkling duration. Since the test runs for a minimum duration of four hours, therefore the infiltration rate values for each 10 minutes are calculated and related to time.

3.4.3 INFILTRATION TEST IN RELATION TO SLOPE GRADIENTS

In this study, the infiltration rate of water through the soil with respect to the slope steepness of the model was also considered. The slopes of 0^0, 15^0, 30^0 and 45^0 was tested. The gradient for the slope model were achieved using a hydraulic jack placed at the bottom of the infiltration sprinkler model.

For different slope angles, different piping system was used. Therefore, between each tests, the pipes have to be changed with the 45^0 slope model having the longest piping system connected to the water storage tank and the 0^0 slope having the shortest pipe.

3..4.4 INFILTRATION TEST IN RELATION TO DIFFERENT SOIL SURFACE COVERS

In this study, the infiltration rate of water through the soil also considered the different types of soil surface cover on different slopes. There are two different types of soil surface covers used in this investigation:

i) Synthetic covers/ geotextile (Lanlock)

ii) Grass

The synthetic cover is a net of synthetic non-woven fabric (green coloured), which is usually used at the site to cover the slope to prevent erosion. The synthetic cover was cut into the shape of the soil sample in the infiltration model and was fixed to the soil surface. Then, a series of infiltration tests were done with slope angles of 0^0, 15^0, 30^0 and 45^0.

The infiltration tests were also carried out using grass as the soil surface cover at different slope steepness. The grass was laid evenly on a soil surface and given a time of three weeks to grow and to give time for its roots to penetrate the soil. Before the grass was transferred to the model, the roots were washed thoroughly to make sure that the soils in the model are from the same type. With the grass as its soil surface cover, a series of infiltration tests were carried out at slope angles of 0^0, 15^0, 30^0 and $45^{0.}$

3.5 INTAKE FLOW METER

The function of this flow meter (as shown in Plate11.0) was to give the cumulative volumetric readings of water that have passed through it. The water that passed through this flow meter was sprinkled onto the soil surface by sprinkle head. In other words, the reading from this flow meter was actually the total intakes of water given to the surface of the soil. Before the flow meter was used, calibration was carried out manually to confirm with the manufacturer's settings. During calibration, water was collected by a big container in a given time duration and measured with measuring cylinder. A few discharge rates were applied in the calibration for confirmation.

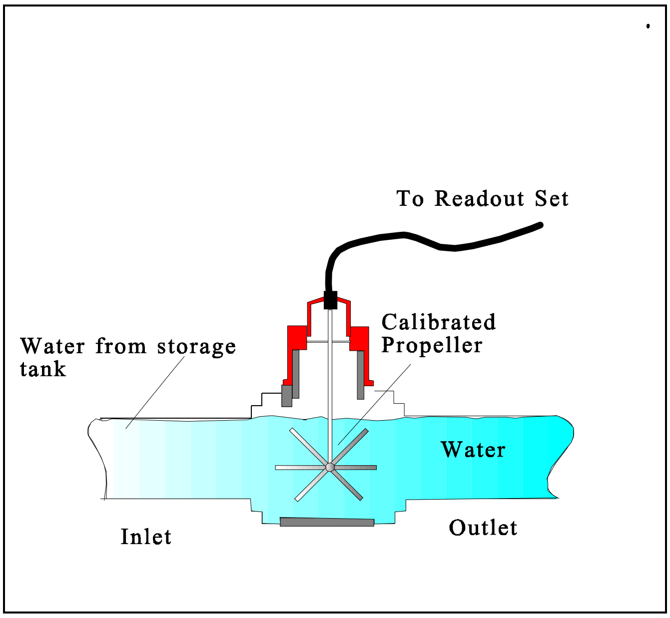

Figure 3.6 The Layout of The Flow Meter

The flow meter has a built-in propeller that turn as water passes through it. The speed at which the propeller turns determines the volume of water that passed through the flow meter, which has been calibrated (refer to Figure 3.6). The flow meter was connected to a flow digital display (as shown in Plate 12.0) that gave the visual readings of the intake volume in litres.

3.6 RUNOFF FLOW METER

The function of this flow meter was to give cumulative volumetric readings of runoff water. The water that passes through this flow meter comes from the surface runoff collection tank. When the valve between the collection tank and the runoff flow meter was opened, the water flowed out through the flow meter. In other words, the volume of water readings taken from this meter was the volume of runoff washed away from the soil surface. In order to obtain the actual runoff volume with time, as mentioned earlier, the water level in the runoff tank was kept constant all time and this could be done by controlling the valve of the runoff tank. This flow meter was also connected to the flow monitor that gives the visual readings of the runoff volume in litres.

3.7 SOIL SUCTION MEASUREMENT DURING INFILTRATION

In this study, soil suction was also investigated during the infiltration events to determine the stabilisation of infiltration process and to determine the wetting front during the infiltration test. During the study of infiltration behaviour in relation to different slope steepness and different soil surface cover, the soil suction was also studied during all these tests. The soil suction was measured using the small tip tensiometer as shown in the Figure 3.7 and Plate 13.0).

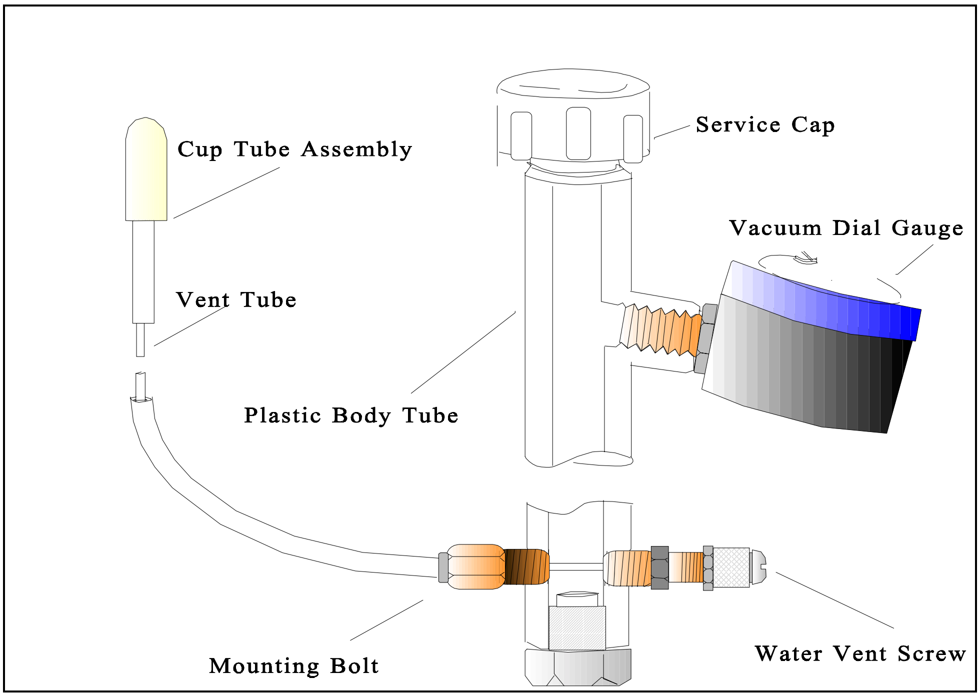

Figure 3.7 Small Tip Tensiometer

3.7.1 PREPARATION PROCEDURES FOR SMALL TIP TENSIOMETER

Prior to the placement of the small tip tensiometer into the soil, the unit was filled with deaired water. This deaired water was obtained from the deairator. During the process of deairing, the deairator was first filled up with distilled water. The main purpose of using distilled water was to prevent the blockage in the tubing of the tensiometer by any unwanted suspended particles in the tap water. The process of deairing normally took about half an hour, depending on the vacuum pressure applied on the deairator. All the deaired water obtained was kept in a closed container to prevent air from re-entering the water. It is recommended that all the deaired water shall be filled the tensiometers on the same day.

The first step in preparation of the small tip tensiometer was to immerse the porous Ceramic Cup in water and submerged the ceramic tip for one day or more for saturation purposes. To speed up the process, deaired water was used for the saturation.

3.7.1.1 FILLING AND DEAIRING OF TENSIOMETER

In order to fill the small tip tensiometer with water, a plastic bottle was used to push the deaired water into the tensiometer. During the filling of the small tip tensiometer with deaired water, the service cap on the unit was unscrewed and the applicator bottle was inserted loosely into the filler end. By squeezing the plastic bottle, a fine stream of water was directed toward the inner wall of the plastic body tube (refer Figure 3.8). The unit was filled slowly so that the water runs down the inside wall. By filling slowly, the entrapment of air of large volumes in the tube that were prevented.

After the filling, the water vent screw was then removed to insert the applicator bottle firmly into the “filler end” so that it makes a seal at the “O” ring. The bottle was then squeezed to force the water through the outer nylon tube, to the porous ceramic cup and back through the vent tube and out of the vent , thus purging air from the system. These processes were continued until a clear flow of water, without air bubbles, came out of the vent. Before the water vent screw was replaced, the tubing of the tensiometer needs to be checked again to confirm that no air was trapped in the system.

The process mentioned above was repeated several times to remove as much air as possible from the tensiometer. Again, the water vent screw was loosened and the water was purged through the nylon tubes and the water vent screw was tightened. After making sure that nylon tube was free from air, the deairation of air entrapped in the gauge was carried out by means of a hand pump. A hand vacuum pump was placed firmly in the filler end and vacuum was applied to suck out the air entrapped in the gauge. The service cap was put on after ensuring that the tensiometer was full of water and air-free. Extra moisture on the porous ceramic cup was removed with absorbent tissue and the plastic body tube was supported vertically to ensure the moisture free to evaporate from the porous ceramic cup.

As water evaporates from the cup surface, the dial gauge reading will rise as the vacuum inside the unit increases. As this occurs, any entrapped air in the system and water will form bubbles. After two hours, when the dial gauge reading raised to 60kPa (suction) or more on the scale and there is a possibility of considerable accumulation of air in the nylon tubes and in the plastic body tube. In order to release this trapped air, the plastic body tube was tapped few times to release as many air bubbles as possible that cling to the inner wall. The deairing process is carried out again if required. After all the processes, the small tip tensiometer was ready for its installation into the soil.

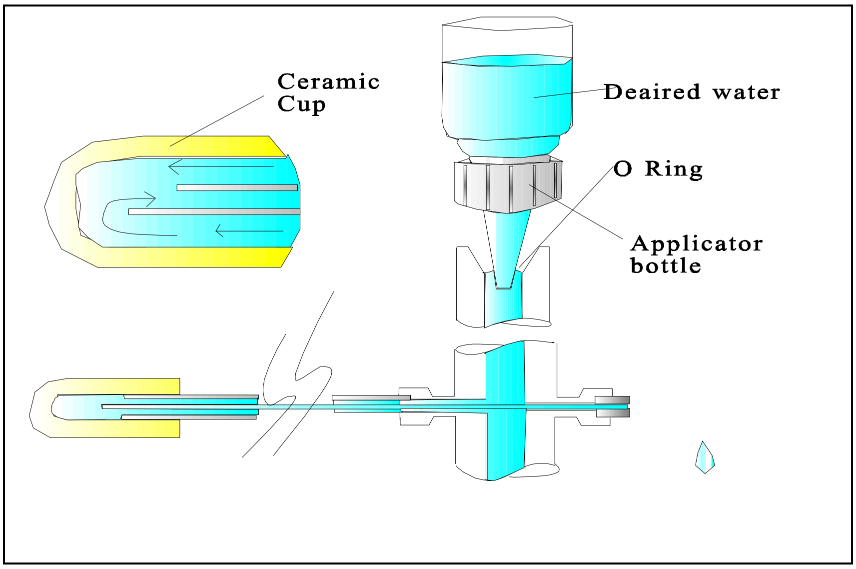

Figure 3.8 Filling Up and Deairing of Tensiometer

3.7.2 INSTALLING THE SMALL TIP TENSIOMETER INTO THE SOIL

The porous ceramic cup was placed into the region where soil suction values were required. Five small tip tensiometers were used in this study. Due to insufficient numbers of tensiometer available, for each of these small tip tensiometers, the porous ceramic cups were placed in the middle of the sample in a straight line at specific depths as shown in Figure 3.9.

3.8 TEST SERIES

The tests for the infiltration study were divided into 3 main series. The 1st. series was carried out by looking into the effects of surface cover, depth of test pits (considering the vegetation roots effects), moisture content of soils.

The second test series was concentrated on the effect of weathering grades. The infiltration test for this series was carried out at the study site.

The 3rd. series was carried out in the laboratory with the hydrological sprinkle model. In this series, the infiltration study covered the effects on surface cover and slope angle.

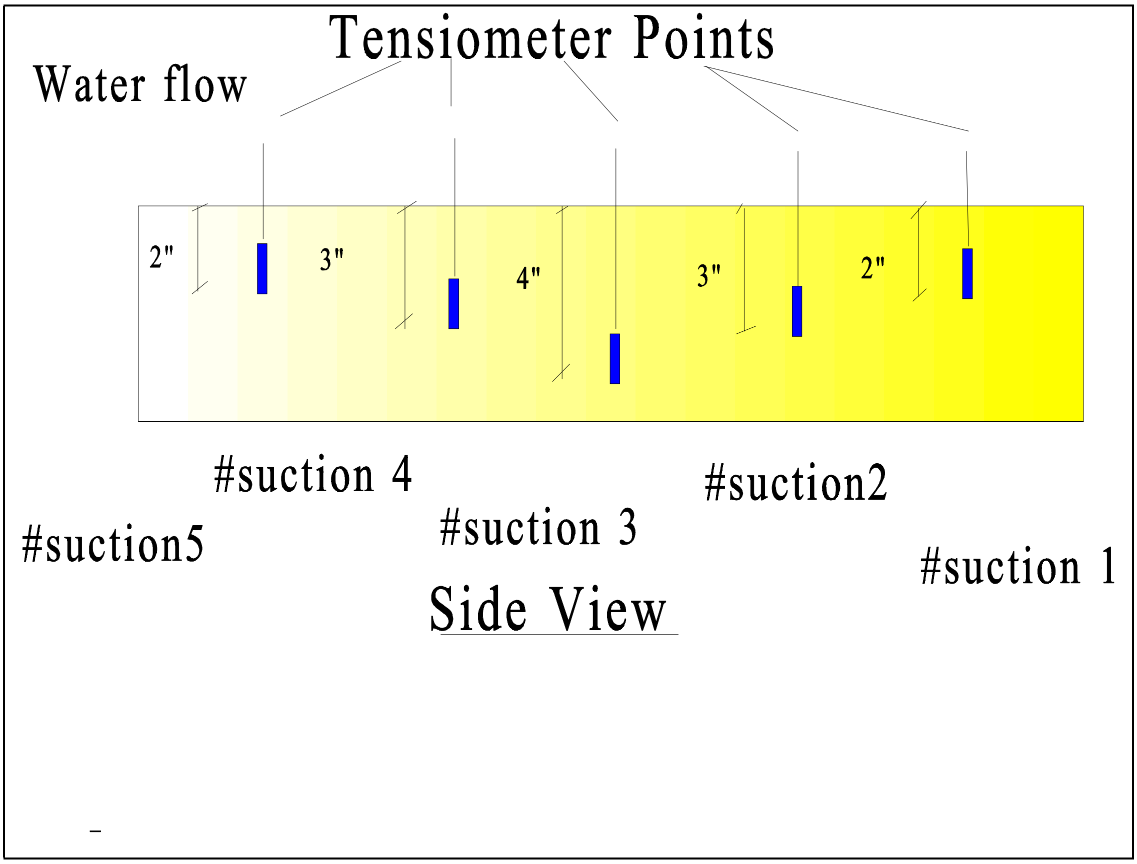

Figure 3.9 Schematic Layout of Tensiometers Ceramic Tips

3.9 PARAMETRIC STUDIES

Simple parametric studies were carried out to investigate the effects of water infiltration on slope stability. This study were carried out to investigate the factors that contributing to slope instability, especially, rainfall intensity, slope heights, perched water table, soil permeability.

In this study, the water flux and seepage on slopes were simulated first by using water seepage (SEEP/W) software (refer to Figure 3.10 for typical output). The output from SEEP/W was then exported to slope analysis (SLOPE/W) software to find the safety factor of slope (refer to Figure3.11 for typical output).

Before using SLOPE/W, the moisture condition for transient analysis from SEEP/W has to be clearly defined. The output at different interval of time was combined with SLOPE/W to make it possible to determine the factor of safety of each interval of time. For all cases, Bishop method of analysis was chosen for the stability check.

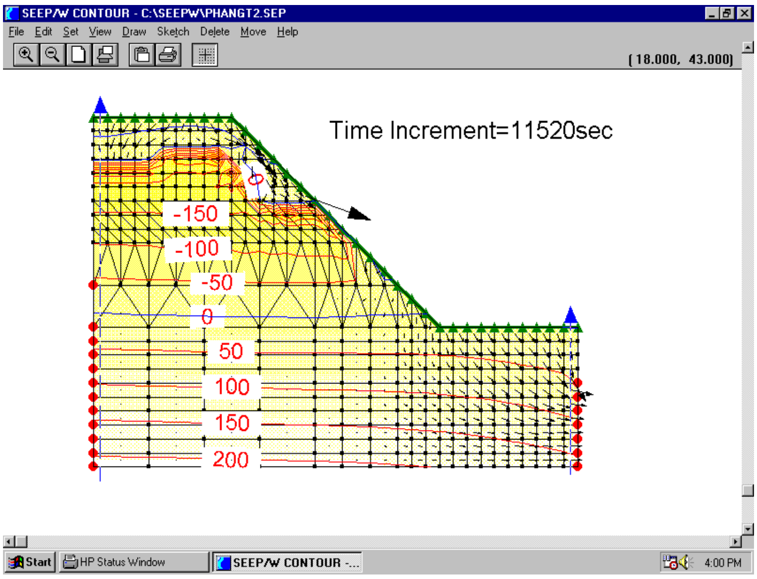

Figure3.10 Typical output from SEEP/W

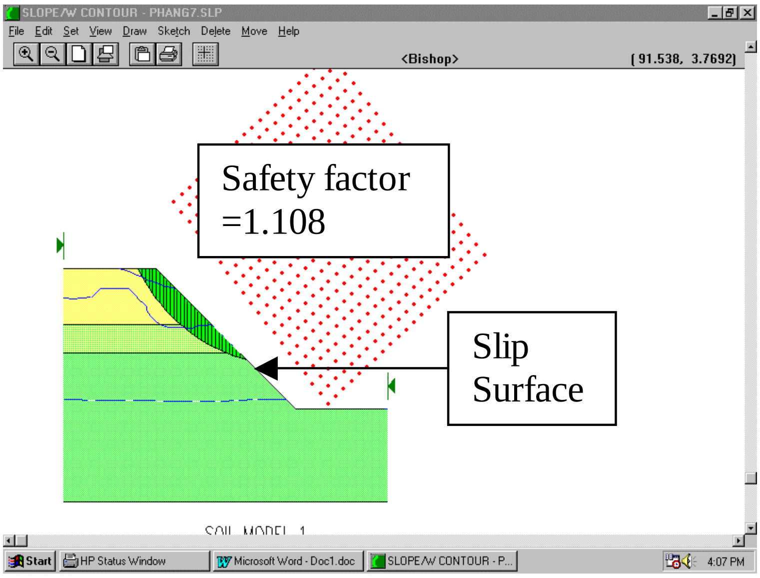

Figure3.11. Typical output from SLOPE/W

3.9.1 WATER SEEPAGE ANALYSIS

The transient ground water flux variations and seepage of slopes were first simulated by using SEEP/W software.

All water seepage analyses were first specified as steady state and in two-dimensional view. This was to develop an initial ground water flux condition. The level of ground water table was fixed for every initial condition in the analyses to avoid the influence of ground water table onto slope stability.

3.9.1.1 HYDRAULIC CONDUCTIVITY AND VOLUMETRIC WATER CONTENT FUNCTION

Hydraulic conductivity functions used in the analyses were based on database built in the software. The criteria of choosing the hydraulic conductivity function were based on the soil material types.

3.9.1.2 BOUNDARY CONDITIONS

For steady state analysis, a small intensity of rainfall has been defined on the surface of the model. A very low intensity was defined to prevent very high and unreasonable matric suction of soil near ground level and gives unacceptable analysis. The type of boundary condition used was unit flux (q) versus time. This boundary type was set to H = elevation (y-coordinates) of the node if the unit flux was greater than the saturated hydraulic conductivity. Whenever the rainfall intensity is greater than the permeability k_{sat} of soil, the excess rainwater would be simulated as surface runoff.

Both the vertical edge boundaries were set with water head boundary for water table generations. At the bottom edge boundary the slope, the boundary type was set for Q = 0 to restrict water from flowing through the bedrock.

3.9.1.3 TRANSIENT ANALYSIS

The steady state analysis file was saved as another file to run the transient analysis. In order to solve for the new head at the end of the time increment, it is necessary to know the head at the start of the increment. Generally, the initial conditions must be known in order to perform a transient analysis. Thus the steady state analysis needs to be carried out first before transient state analysis.

3.9.1.4 TIME INCREMENT

The time increment has to be defined in transient analysis as it changes with respect to time. The starting time is set to 0 with the initial increment as 1000. The number of increment = 12 and increment limit = 12000 sec. The expansion factor for time increment is equal to 2. The results will be saved starting from first increment for multiples of 1 i.e. every step of time increment will be saved and can be viewed.

3.9.2 SLOPE STABILITY ANALYSIS

After the transient seepage analyses, for every time steps, the seepage files were exported to slope analyses program (SLOPE/W) to analyses the slope stability.

In the analyses, the strength parameters for soils were defined as follows:

Unit weight (γ)	= 18 kN/m^3
Angle of friction (phi)	= 20^0
Cohesion (C)	= 20 kN/m^2

The strength parameters were used for all soil types to eliminate the effects of soil strength onto the slope instability.

3.9.2.1 PERCHED WATER TABLE GENERATION

Two types of materials with different permeability were specified in the analyses. In order to generate a perched water table, sensitivity analysis were carried out to determine the permeability ratio (ratio of permeability of a permeable stratum to impermeable stratum) of both the soils used.

The pattern of rainfall chosen was constant rainfall with intensity 2.1 x 10^{-4} m/s for all cases. The duration of rainfall was 12000 sec (3.333 hrs). Under this type of rainfall intensity perched water table were generated in most of the cases. Thus the effect of perched water table under these specified parameters can be studied carefully.

The effects of the permeability ratio (ratio of permeability of a permeable stratum to impermeable stratum) were also studied. The critical ratio that causes perched water table was determined.

The parameters chosen were as below:

i) 2.1×10^{-4} m/s for infiltration rate and for sloping surface was 1.05×10^{-4} m/s.

ii) Thickness of impermeable layer was 2m and it was modeled at 4m below top surface.

iii) Height of slope was 8m.

iv) Permeability of impermeable layer had been selected as 1×10^{-8} m/s. The ratios were defined in the range of 30000 to 100000.

In this study some possible cases that were considered include: -

1) Effect of position of impermeable layer.
2) Effect of dipping of impermeable layer (refer to Figure 3.12).
3) Effect of thickness of impermeable layer.
4) Effect of number of impermeable layer.
5) Effect of rainfall intensity

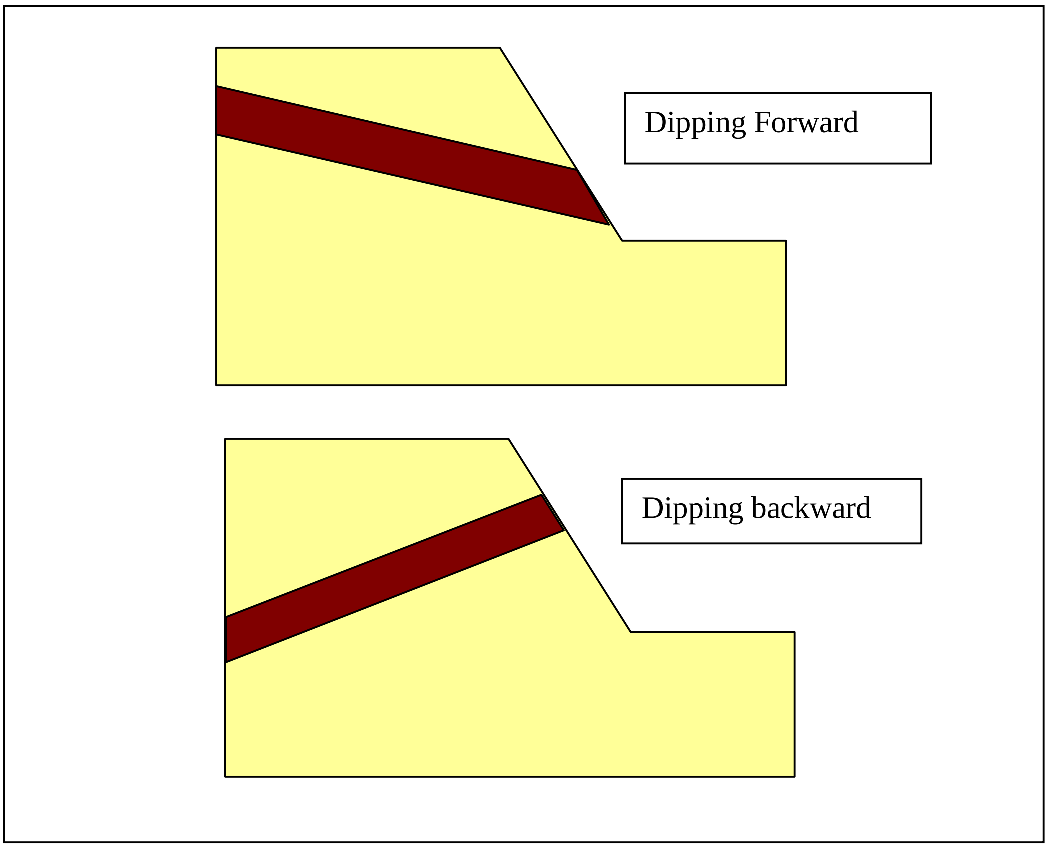

Figure 3.12 Typical profile showing the impermeable stratum

Plate 1.0 Pit hole preparation for infiltration test

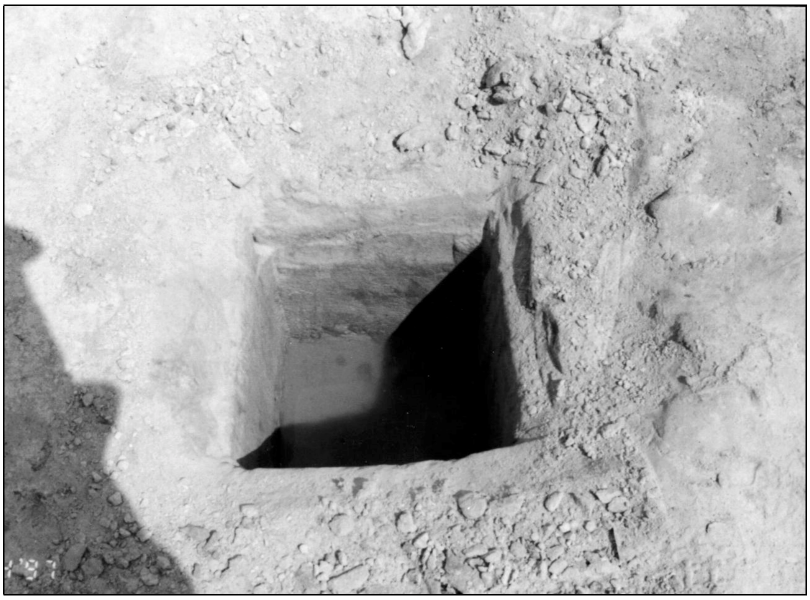

Plate 2.0 Pit hole for infiltration test

Plate 3.0 Filling up water into infiltrometer tank

Plate 4.0 Complete infiltrometer setup

Plate 5.0 Infiltration test in progress

Plate 6.0 Soil compaction for sprinkler model

Plate 7.0 Soil sample after compaction

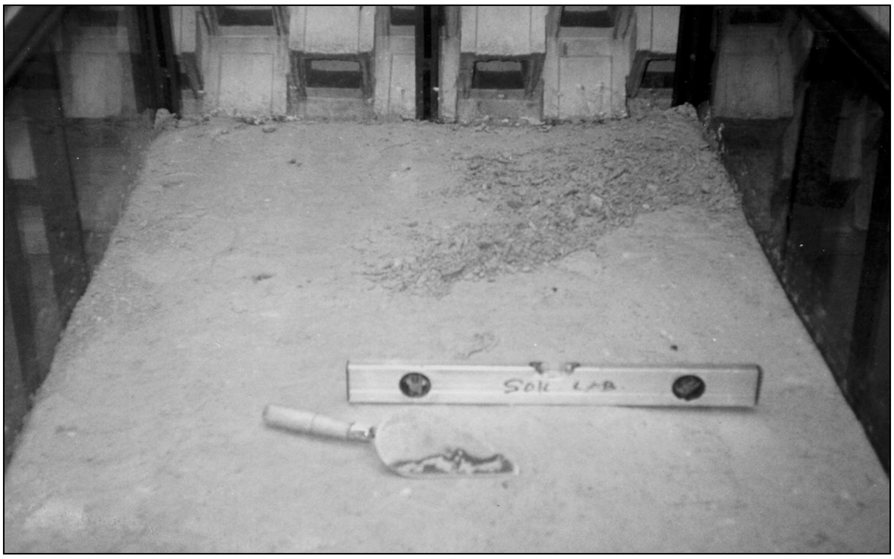

Plate 8.0 Surface leveling after compaction

Plate 9.0 Hydraulic jack for sprinkler model

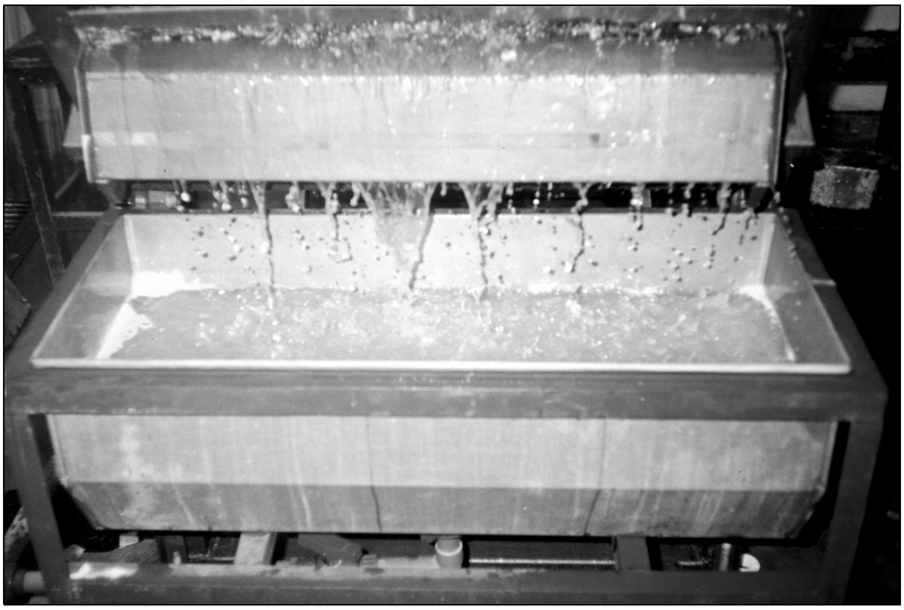

Plate10.0 Surface water runoff collection tank

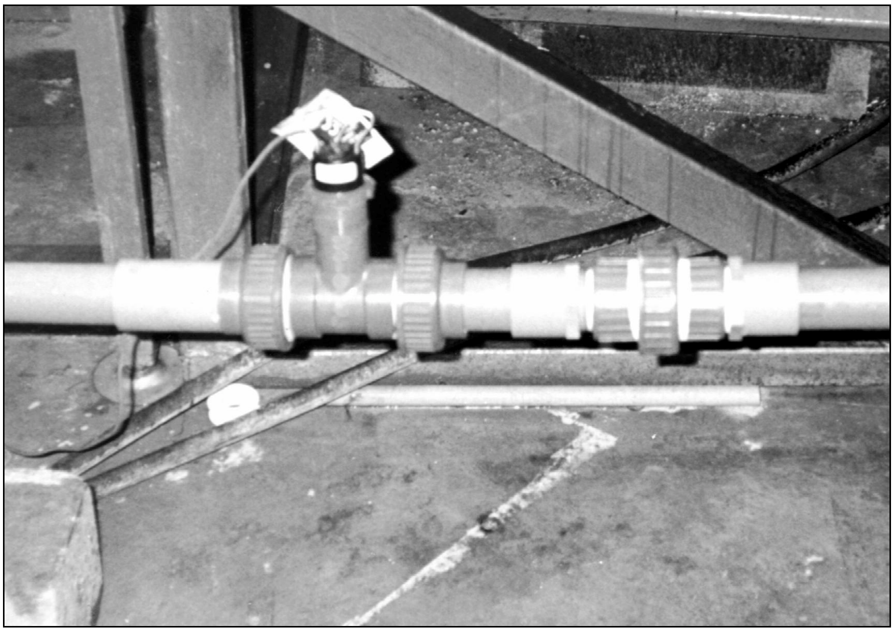

Plate 11.0 Flow meter for sprinkler model

Plate 12.0 Flow meter digital display

Plate 13.0 Small Tip Tensiometers

Plate 14.0 Fine grain soil collector

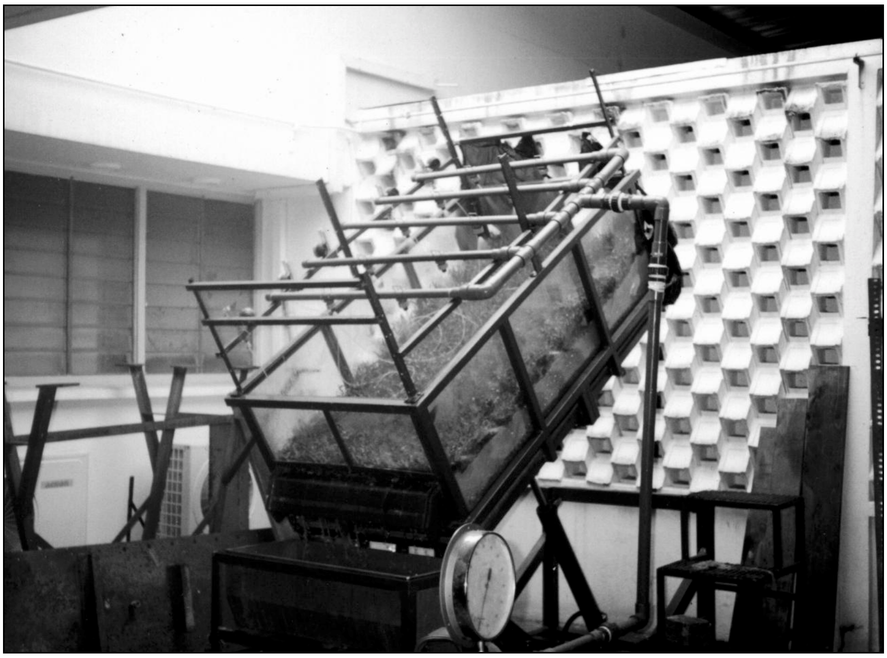

Plate 15.0 Sprinkler model setup

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CHAPTER 4
RESULTS AND ANALYSES

4.0 INTRODUCTION

In this chapter, the results of the infiltration tests carried out at the sites and in the laboratory are presented in details. Discussion on the results with respect to all the factors mentioned earlier are presented in Chapter 5 “Discussion”.

4.1 SOIL PROPERTIES RESULTS

The properties such as particle size, porosity, density, mineral contents etc., are presented.

4.1.1 SOIL PROPERTIES RESULTS FOR TEST SITE 1

The soil can be described as yellowish silty, sandy clay with distinct and indistinct relict structures and quartz veins. From the X-ray diffraction test, it was deduced that the clay mineralogy of this study site only consisted of kaolinite. The particle size distribution of the soil varies from one weathering grade to another. Basically, the clay content reduced from grade 6 to grade 2. Table 4.1 shows some properties obtained from the site.

TABLE 4.1 : DESCRIPTIVE SOIL PROPERTIES AT 31$^{ST.}$ km KARAK HIGHWAY

	Grade 6	Grade 5	Grade 4	Grade 3	*Grade3-2
Specific Gravity	2.61	2.63	2.59	2.59	2.60
Bulk Density (g/cm^3)	1.89	1.79	1.38	1.44	1.50
Dry Density (g/cm^3)	1.67	1.61	1.27	1.28	1.41
Void Ratio	0.57	0.63	1.04	1.01	0.85
Porosity	0.36	0.39	0.51	0.50	0.46
Clay Content %	48.1	4.4	17.3	12	6.8
Silt Content %	8.8	23	25.7	19.3	11.3
Sand Content%	43	70.8	51.3	58	77.2
Gravel Content %	0.1	1.8	5.7	10.7	4.7

Note :-* Lower boundary of grade 3

4.1.2 SOIL PROPERTIES RESULTS FOR TEST SITE 2

The study was carried out on a slope along the link road of the Kuala Lumpur International Airport (KLIA) Quarters at Mukim Labu, Sepang. The slope consists of two different types of soil, i.e., weathered shale and sandstone with quartz veins. The soils come in alternate bedding that is almost vertical. The weathered sandstone beds are thicker and the study concentrated on one of these beds. During study, the slope at the mentioned site was under construction.

The soil sample used in the laboratory model was obtained from Berm 3 (from the top) of the slope. Since the slope was under construction, the soil sample could be obtained easily from the slope cutting without causing disturbance to the stability of the slope. Samples from a weathered sandstone bed were taken.

The reason for choosing the sample from the berm 3 was that it has less clay content (2%) so as to facilitate the infiltration test in the laboratory. Choosing a clayey soil would cause the duration of the infiltration test to be much longer, which will cause water wastage during the test. Furthermore, to prevent instability caused by disturbance, the sample was not obtained from the berm 1 and berm 2 (from the top) which were completely cut.

The soil can be described as light yellowish silty sand with distinct and indistinct relict structures and quartz veins. From the X-ray diffraction test, it was deduced that the clay mineralogy of this study site only consisted of kaolinite. The insitu density of the soil taken was 1.785 Mg/m^3 with dry density 1.477 Mg/m^3. The particle distribution of the sample was clay (2%), silt (4.1%), sand (82.9%) and gravel (11%). The sand content for the samples mostly could be categorized as fine sand and gravel content was due to quartz veins.

4.2 FIELD INFILTRATION RESULTS

The results of infiltration rates using infiltrometer P-88 with respect to weathering grades, surface cover, and depth (at Karak Highway site) are presented in this section. The field infiltration results for Sepang site are also presented.

4.2.1 RESULTS FROM STUDY SITE -1 (KARAK HIGHWAY)

4.2.1.1 INFILTRATION TEST USING CASING (MODIFIED METHOD)

In order to study the effects of grass surface cover on water infiltration rate, a casing was used instead of digging a pit hole recommended by the manufacturer. Figure 4.1 shows the results of the two tests carried out using the modified method (with casing) and the test pit method. After the infiltration test had stabilized, both the tests almost reached the same infiltration rate. For the test with casing, the infiltration capacity was lower than the test carried out by the usual way. The difference may be due to the spreading effect of water in the soils.

4.2.1.2 INFILTRATION ON DIFFERENT SOIL MOISTURE

From the graph in Figure 4.2, it is clearly shown that when the initial moisture content of the soil is low, the infiltration rate is high. When the water infiltration process has stabilized, the infiltration rates of both tests converge close to each other. The test on the drier soil (12%) gave a higher value compared with the wetter soil condition. The infiltration capacity for both the drier and wetter soils is 1.23 x10^{-5} mm/s and 0.27 x 10^{-5}mm/s, respectively.

4.2.1.3 INFILTRATION CONSIDERING SURFACE COVER AND VEGETATION ROOTS

Figure 4.3 shows the results of the infiltration test that was carried out using the infiltrometer at different depths and with grass cover. The infiltration results for the 3 cases shown in the graph were carried out at the same test point. The test with grass cover was performed first followed by the method using test pit without surface cover with depth of 200mm and 300mm respectively. The main reason of carrying out infiltration tests at different depth is to study the influence of vegetation roots on infiltration. The initial infiltration rates for the 3 results show a great difference especially with grass cover and without grass cover. The difference is mainly due to the changes of moisture content. After the test on grass cover was performed, the moisture content in the soil increased. Therefore, for the following tests, the initial infiltration rate was much lower. The infiltration rate after steady state condition for the grass cover, 200mm depth and 300mm depth of the test pit are 2.1×10^{-5} mm/s, 1.26×10^{-5}mm/s and 0.33×10^{-5}mm/s respectively.

4.2.1.4 **INFILTRATION CONSIDERING SOIL WEATHERING GRADES**

Figure 4.4 to Figure 4.8 show the infiltration results obtained from different berm at Karak Highway. The infiltration test was carried out based on the location specified by Raj (1985) to study the infiltration characteristics on different weathering grades.

Since grade 1 and 2 are consisted mainly rock material, tests could not be carried on these grades. Infiltration tests could be only carried out on grade 3 to grade 6 only. Figure 4.4 and Figure 4.5 shows the results obtained from grade 3 materials but on the upper and lower boundary of the 3rd. grade. For grade 4, 5 and 6, the results are shown in Figure 4.6, 4.7 and 4.8, respectively.

TABLE 4.2 :INFILTRATION RATE CONCERNING SOIL WEATHERING GRADES

Weathering Grade	Infiltration Rate (mm/s)
Grade 6	8.35×10^{-5}
Grade 5	1.22×10^{-4}
Grade 4	1.47×10^{-4}
Grade 3 Upper boundary	1.22×10^{-4}
Grade 3 Lower Boundary	4.28×10^{-5}

Table 4.2 is clearly showing that the infiltration varies from one grade to another. Grade 4 materials showing the highest infiltration rate. Moving from grade 6 to grade 3, the infiltration rate increases and reduces after grade 4. The variation in the infiltration rate will be discussed in detail in Chapter 5.

4.2.2 RESULTS FROM STUDY SITE -2 (KLIA ,SEPANG)

Construction of the road and slopes was carried out during the study at test site -2 (Sepang). Therefore, the infiltration tests were carried out only on the weathered sandstone material and concentrated mainly on the sampling location for the laboratory model. Three tests were carried out and the results (refer to Figure 4.9) and the average infiltration rate obtained was 6.07mm/s.

4.3 LABORATORY INFILTRATION RESULTS

The results for the laboratory infiltration test were obtained from the test using laboratory sprinkler model.

4.3.1 INFILTRATION RATE IN RELATION WITH TIME

Generally, the infiltration characteristics' pattern obtained from the laboratory model is the same as the field results. Figure 4.10 - Figure 4.17 show that the initial infiltration rates are high and reduce until reach a steady state condition. The reduction of the infiltration rate to an equilibrium stage is largely controlled by factors such as swelling of soil colloids, soil particle rearrangement, closing of small cracks (which progressively seal the soil surface), changes in suction head etc.

4.3.2 INFILTRATION IN RELATION WITH SLOPE ANGLE

By comparing the graph shown in Figure 4.10 - Figure 4.17, the infiltration reduces with the increase of slope steepness. It is also showed that the water infiltrate better with grass as surface cover, followed by Lanlock (geosynthetic cover) system. The infiltration values are shown in Table 4.3.

TABLE 4.3 :INFILTRATION RATE OBTAINED FROM THE LABORATORY MODEL

SOIL SURFACE COVER	SLOPE ANGLE (Deg.)	INFILTRATION RATE (mm/s)
Bare soil	0^o	2.22×10^{-2}
Lanlock	0^o	2.45×10^{-2}
Lanlock	15^o	1.74×10^{-2}
Lanlock	30^o	1.64×10^{-2}
Lanlock	45^o	1.5×10^{-2}
Grass	0^o	2.45×10^{-2}
Grass	15^o	1.92×10^{-2}
Grass	30^o	1.75×10^{-2}

For bare soil surface, the test was only carried out on a 0^o slope angle (horizontal) because the erosion was very significant. As for grass cover, the infiltration test on 45^o was not carried out due to the slope failure (for 2 trials). As for lanlock, the geosynthetic fabric was nailed to the soil with some nails.

4.3.3 SOIL MATRIC SUCTION RESULTS

Figure 4.18 - 4.25 show the changes of suction values against time. It is clearly shown, from this graphs, the suction value decreased during the infiltration test and stabilized when it reaches steady state condition.

4.4 RESULTS FROM PARAMATRIC STUDIES

Before the parametric study, verification of the suction values was carried out by comparing the measured suction values in the laboratory sprinkler model with the simulated suction values by the SEEP/W program. Figure 4.26 shows one of the typical variations of with time. The difference of the lowest simulated and measured suction is just 2 kPa. However, there is a time lag of about 100 minutes between the simulated and measured suction values. The rainfall pattern agrees well with the drop in suction. The trend in recovery of the suction values for the simulated and site values were also found to be almost the same. The initial difference of the suction values might be due to the hysteresis effect of the soil water characteristics of the sample used.

The results from the parametric studies will be presented and discussed in details in Chapter 5.

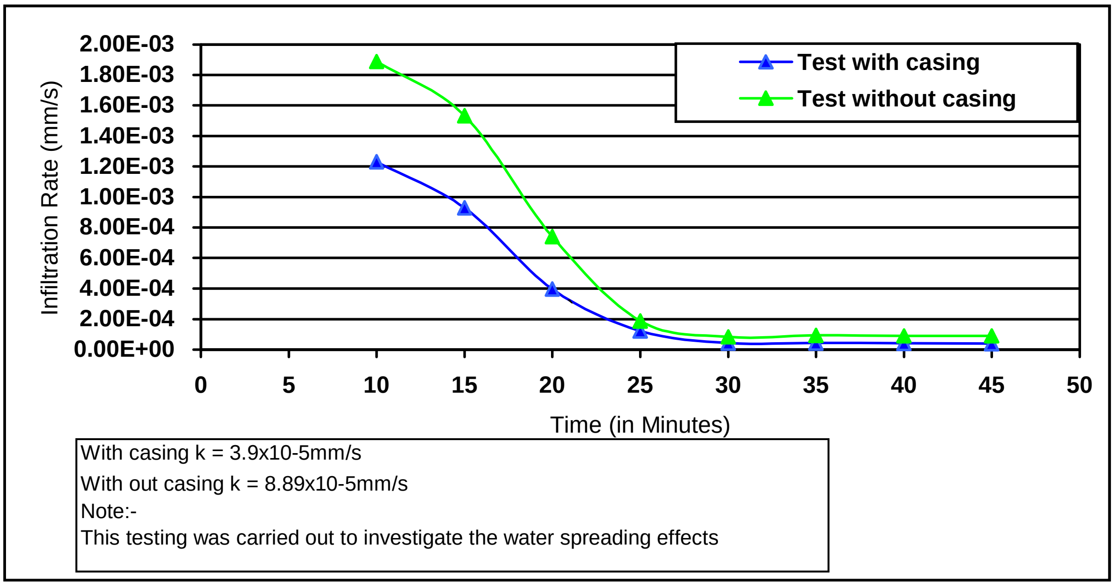


Figure 4.1 Infiltration test with and without casing

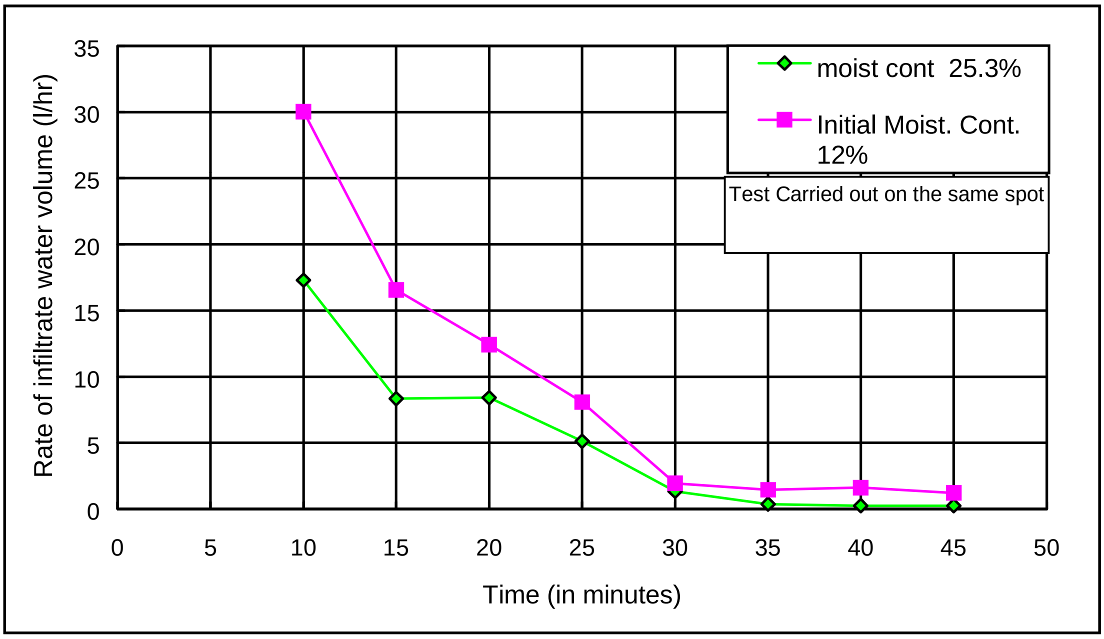


Figure 4.2 Infiltration vs. time: Grass cover with different moisture content

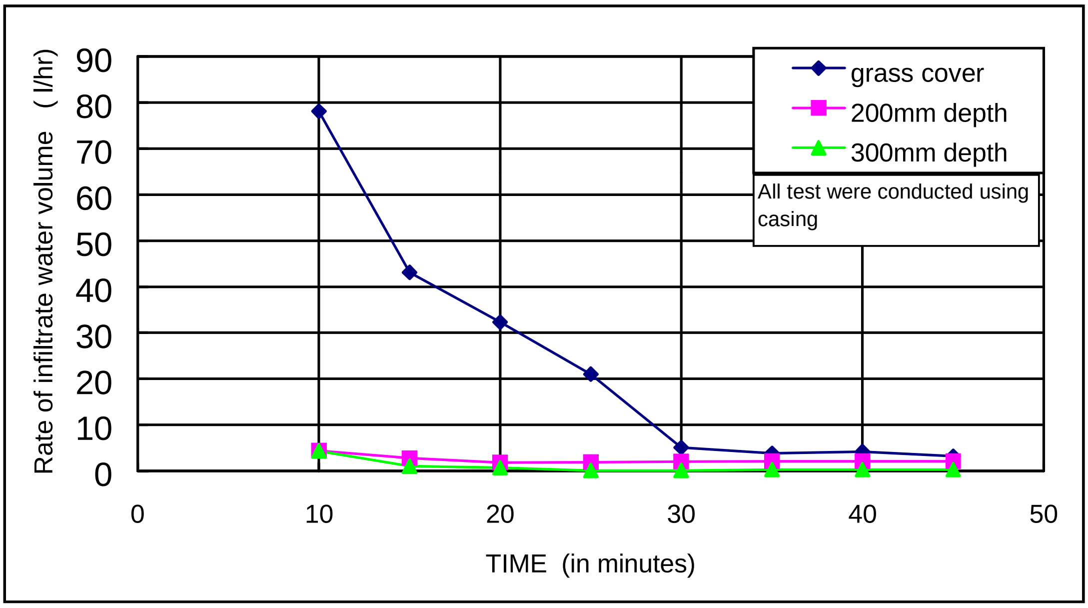


Figure 4.3 Infiltration vs. time: With and without surface cover

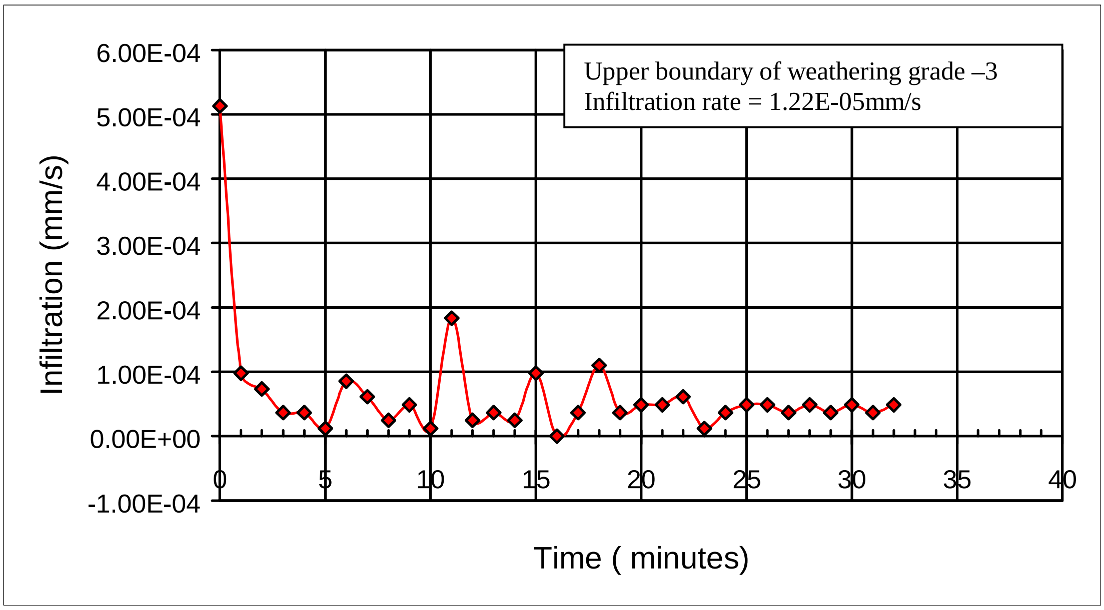


Figure 4.4 Infiltration test on slope at 31st. km Karak Highway (3rd Berm from Top)

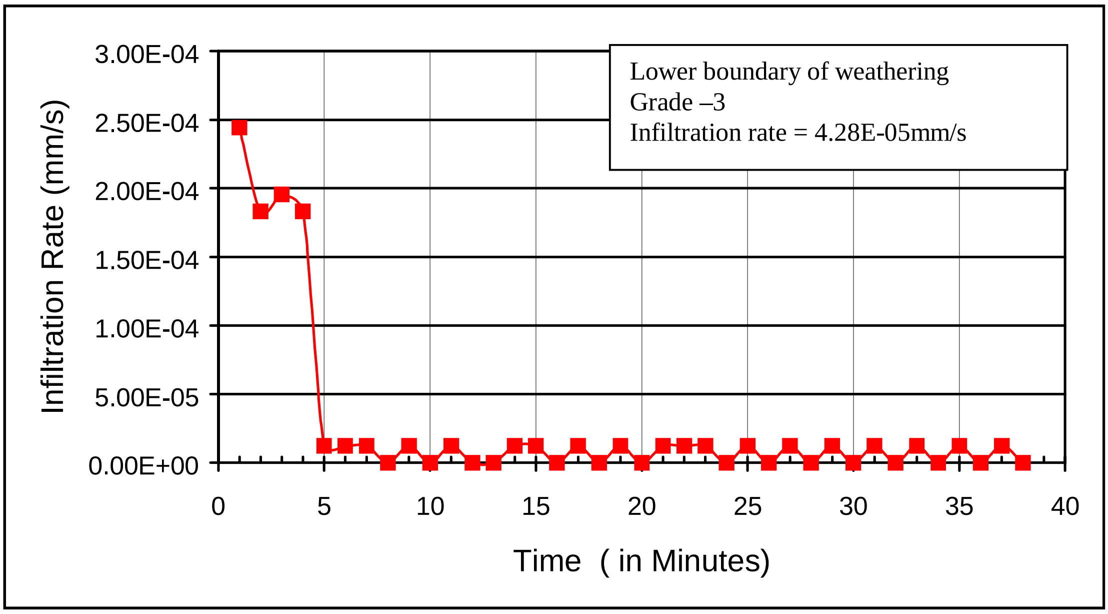


Figure 4.5 Infiltration test on Slope at 31st. km Karak Highway (2nd. Berm from Bottom)

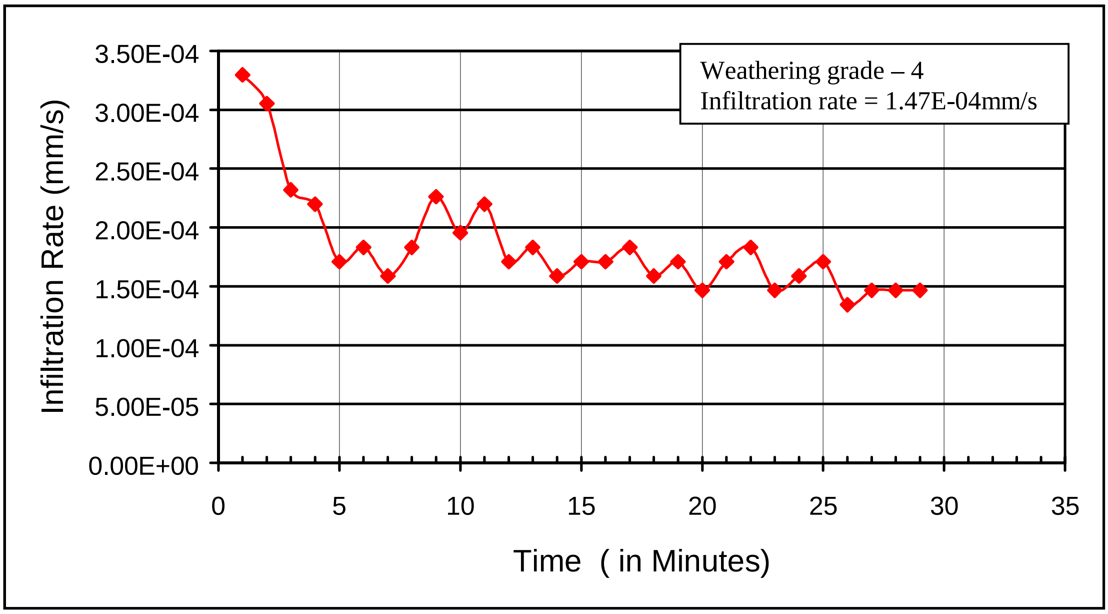


Figure 4.6 Infiltration test on Slope at 31st. km Karak Highway (4th. Berm from Bottom)

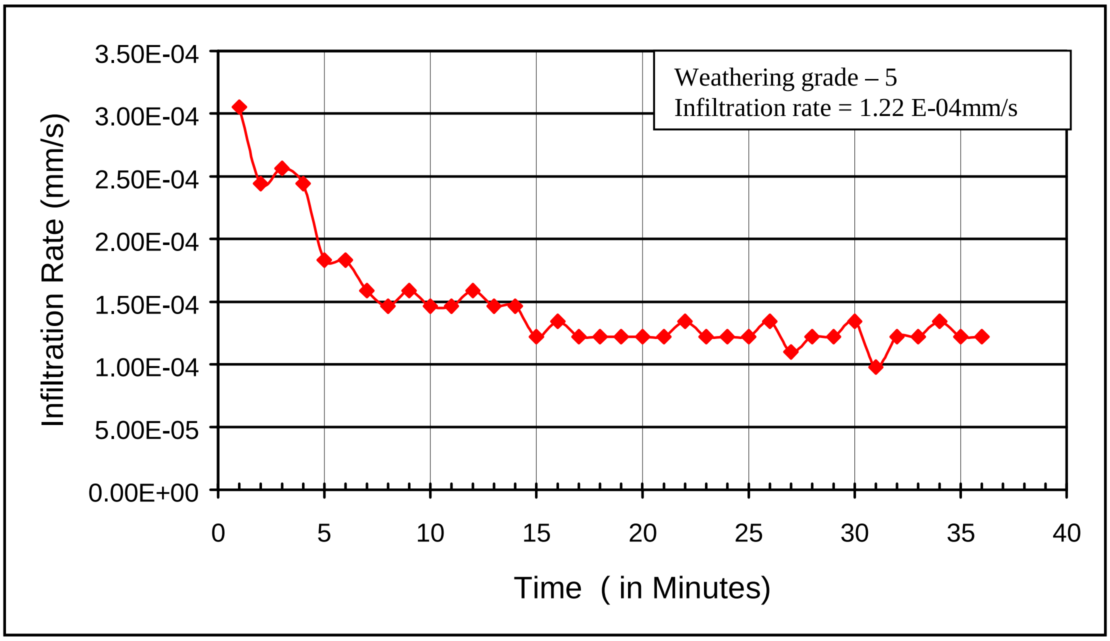


Figure 4.7 Infiltration test on Slope at 31st. km Karak Highway (6th. Berm from Bottom)

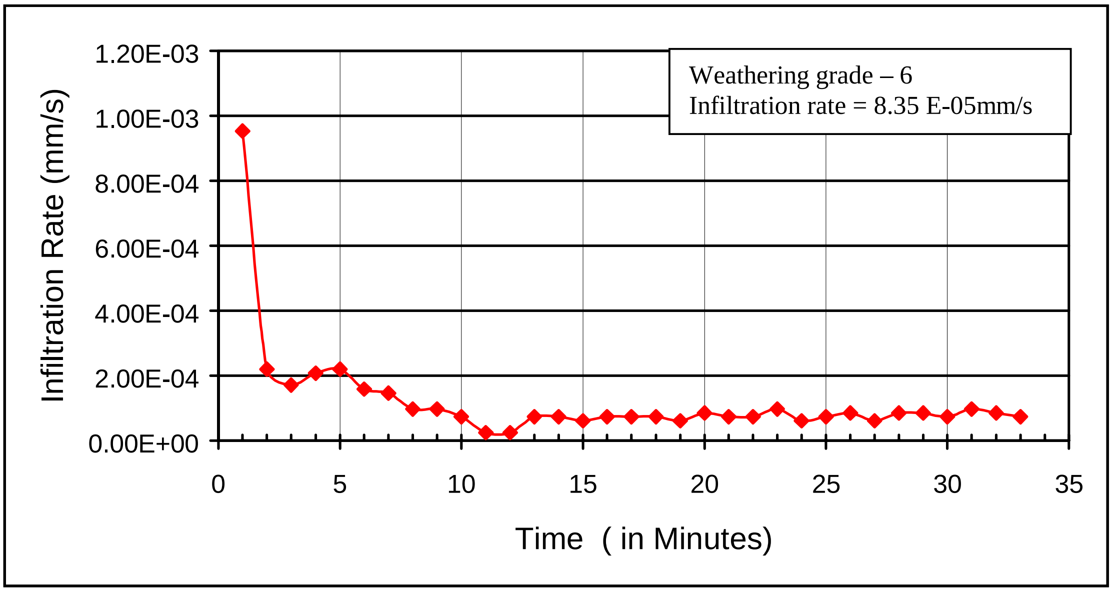


Figure 4.8 Infiltration test on Slope at 31st. km Karak Highway (8th. Berm from Bottom)

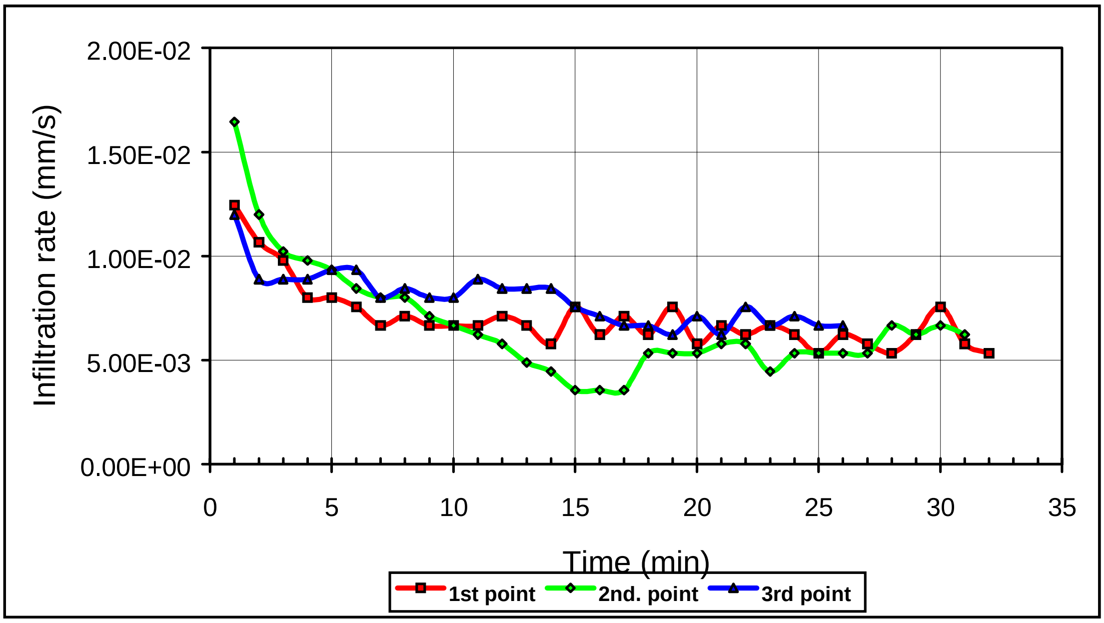


Figure 4.9 Infiltration test on slope at Sepang KLIA (3^{rd}. Berm From Top)

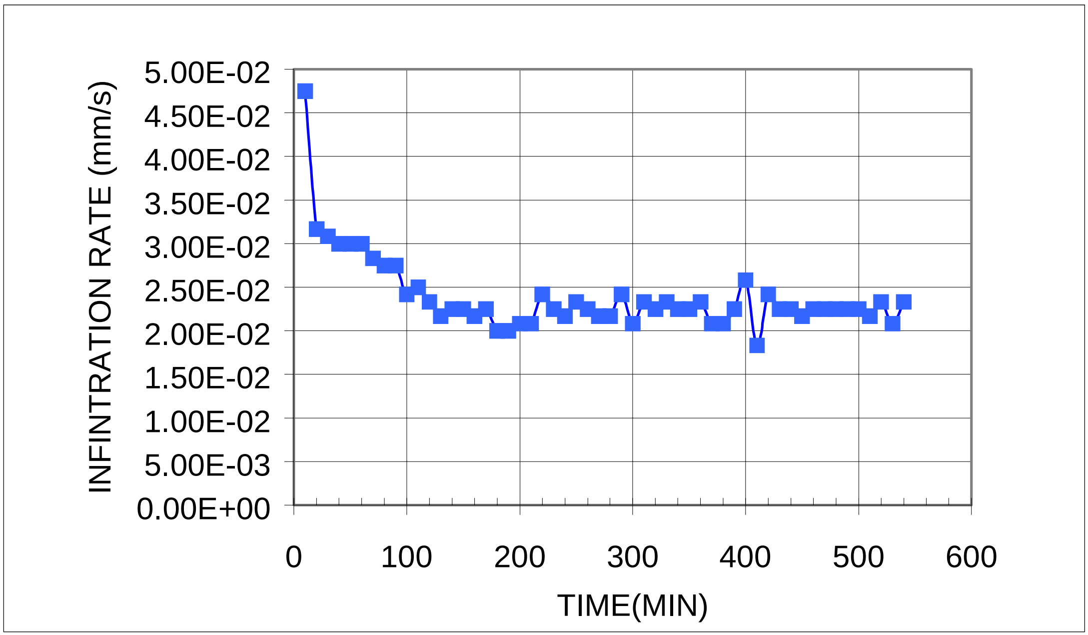


Figure 4.10 Infiltration rate vs. time (for 0^o slope without surface cover)

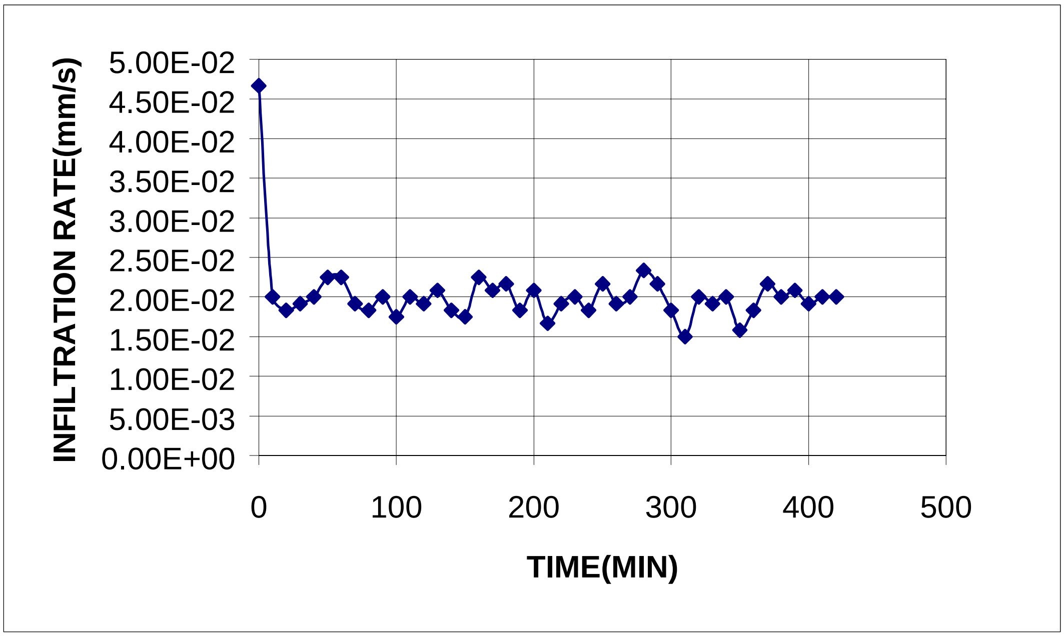


Figure 4.11 Infiltration rate vs. time (for 0^o slope with Lanlock)

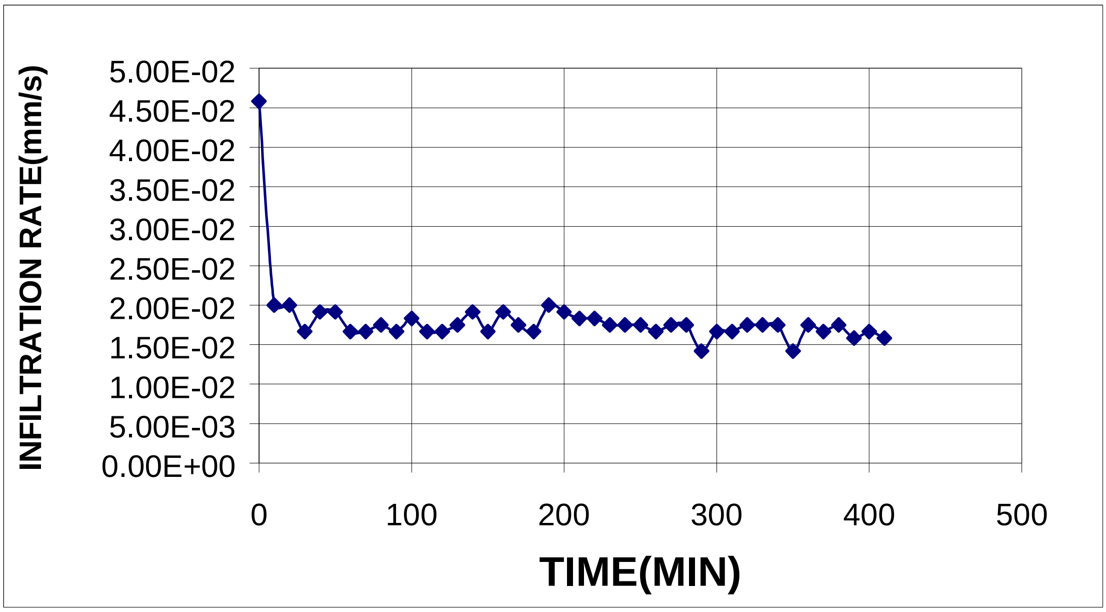


Figure 4.12 Infiltration rate vs. time (for 15^o slope with Lanlock)

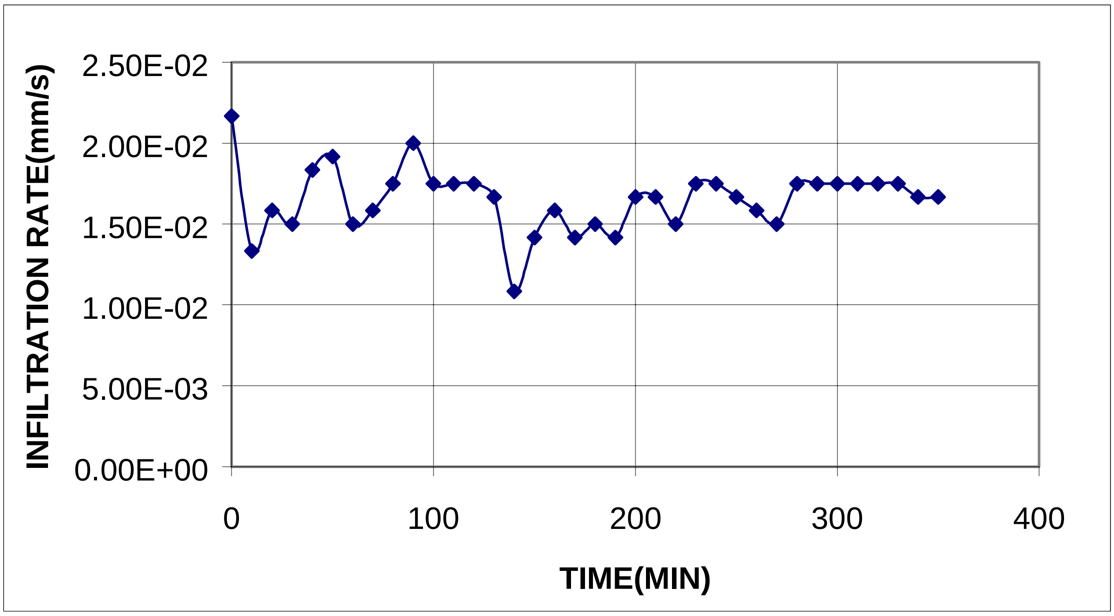


Figure 4.13 Infiltration rate vs. time (for 30^o slope with Lanlock)

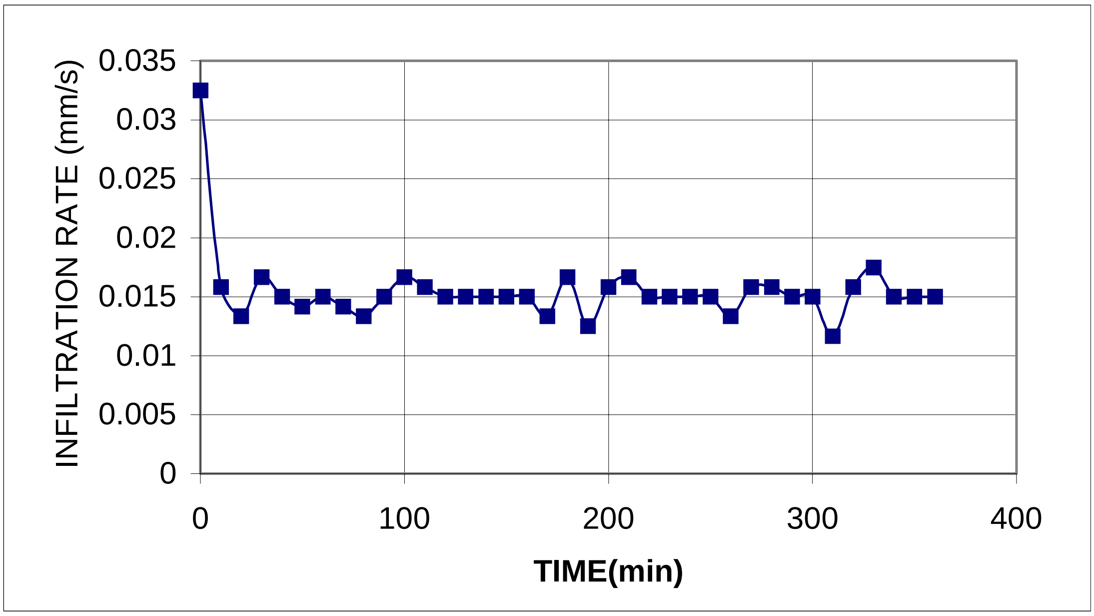


Figure 4.14 Infiltration rate vs. time (for 45^o slope with Lanlock)

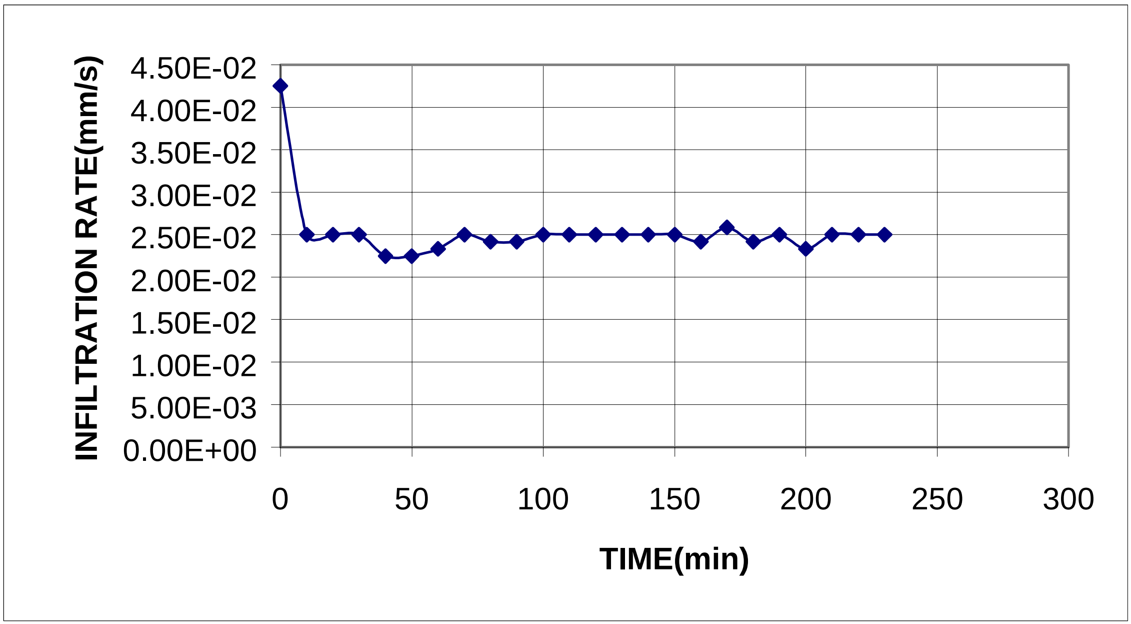


Figure 4.15 Infiltration rate vs. time (for 0^o slope with grass cover)

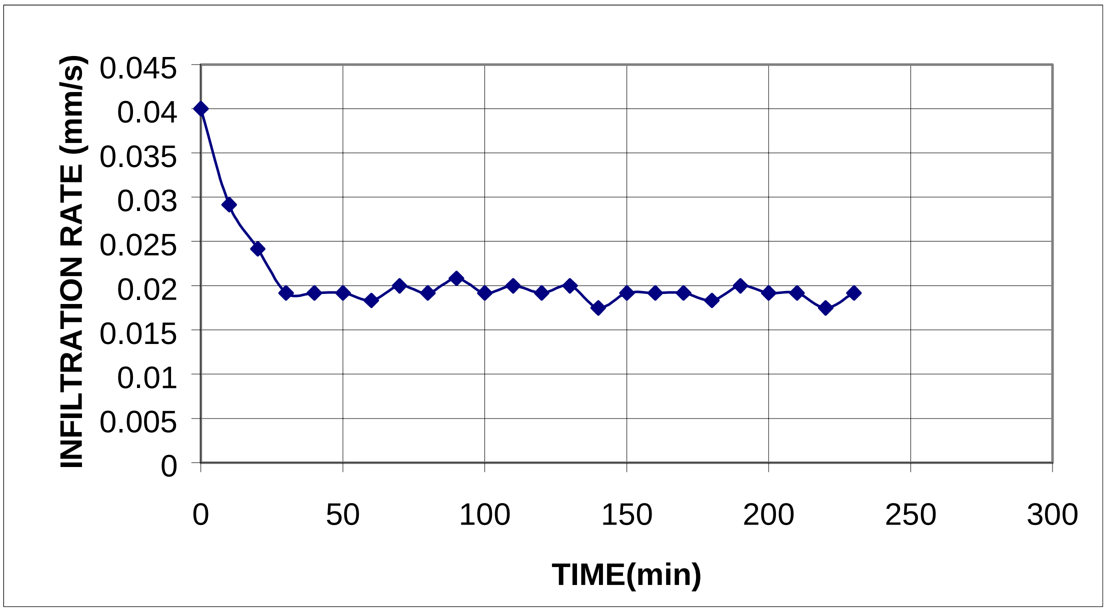


Figure 4.16 Infiltration rate vs. time (for 15^o slope with grass cover)

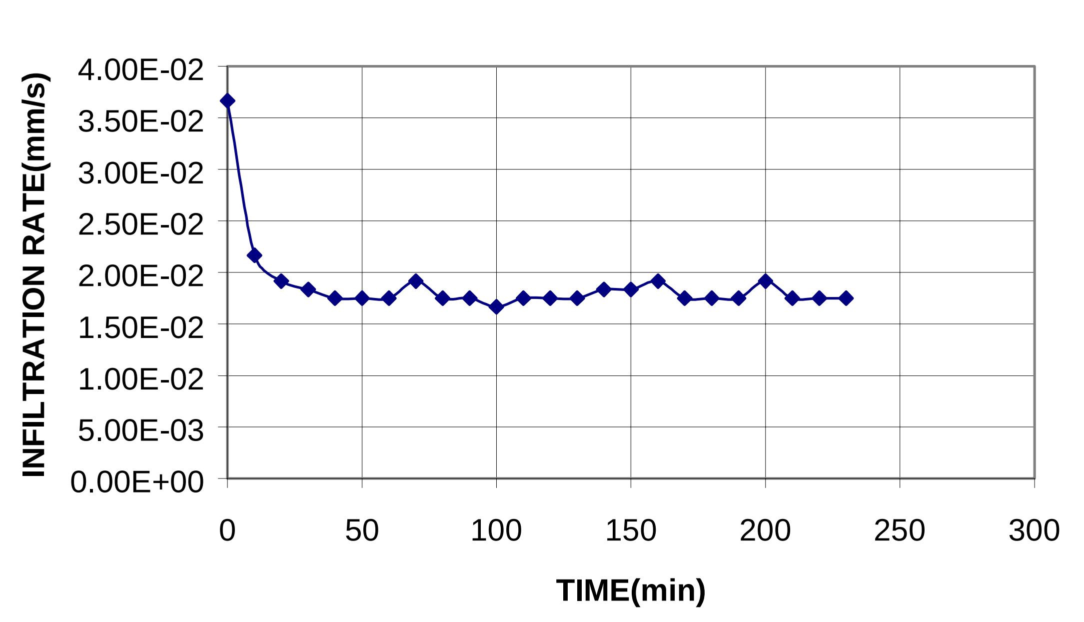


Figure 4.17 Infiltration rate vs. time (for 30^{o} slope with grass cover)

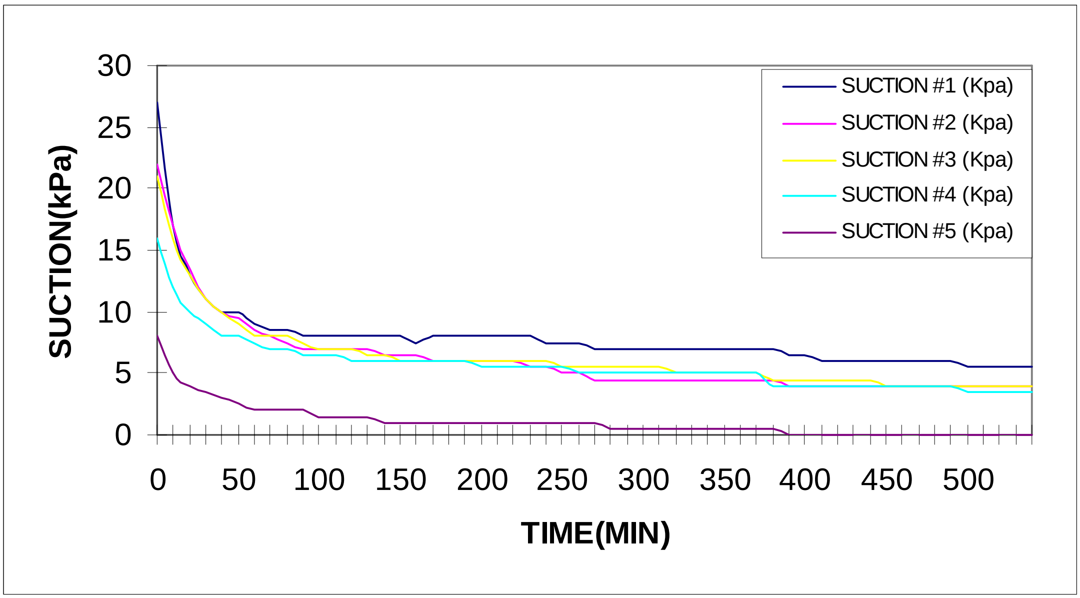


Figure 4.18 Suction vs. time (for 0^{o} slope without surface cover)

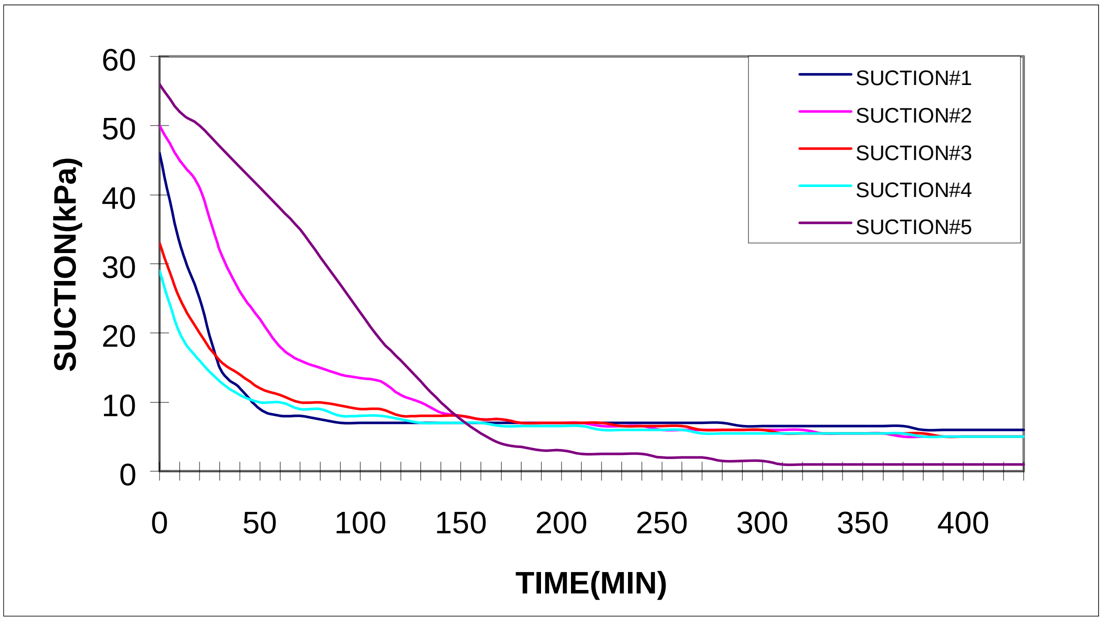


Figure 4.19 Suction vs. time (for 0^{o} slope with Lanlock)

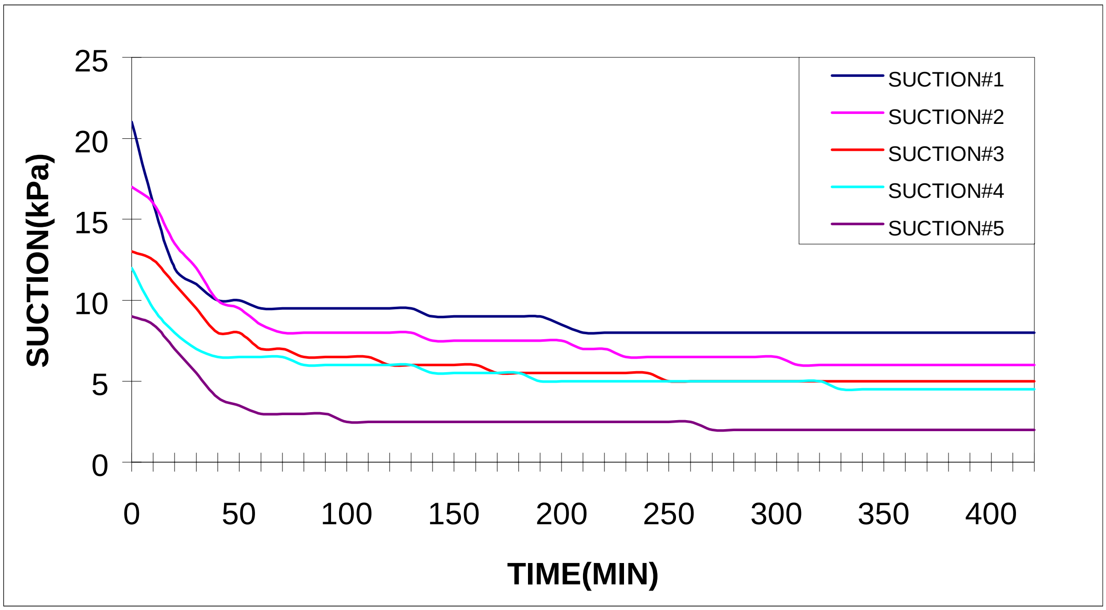


Figure 4.20 Suction vs. time (for 15^{o} slope with Lanlock)

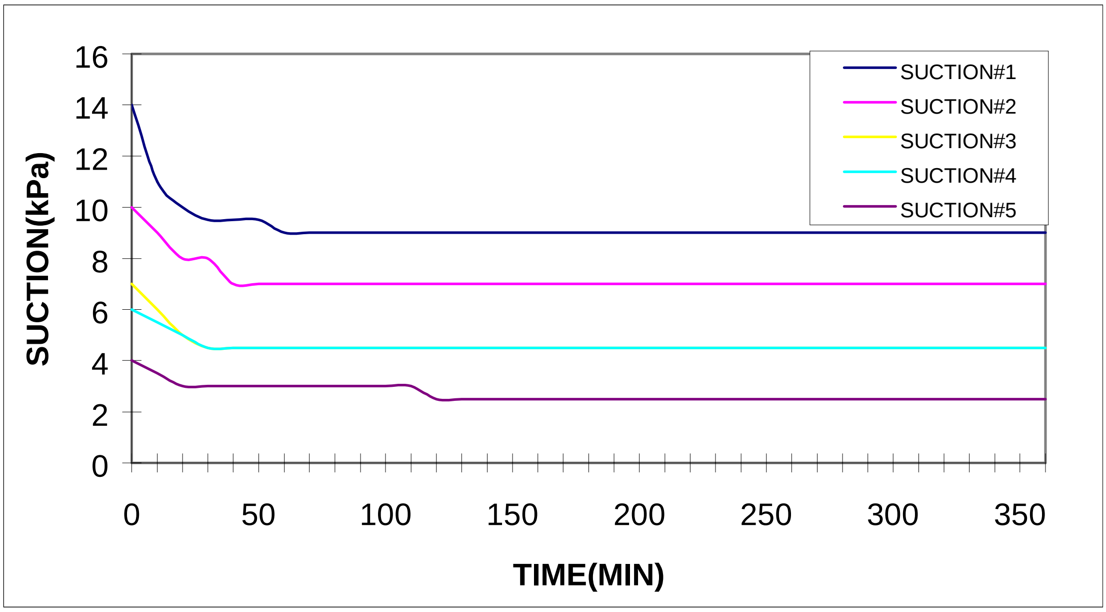


Figure 4.21 Suction vs. time (for 30^{o} slope with Lanlock)

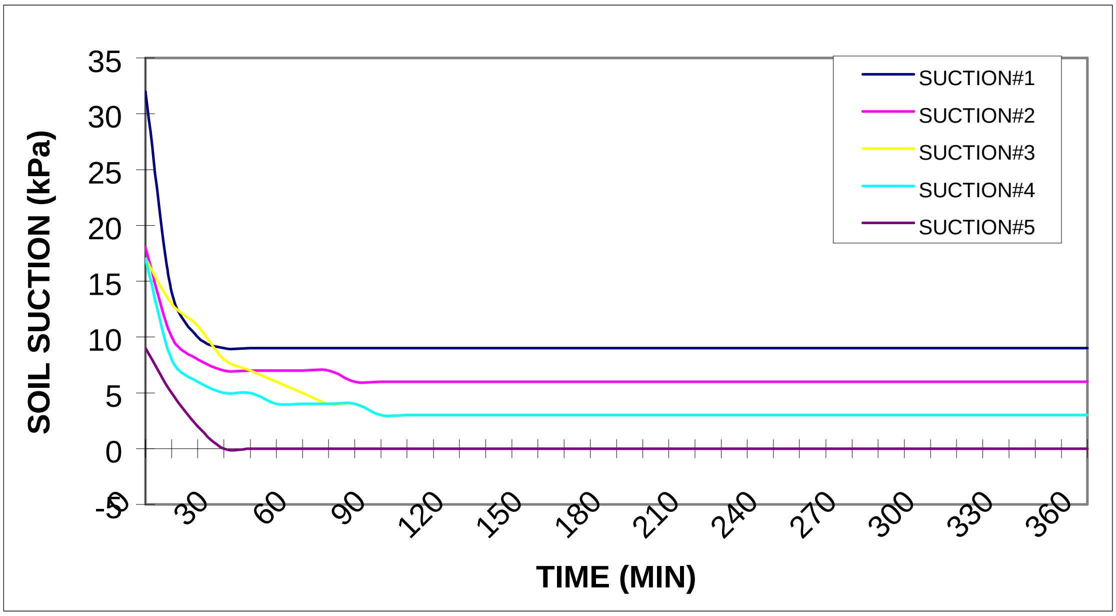


Figure 4.22 Suction vs. time (for 45^{o} slope with Lanlock)

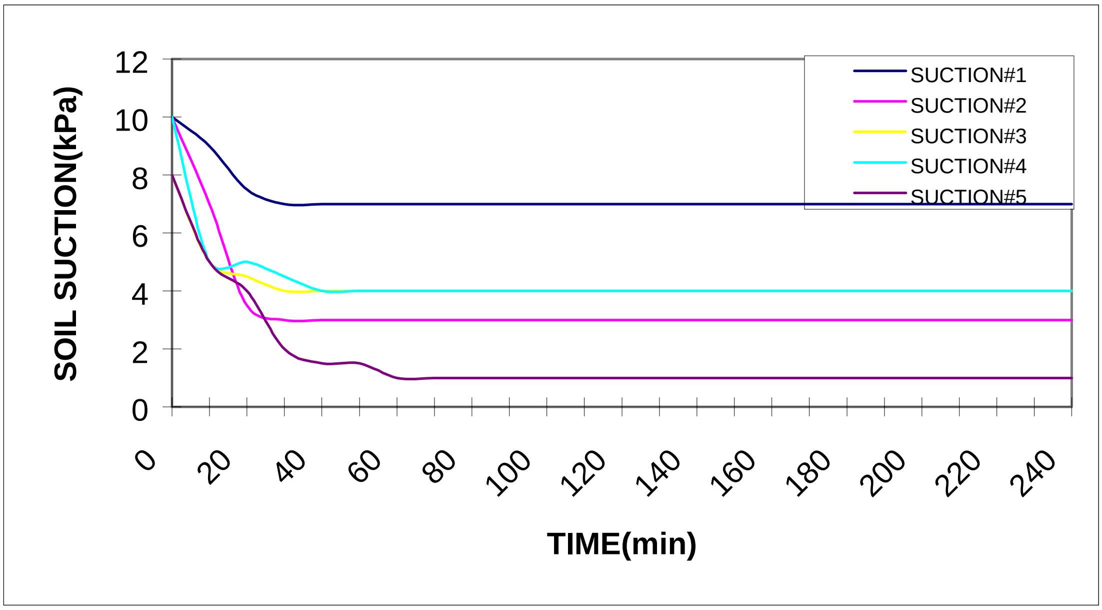


Figure 4.23 Suction vs. time (for 0^{o} slope with grass cover)

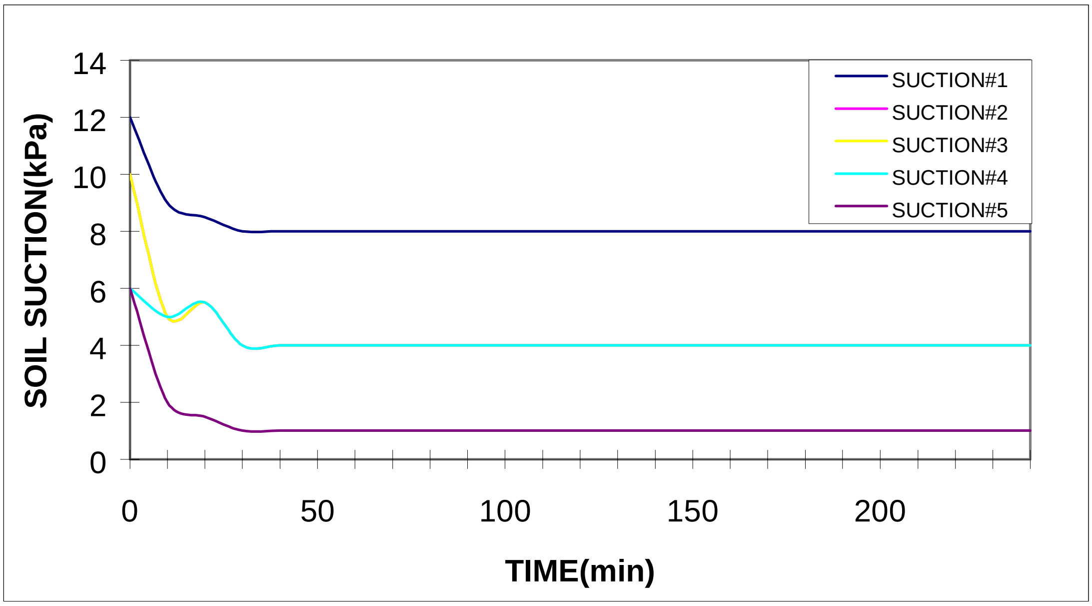


Figure 4.24 Suction vs. time (for 15^{o} slope with grass cover)

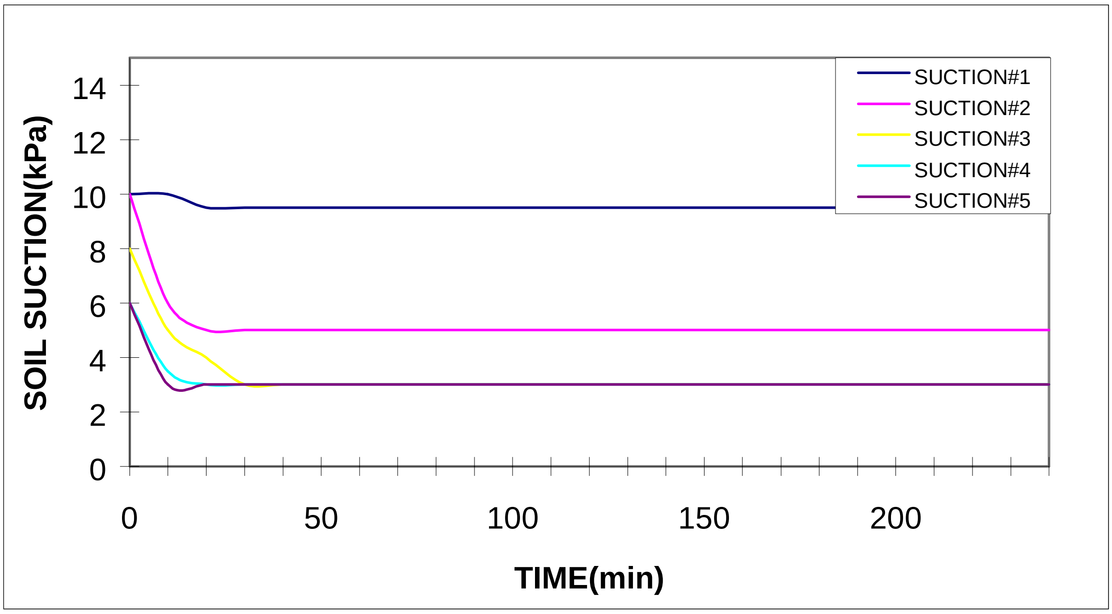


Figure 4.25 Suction vs. time (for 30^o slope with grass cover)

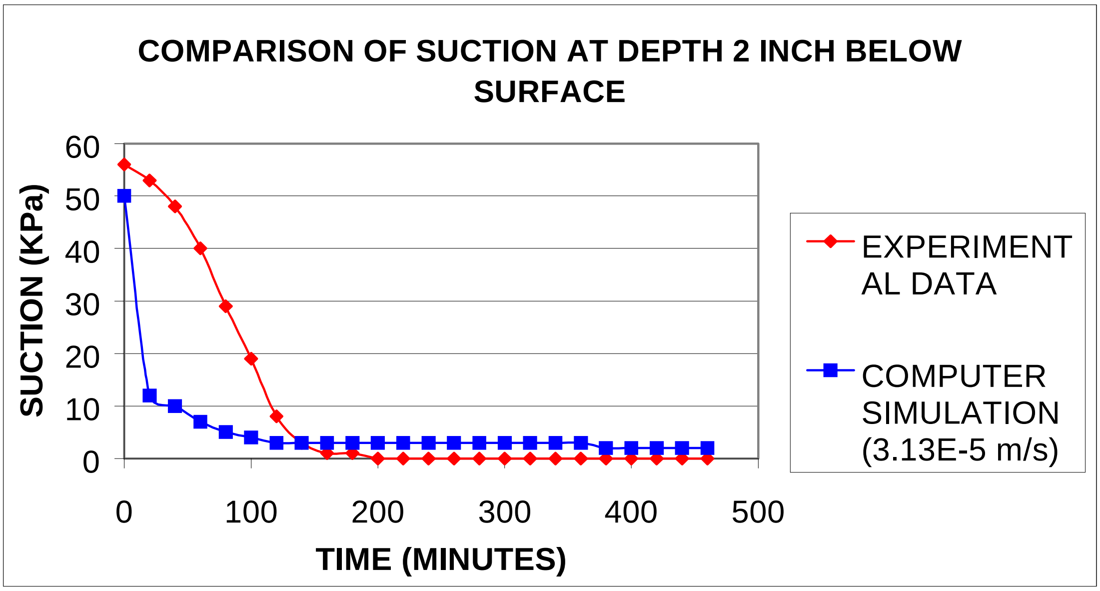


Figure 4.26 Comparison of simulated and measured suction value.

CHAPTER 5

DISCUSSION

CHAPTER 5

DISCUSSION

5.1 INTRODUCTION

In this chapter, the discussion is mainly about the differences in infiltration rates in the test and the results obtained from parametric studies. All the possible factors that affect the infiltration and factors affecting slope instability due to water infiltration will also be discussed in detail in this chapter.

5.2 COMPARISON OF FIELD AND LABORATORY RESULTS

The average infiltration rate at Sepang (KLIA) site is 6.07 x 10^{-3}mm/s (refer to Figure 4.3) and for the laboratory sprinkler model results, the infiltration rates on 0^o slope angle gives a value of 22 x 10^{-2}mm/s (refer to Figure 4.9). It is clearly shown that the laboratory results give a higher infiltration rate. The difference may be due to the reasons below: -

a) Disturbance - The infiltration tests carried out in the laboratory was done on disturbed soil samples by means of compaction. Though the density was the same as the field density, the particles' arrangement might be different. Besides, the soil compaction for the model might not be evenly compacted and carried out efficiently.

b) Thickness of the soil bed in the laboratory model - As mentioned in chapter 2, the resistance of the water flow in the soil is proportional to the depth of the soil. The resistance force of the soil will go against the downward forces (i.e., water head and the capillary head) during the infiltration process. When the resistance is equal to the downward forces, the infiltration will reach steady state condition. Since the thickness of the soil in the laboratory model is only eight-inch thick, the resistance of the water flow in the soil is not significant and causes the infiltration process to reach the steady state condition at a higher value. However, the main objectives of the infiltration tests carried out using the laboratory model is to study the effects of the of slope angles on the water infiltration.

5.3 INFILTRATION CHARACTERISTICS IN RELATION WITH TIME

From all the tests carried out in this study, the infiltration pattern with respect to time is almost the same; initially the rate is high and stabilizes at a lower infiltration rate. There are a few reasons to explain this behavior.

One of the main reasons is the difference of suction head in the soil. When the infiltration test is carried out, initially the surface of the test point becomes wetter than the lower layers. Due to the difference in the suction head, downward forces (due to the suction head and pressure head from the saturated top layer) with the gravity force will act on the water and force the water to infiltrate into the soil.

At the beginning of infiltration, the downward forces are large compared to the flow resistance of the soil, and water enters the soil rapidly. Nevertheless, with the passage of time, resistance that is caused by swelling of clay particles and entrapped air increases. Therefore, there is not much difference between the values of downward forces and resistance and thus, the rate of infiltration reduces. When the downward forces and resistance have equalized, the rate of infiltration becomes constant and stabilizes.

5.4 INFILTRATION CHARACTERISTICS IN RELATION WITH SOIL SURFACE COVER

5.4.1 RESULTS OBTAINED USING INFILTROMETER

From the infiltration test carried out at the test site, the infiltration rate increases with soil surface cover; i.e., grass cover. From Figure 5.1, grass cover actually increases the infiltration rate from 1.33x 10^{-5}mm/s to 5.47 x 10^{-5}mm/s. The increment in the infiltration rate with grass cover may be due to the water passage created by the roots of the vegetation. Besides, the water paths in the soil may be also caused by the activities of the microorganisms. Figure 5.1 clearly shows that when the infiltration test was carried out at a deeper depth (referring to the test pit), the infiltration rate actually reduces. The main reason for this behavior is that when the depth increases, the water paths cause by the roots reduces. Therefore, at the greater depth from the ground level, the influence of vegetation is less significant.

When comparing the infiltration rate for test with grass cover and without grass cover for the depth of 200mm in the field as shown in Figure 5.1, the infiltration rate with grass cover shows a lower infiltration rate. This may be due to some reasons below: -

1) Mechanical disturbance i.e., human activities (as mentioned in Chapter 2) causes a denser and less permeable crust at the surface.
2) The infiltration test using infiltrometer for both cases was subjected to an area of 25cm x25cm. For test with grass cover, the effective area subjected to infiltration is less due to the existing of vegetation and therefore the infiltration rate is lower.
3) When rain falls, the impact of the raindrop will actually break the soil and

with sorting action, the fine particles will be deposited in the voids and cause the reduction of water infiltration. For infiltration with grass cover, raindrop impact does not play an important role in reducing the water infiltration. The grass cover or the vegetation reduces the impact of the raindrop before reaching the soil. The only contribution of the rainwater is to wash the fine particles to deposit in the voids or cracks at the surface. That is the reason why in Figure 5.1 the infiltration rate for the depth of 200mm (contained vegetation roots) gives the higher value compared to the test carried out on grass cover.

The effects of water ponding caused by the vegetation cannot be studied using infiltrometer because during the test a constant water level is maintained. The water ponding effects will be discussed in detail in section 3.4.

5.4.2 RESULTS OBTAINED USING LABORATORY SPRINKLER MODEL

From Figure 5.2, it is shown that the surface covers (grass and Lanlock) give a higher water infiltration rate as compared with the bare surface. The grass cover gives the highest water infiltration followed by bare surface and Lanlock.

Chapter 5 DISCUSSION

From the results, the infiltration rate for test with Lanlock is lower than the bare surface.

The main reasons are as below: -

1) Rapid runoff: For the bare soil sample, the fine particles, which were broken up by the impact water drops could have been washed away rapidly. Thus, this does not allow these fine particles to fill the voids to reduce the water infiltration.

2) Water ponding: Due to the impact of the water drops and surface erosion, the bare soil surface become unlevelled anymore since the particles were being washed and eroded away. Therefore, this creates crater like features on the soil surface, which would encourage water ponding and indirectly increased the water infiltration.

From the results, the grass cover gives the highest infiltration rate. This results are as expected because the presence of the grass encourages more water ponding than Lanlock cover. Besides, the roots system also helps in increasing the water infiltration.

5.5 INFILTRATION CHARACTERISTICS IN RELATION WITH SOIL WEATHERING GRADES

Figure 5.3 shows the summary of the infiltration results carried out on a slope (with respect to soil weathering grades) at Karak Highway. From the results, weathering grades of 4 of that slope gives the highest infiltration rate. The infiltration reduces when the soil weathering grades increase up to grade 6 and down to grade 3. There are several reasons to explain these phenomena.

a) SOIL POROSITY

The soil porosity is expected to have a close relationship with the hydraulic conductivity of the soil. This hydraulic conductivity is one of the flow parameters in the infiltration analysis. Overall, the higher the porosity, the higher the infiltration rates will be. Table 5.1 shows that the variation of the porosity of the soil with different weathering grades matches well with the infiltration rates obtained. The weathering grade of 4 shows the highest porosity and infiltration rate compared with other grades.

TABLE 5.1: SOILS POROSITY VALUES AGAINST INFILTRATION RATES

	Grade 6	Grade 5	Grade 4	Grade 3	*Grade3-2
Infiltration Rate (x 10^{-5}cm/s)	8.35	1.22	14.7	12.2	4.28
Porosity	0.36	0.39	0.51	0.50	0.46

Note :-* Lower boundary of grade 3

Figure 5.4 shows the relationship of porosity of soil with the water infiltration rate of Karak Highway Site. From the graph, the water infiltration increases with the porosity of the soils. The relationship of porosity and water infiltration is not linear. Water infiltration increases rapidly when the porosity is more than 0.5.

b) **VOID RATIO**

Void ratios have a direct relationship with soil porosity. From Figure 5.5, the relationship of void ratios against water infiltration is almost the same as the relationship with soil porosity, i.e., not linear and water infiltration increases with the increment of void ratios. From the graph, water infiltration increases rapidly when the void ratio more than 1.

c) **DENSITY**

Figure 5.6 and Figure 5.7 show the relationship of bulk density and dry density against water infiltration rates. From the two figures, it is clearly shown that the water infiltration experienced the same behavior on both the bulk density and dry density. The higher the bulk density, the lower the water infiltration and vice versa. The higher the density, the denser the soil and the lesser the pore spaces or water passage in the soil, thus the infiltration reduces.

d) **SOIL PARTICLES CONTENT**

As soil goes through weathering process, generally, the higher weathering grades have higher finer particles. Beside the soil properties mentioned above, fine particles play an important role in affecting the water infiltration. As shown in Table 5.1, a grade 6 material has more clay particles compared to the others. The clay particles in the soil may experience swelling and block some of the pores or reduce the pore size in the soil structure during the water infiltration process. This explanation agrees well with the findings of Kirby (1976).

The combination of the soil particles also affects the water infiltration. A well-distributed soil particles will give a denser arrangement, which cause a lower porosity, and reduce the water infiltration. From table 5.1, some weathering grades contained little amount of clay but still have lower infiltration rates, e.g., the lower boundary of grade 3 material. In the lower boundary of grade 3 material, i.e. the least weathered grade, the undisturbed soil particles are still intact to each other causing the water paths to become lesser and reduce the water infiltration.

There is no clear relationship of water infiltration with the size of soil particles. The water infiltration is affected by combination rather than individual soil particles group.

5.6 DIFFERENCE OF INFILTRATION RATE IN RELATION WITH SLOPE STEEPNESS

The differences of water infiltration in relation to slope steepness were obtained from the laboratory sprinkler model. As mentioned earlier, four different slope angles were tested, i.e., 0^o, 15^o, 30^o, and 45^o**.** Three different slope surfaces were studied, i.e., bare, Lanlock cover and grass cover. The differences of the infiltration rates are discussed in detail.

5.6.1 BARE SURFACE

In this test, the sample was left bare without any surface cover. Only one test was performed for the slope angle of 0^o because it was expected that the erosion at more steep slopes would be excessive and thus, this would give a more unreliable infiltration rate (after soil eroded, uneven surfaces formed and caused water ponding at different spots).

Furthermore, excessive erosion would mean that excessive particles will be washed away as surface runoff and damaged the runoff flow meter. Therefore, for the bare soil, the infiltration test at steeper angle of slopes was not carried out.

5.6.2 LANLOCK AS SOIL SURFACE COVER

In this test series, the sample is tested with Lanlock as its surface cover. The tests were carried out at 0^o, 15^o, 30^o, and 45^o. The infiltration rate values for the tests are given in Table 4.3, Chapter 4.

From the infiltration rates, it can be seen that the infiltration rate decreases with the increase of the slope steepness. This is because, the slope of the surface indirectly influences the infiltration rate of the soil sample. On steeper slopes, the water that sprinkled onto the surface more rapidly over the surface, thus allowing little time for the water to infiltrate through the soil. Whereas, on gentle slopes, water either moves slowly or ponded back, therefore, encouraging higher water infiltration through soil. Besides, for a steeper slope angle, the gravitational force that acts as a downward force in infiltration process is resolved according to the cosine of the slope angle and acting perpendicular to the slope surface. With a smaller downward force, the infiltration reduces.

5.6.3 GRASS AS SOIL SURFACE COVER

In this series of tests, the sample is tested with grass as its soil surface cover. The tests were carried out on 0^o, 15^o and 30^o slopes. The test on 45^o was not carried out because the slope failed.

From the infiltration rate values, it can be seen that the infiltration rates also decreased with the increase of the slope angle. The reasons are the same as discussed in section 5.6.2 "Lanlock As Soil Surface Cover".

5.7 THE CHANGES OF MATRIC SUCTION DURING WATER INFILTRATION

The main purpose of the suction monitoring during the infiltration test is to study the wetting front during water infiltration. As mentioned in Chapter 3 " Test Material and Methodology", 5 numbers of small tip tensiometers were used in this study. In this suction, the position of the small tip tensiometers will be named according to Figure 3.8 in Chapter 3; '#suction1', '#suction2', '#suction3', '#suction4' and '#suction 5' respectively.

From the results show in Figure 4.17- Figure 4.24 all the suction values reduces and stabilizes after some time during the infiltration tests. The soil matric suction reduces because water infiltrates into the soil and increases the saturation of the soil. Most of the tensiometers did not or difficult to reach the suction values of zero. This may be due to the entrapped air in the soil that retards the saturation process.

5.7.1 BARE SURFACE

As mentioned earlier, only one infiltration test is done for the slope angle of 0^o. This is because it was expected that extensive erosion would be occurring at steeper slopes that would affect the accuracy of the small tip tensiometer reading as the ceramic cups beneath the soil could be exposed because of the extensive erosion and thus, giving a totally inaccurate reading of soil suction.

For this series, as expected, the soil suction values at all the five points in the sample decrease with time till it reaches a steady state condition. Table 5.2 shows the suction values of all the five tensiometers at its steady state condition.

TABLE 5.2: THE SOIL SUCTION VALUES AT STEADY STATE CONDITION FOR BARE SURFACE.

#Suction1	#Suction 2	#Suction 3	#Suction 4	#Suction 5
5.5 kPa	4kPa	4kPa	3.5kPa	0kPa

It is expected that the suction value for tensiometer #suction 5 should be the same as tensiometer #suction 1 since their porous ceramic tip of the tensiometers are placed at the similar depths (at 50mm depth below surface level). From Table 5.2, both the tensiometers do not show values as expected. The same condition goes to tensiometer #Suction 2 and tensiometer #Suction 4 that supposed to have the same values. (Both the porous ceramic tips of #suction 2 and #Suction4 are placed at similar depth, i.e., 75mm). The different values of the tensiometers mentioned show that the wetting front of the water infiltration is not parallel to slope surface. The soil at the toe (near the runoff out flow) experienced more water infiltration than the soil at the other end.

There are a few reasons why the wetting front entering the soil is not horizontal: -

1) Direction of the runoff - Though the surface is horizontal, the water tends to flow to the outlet of the chamber. When water flows to the outlet, the soil near to the outflow experiences higher water ponding than the soil near the Tensiometer #Suction 1. As water sprinkled onto the soil, the water has more time to infiltrate as it moves towards the outlet.

2) Boundary Condition - If the surface is horizontal at the natural field condition, since the boundary can be considered as infinite or very far, thus water will flow in all directions. In this case, the water can enter the soil parallel to the soil surface.

3) Water ponding - As water flow from one end to the other, due to the drag friction between the water and the soil, the possibility of ponding is more as the distance of flow increases. From the observation during the test, it clearly shows that the water ponding increasing towards the outlet.

5.7.2 LANLOCK AS SURFACE COVER

There were four tests done using Lanlock as soil surface cover and their respective soil suction values at steady state condition are as shown in Table 5.3.

TABLE 5.3: THE SOIL SUCTION VALUES AT STEADY STATE CONDITION FOR LANLOCK SURFACE COVER.

Slope angle	#Suction 1 (kPa)	#Suction 2 (kPa)	#Suction 3 (kPa)	#Suction4 (kPa)	#Suction 5 (kPa)
0^o	6	5	5	5	1
15^o	8	6	5	4.5	2
30^o	9	7	7	4.5	2.5
45^o	9	6	6	3	0

Generally, from the suction values, it is seen that the wetting front of the water does not move into the soil parallel to the surface. Soil at the toe of the slope model experienced more wetting than the soil at the top of the slope. Therefore, it is clearly shown that the longer the slope surface, more water will infiltrate into the soil especially near the toe. For a long slope surface, it is recommended to divide it into berms with berm drains to minimized water infiltration.

For a steeper slope angle, the suction values at the top of the slope model (readings for #Suction 1) always experienced the highest reading. This indicates that the water infiltration is less at the top of the slope surface compared to the toe.

When the slope angle increases, the suction values for tensiometer #Suction 3, #Suction4, and #Suction 5 during steady state condition reduce. The toe experiences more wetting as the slope angle increases. This indicates that the steeper the slope angle, the more incline the wetting front is to the slope surface.

5.7.3 GRASS AS SURFACE COVER

The constant soil suction values at steady state condition are as shown in Table 5.4. The pattern of the soil suction behavior is the same as discussed in Section 5.7.2 for Lanlock as surface cover.

TABLE 5.4: THE SOIL SUCTION VALUES AT STEADY STATE CONDITION FOR GRASS SURFACE COVER

Slope angle	#Suction1 (kPa)	#Suction2 (kPa)	#Suction3 (kPa)	#Suction4 (kPa)	#Suction5 (kPa)
0^o	7	3	4	4	1
15^o	8	4	4	4	1
30^o	9.5	5	3	3	3

5.7.4 INFLUENCE OF SURFACE COVER ON SOIL SUCTION

From Table 5.2, Table 5.3 and Table 5.4, it can be seen that the suction values at steady state for tests with grass cover as its surface cover, are the lowest at its respective points for its respective slope angles. This may be due to the effects of roots that formed abnormal water passage during the water infiltration.

5.8 SOIL EROSION FOR DIFFERENT SURFACE COVER

The erosion of soil that occurred in each test in the laboratory is as given in Table 5.5. it is seen that grass cover drastically eradicated soil erosion compared to Lanlock system and bare soil. This is because the roots of the grass hold the soil particles together and therefore reduces the erosion. However, if the slope angle is too steep, the grass cover tends to pond back the water between the grass and increase the load that may cause instability to the slope if the roots do not penetrate deep enough (test on 45^o slope with grass as surface cover experienced failure during the sprinkling process).

TABLE 5.5: SOIL EROSION DURING LABORATORY INFILTRATION TEST

INFILTRATION TEST	ERODED SOIL MASS (g)
Bare soil Surface with 0^o Slope	9053
Lanlock Surface with 0^o Slope	1568
Lanlock Surface with 15^o Slope	15672
Lanlock Surface with 30^o Slope	32325
Lanlock Surface with 45^o Slope	40568
Grass Surface with 0^o Slope	15
Grass Surface with 15^o Slope	109
Grass Surface with 30^o Slope	512

5.9 RESULTS OF PERCHED WATER TABLE SIMULATION

During the analyses, rainfall intensity for all the cases was specified for horizontal surface as well as dipping surface. The water flow into the slopes will be much more complicated as the interference of water flow from horizontal and dipping surface will happen. So, fluctuation is expected.

The conditions that cause slopes to become unstable and the factors that initiate the slip failure should be able to be identified. These factors are the geological structure and hydro-geological conditions of the slope.

Generally in all cases the safety factor drops as the perched water table starts to build up. The drops however are not very large i.e., not more than 20 %.

5.9.1 EFFECT OF PERMEABILITY RATIO OF PERMEABLE LAYER TO IMPERMEABLE LAYER

In the analysis, the permeability of impermeable stratum was fixed to 1×10^{-8} m/s. By varying the permeability ratio, it will affect the seepage and water content in the slope and hence the stability of the slope. From the results shown in Figure 5.8, it is clear that safety factors drop at certain interval of time when perched water table starts to build up. The perched water table starts to build up earlier for higher permeability ratio and this causes safety factor drop earlier. This is true because the higher ratio means the permeable layer with higher hydraulic conductivity allows water to infiltrate into the soil faster. Generally perched water table starts to build up from interval time 6000 sec to 8000 sec.

5.9.2 EFFECT OF POSITION OF IMPERMEABLE LAYER

By varying the position of the impermeable layer, the time to build up the perched water table seepage infiltration and water content will be affected. From the graph in Figure 5.9, the safety factor of slip surface starts to drop at time 6000 sec. This means perched water table starts to build up at this time. Generally, the effect of position of the impermeable strata is not significant.

5.9.3 EFFECT OF DIPPING OF IMPERMEABLE LAYER

Cases with dipping layers generally have lower safety factor with sloping bed dipping backward (refer to Figure 5.10). This is because the dipping backwards enables more water to accumulate above impermeable layer. The effect of perched water table is more significant as it is easier to form as safety factor drops earlier compare to model with dipping bed gradient same direction with dipping surface.

5.9.4 EFFECT OF NUMBER OF IMPERMEABLE LAYER.

As the number of impermeable layer increases the safety factor drops accordingly as shown in Figure 5.11.

In all the three cases shown in Figure 5.11, the safety of factor seems to drop after a critical duration i.e., about 4000sec. This is due to the build-up of perched water table in the slope.

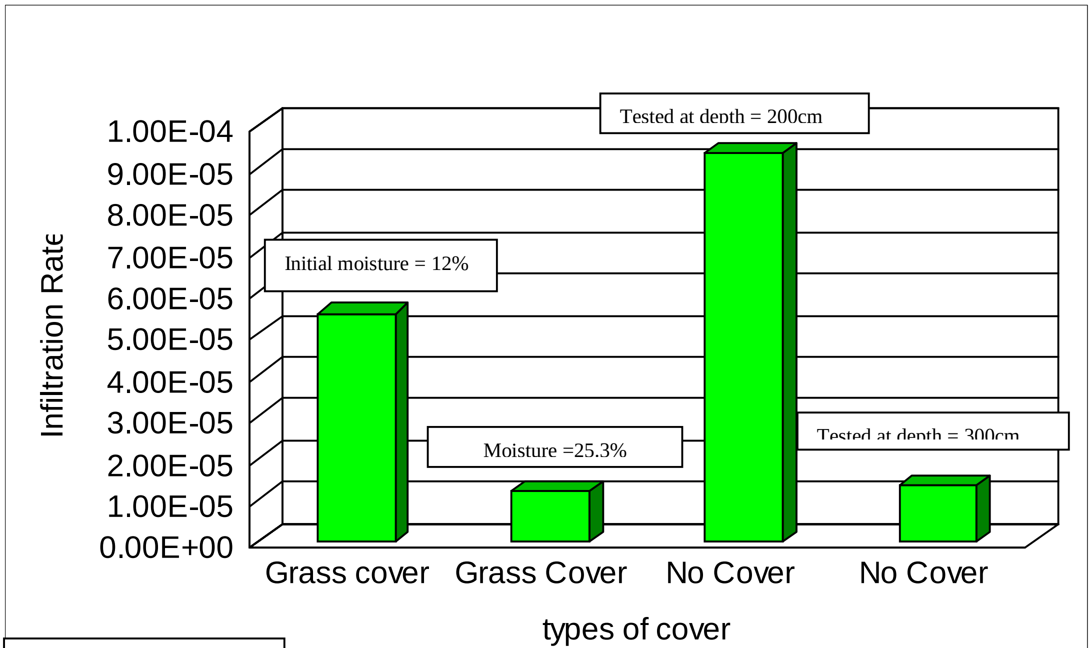
5.9.5 EFFECT OF RAINFALL INTENSITY

Figure 5.12 clearly shows that for rainfall intensity of 1×10^{-5} m/s or less the factor of safety remains constant as no perched water table build up. For rainfall intensity 5×10^{-5} m/s and 5.2×10^{-5} m/s there are only slight drops i.e., not more than 2 %. The drop of safety factor becomes more significant for higher rainfall intensity. Rainfall intensity of 1×10^{-4} m/s records a maximum drop of 4.4% while rainfall intensity of 2.1×10^{-4} m/s records a maximum drop in factor of safety.

Generally, the safety factor starts to drop at time 6000 sec or 7000 sec. The reading is constant for set of data with lower rainfall intensity; as for lower rainfall, intensity the effect of perched water table is not significant. The safety factors for analysis with rainfall intensity 2.1×10^{-4}m/s shows fluctuating trend before perched water table starts to build up. It is mainly due to the seepage of high rainfall infiltration, which is more complicated and difficult to predict. Interference of water flow from horizontal and slope surface is another contributing factor.

The permeability of the soil also plays an important role in this study because when the rainfall intensity is lower then the permeability of the soil, the infiltrated rainwater can dissipate fast into the slope and does not cause perched water table to build up. But, when the rainfall intensity equal to or more then the soil permeability value, perched water table will start to form.

In the analysis, the flux boundary condition needs to be considered carefully. If the rainfall intensity is more then the permeability of the soil, surface runoff needs to be specified.



Infiltration Test on Surface Cover – Grass

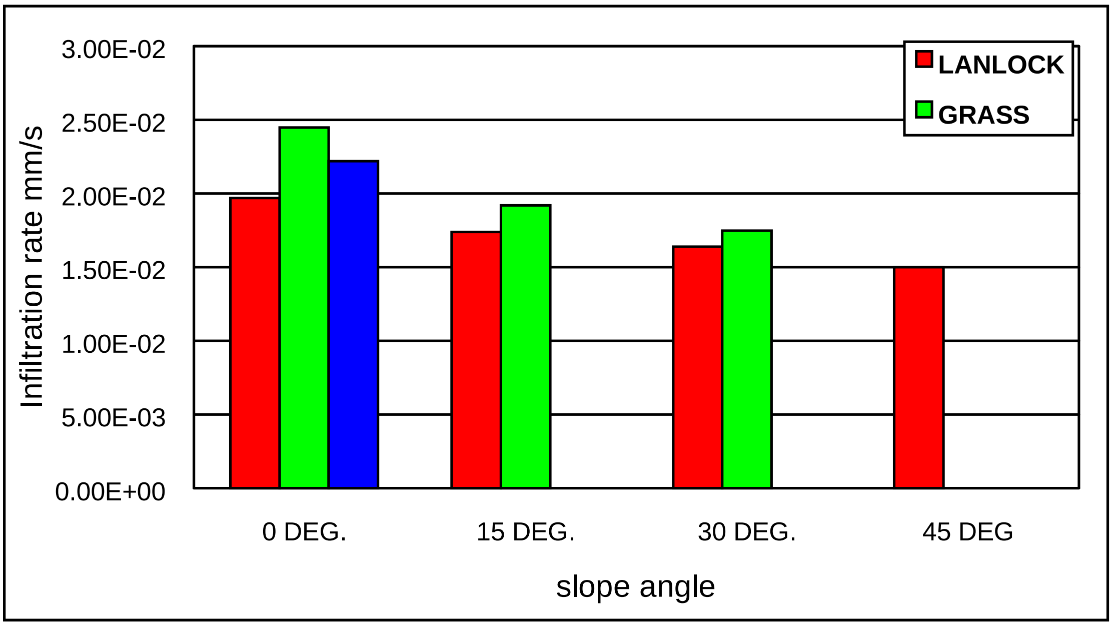


Figure 5.2 Infiltration rate vs. slope angle

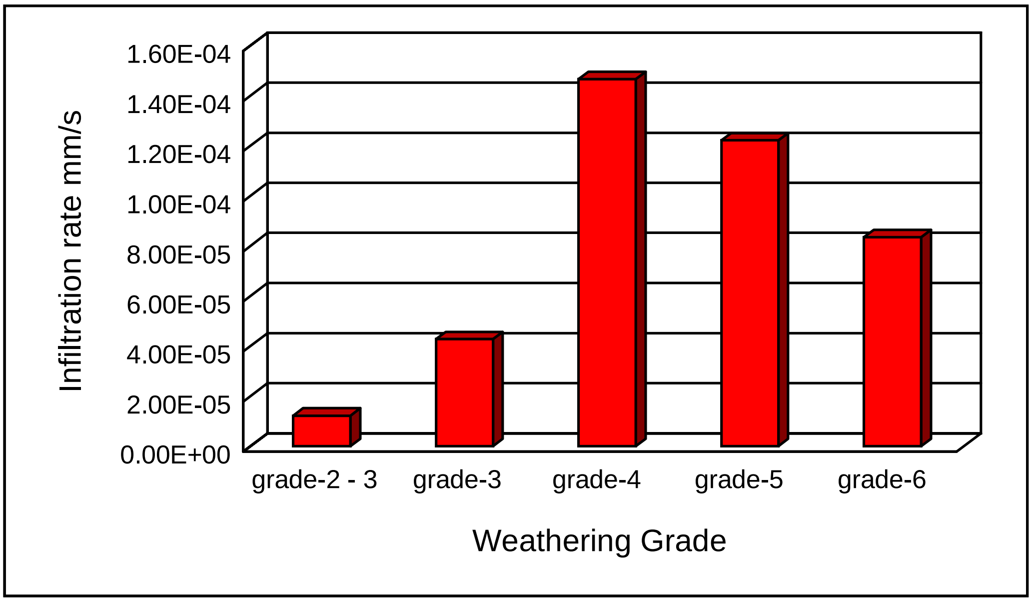


Figure 5.3 Infiltration rate vs. weathering grades (31st. km Karak Highway)

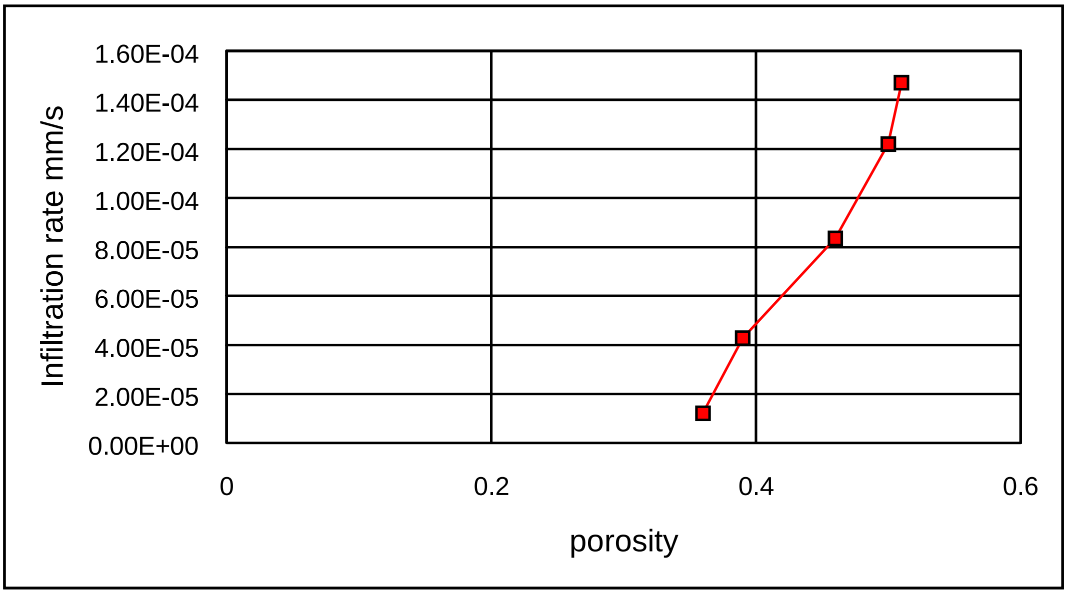


Figure 5.4 Infiltration rate vs. Porosity

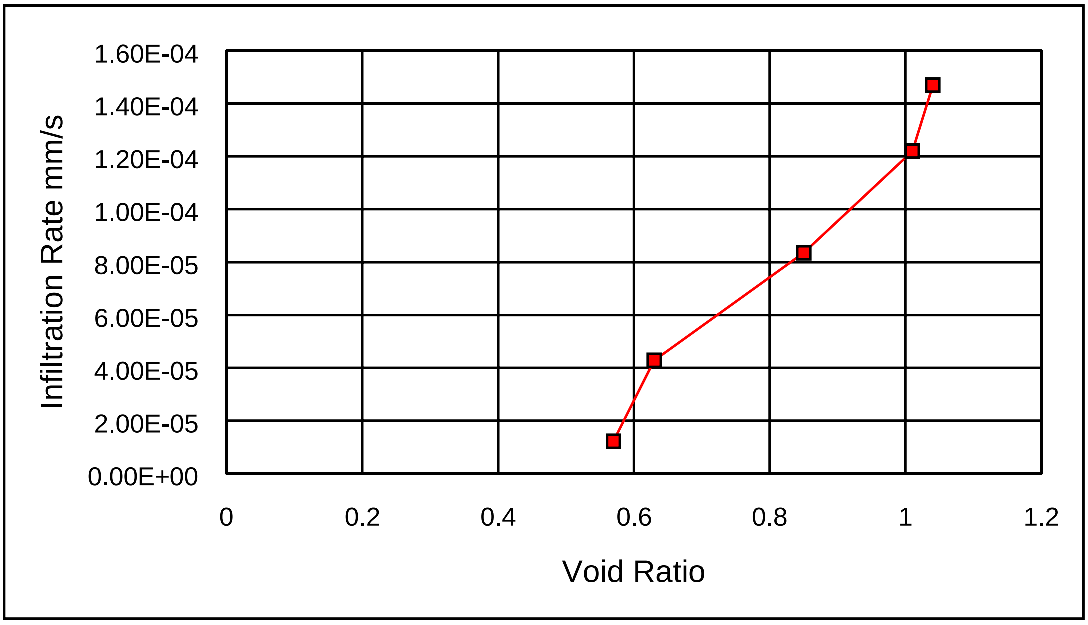


Figure 5.5 Infiltration rate vs. Void Ratio

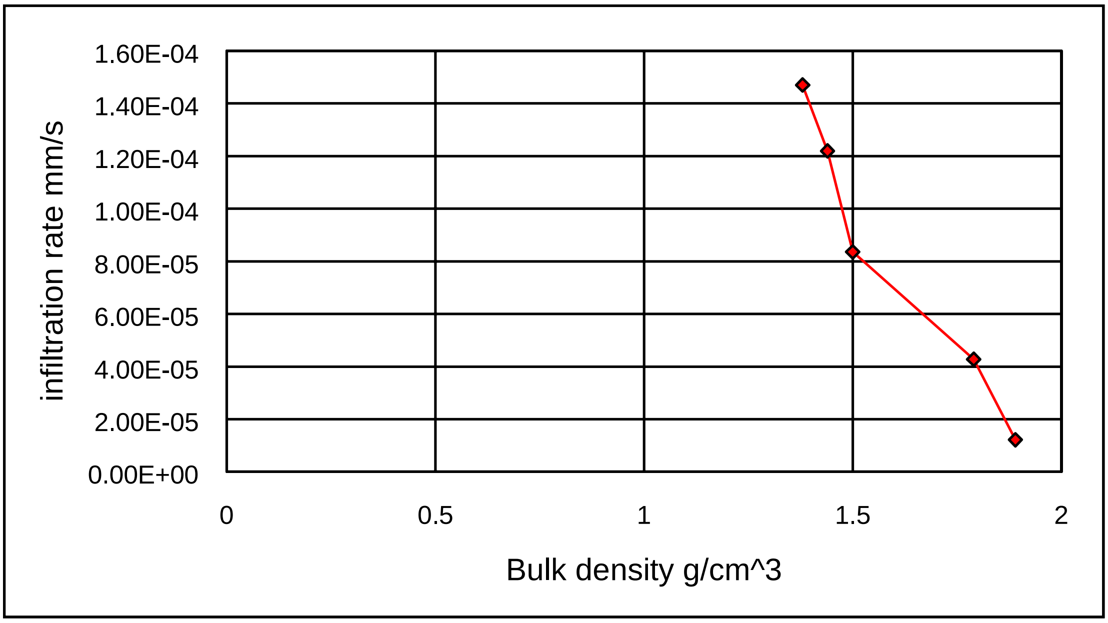


Figure 5.6 Infiltration rate vs. Bulk Density

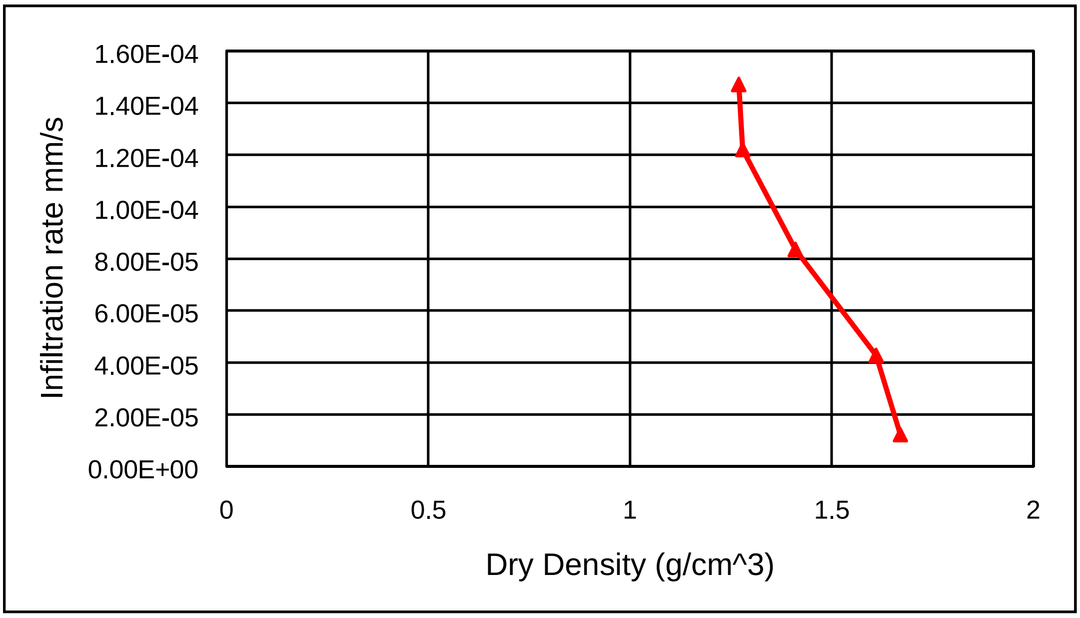


Figure 5.7 Infiltration rate vs. Dry Density

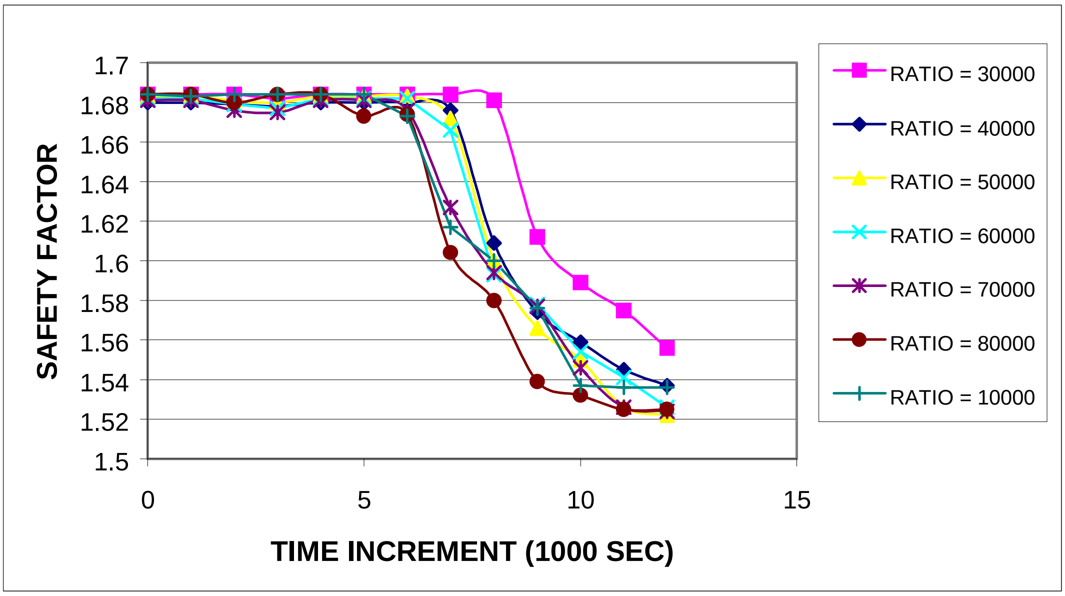


Figure 5.8 Effect of Permeability ratio on factor of safety

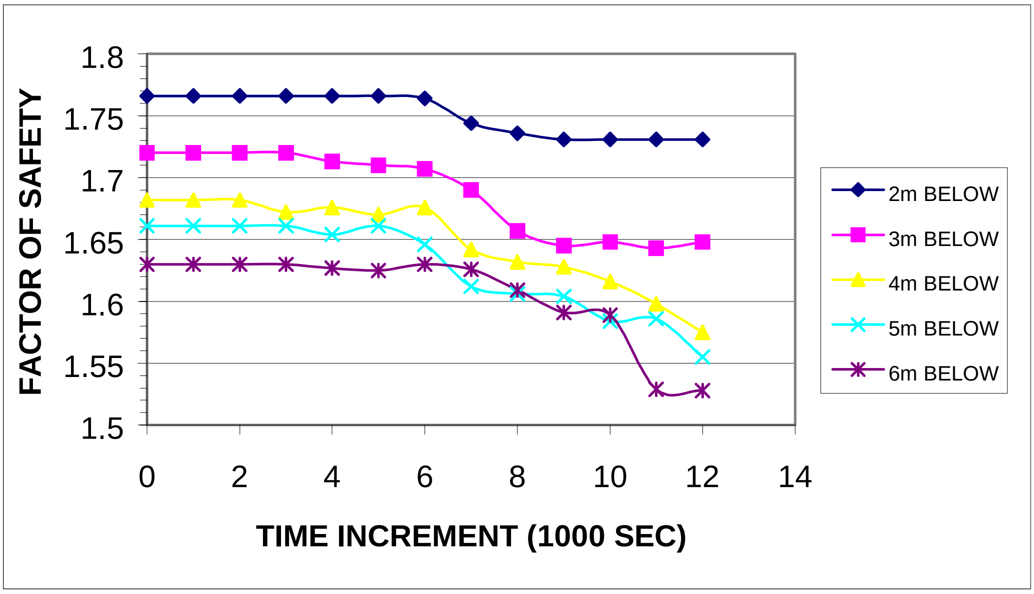


Figure 5.9 Effect of position of impermeable layer on factor of safety

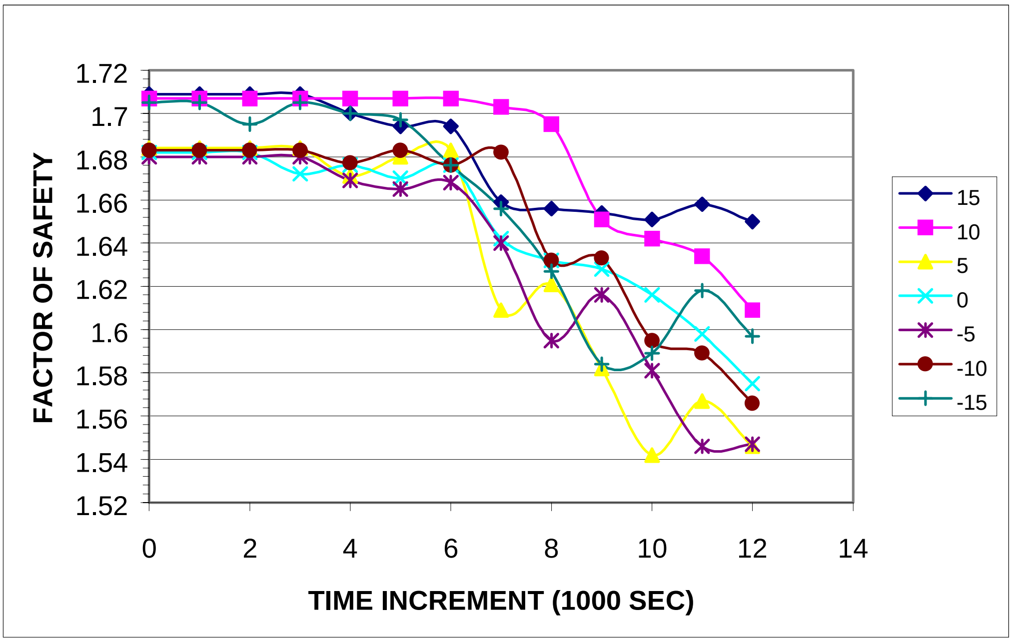


Figure 5.10 Effect of dipping of impermeable layer on factor of safety

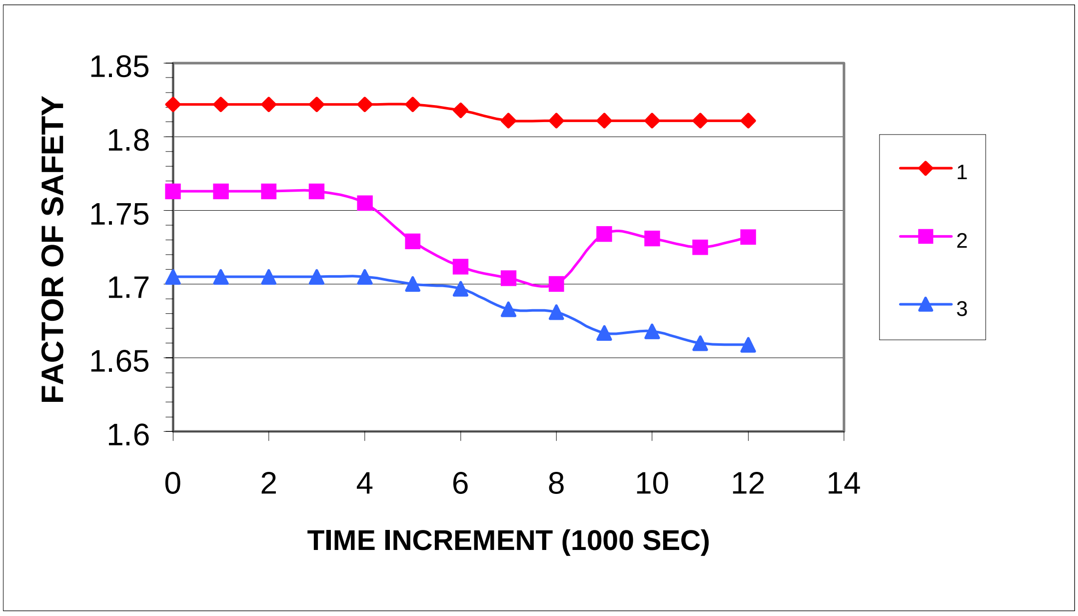


Figure 5.11 Effect of number of impermeable layer (1m thick) on factor of safety.

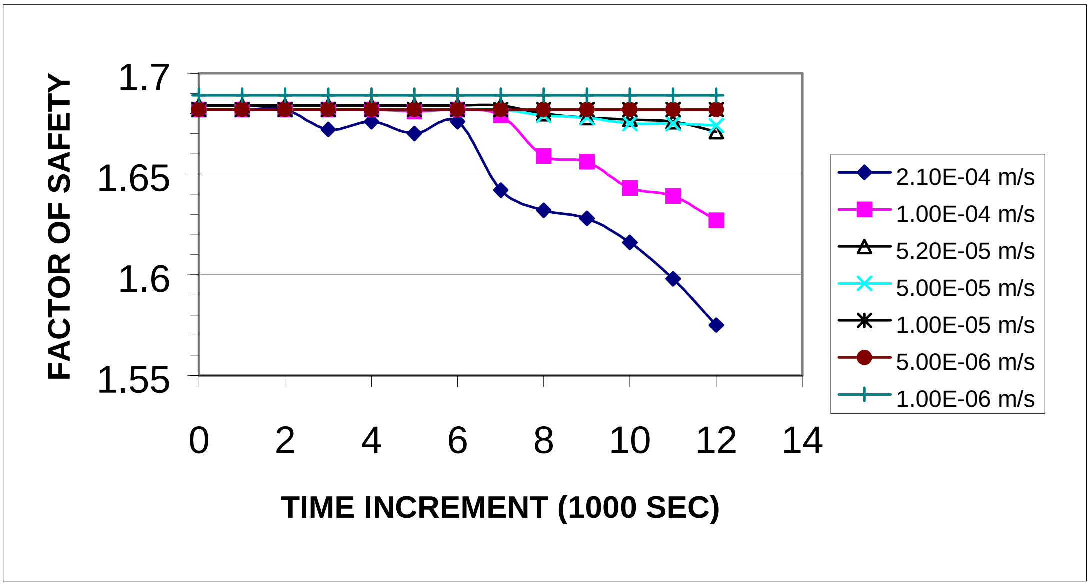


Figure 5.12 Effect of rainfall intensity on factor of safety.

CONCLUSIONS
&
RECOMMENDATIONS

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.0 INTRODUCTION

This chapter consists of the conclusions obtained from the study carried out and some recommendations for future research on slope stability studies.

6.1 CONCLUSIONS

The conclusion for this study can be divided into the following points: -

1) For any infiltration tests carried out, the infiltration rate decreases from an initially high (if the initial moisture content is low) infiltration rate to a steady state condition where the infiltration rate tends to become constant.

2) The sprinkling method gives better results on water infiltration on slope compared with the flooded method (Infiltrometer). For infiltrometer, the test was carried out on a small area which does not necessarily represent the simulated area. Furthermore, the water in the test pit is kept constant at 10cm, which does not happen naturally.

Besides, the infiltrometer method cannot study the effects of slope angles and water ponding of surface cover etc. on slope water infiltration. Infiltrometer can be used only for comparison purposes.

3) Different surface covers on slopes have a direct effect on the water infiltration. Of all the types of surface cover tested, grass cover gives the highest infiltration rate compared to others (bare and synthetic cover). Root system and the nature of water ponding by grass are the main reason for the high infiltration rate. Lanlock (artificial synthetic cover) gives least water infiltration. The fabric structure of the lanlock shields the soil surface from direct impact of the raindrops.

4) From the test carried out in the laboratory, water infiltration decreases with the slope steepness. The increment of water infiltration for the Lanlock cover is not significant. Water can easily flow under the cover in all conditions because the cover and the soil do not have a proper contact (the cover was only nailed at a few points on the model). As for grass covers the increment of water infiltration when the slope angle increases are significant because when the slope angle increases, the surface runoff increases significantly and reduces water from ponding back.

5) Water infiltration rates vary on slopes for weathered residual soils. Due to the

weathering process, the particle's distribution and sizes varies from one weathering grade to another. In the study carried out on weathered granitic residual soil, the weathering grade No. 4 gives the highest infiltration rate. The water infiltration increases from grade No. 6 to 4 and decreases from grade 4 to the lower grades.

6) Water infiltration increases with soil porosity and void ratio. High soil porosity or void ratios allow water to flow easily in the soil and ease the infiltration process.

7) Water infiltration decreases with the soil density. The higher the density, the lower the void ratio and porosity, thus the lower the water infiltration.

8) On slopes, the wetting front initially does not infiltrate parallel to the slopes. Water infiltration is more at the toe compared to the top. The longer the slope, the water has more time to travel on the slope surface and cause higher water infiltration especially down the slope. As time passes, the infiltration rate at the toe reduces (reaching steady state) and the infiltration rates at the top slowly catch up with the rate at the toe.

9) Grass cover is found to be a better cover to prevent erosion compared with artificial synthetic cover. In the field, the slope surface is not cut smoothly and evenly. For

Lanlock (artificial synthetic cover), there is no proper contact between the soil and fabrics. The water that is the main cause of soil erosion, can flow easily under the fabric and erode the soil away. The spacing between the nail during installation of Lanlock should be small to improve the contact with the soil.

10) When water infiltration rates have stabilized, the matric suctions of the soil do not necessarily reduce to zero. For some test carried out in the laboratory, the soil matric suctions at the depth of 50mm did not reach zero even when under four hours of continuous water sprinkling condition.

11) The factor of safety will drop lower for slope with higher ratio of permeability of permeable to impermeable stratum.

12) When perched water table formed, it decreases the factor of safety.

13) Cases with impermeable stratum dipping backward generally gives lower safety factor compares to cases with impermeable stratum dipping forward.

14) As the number of impermeable layer increases the safety factor drops. The drop in safety factor is rapid after a critical duration.

6.2 RECOMMENDATIONS

The recommendation can be divided into three main recommendations, i.e., “Future Investigation”, “Future Development of Apparatus” and “Recommendation on Slope Stability”.

6.2.1 FUTURE INVESTIGATION.

The following are recommended for future investigation of water infiltration on slopes: -

1) Water infiltration studies on slope using sprinkling method at the site: - This method will give a better model of water infiltration on slopes with factors that is difficult to simulate in the laboratory, i.e., undisturbed soil, uneven surfaces, uneven grass distribution etc.

2) The effects of vegetation growth on water infiltration: - The length and the density of the grass play an important role in water ponding effect. Besides, the effects of the vegetation roots on water infiltration with time can also be studied.

3) Water infiltration considering relicts, joints and faults on slopes.

6.2.2 FUTURE DEVELOPMENT OF APPARATUS

1) In the laboratory sprinkler model, the soil particles that were washed away with surface runoff were collected with a big tray equipped with a 63μm sieve to estimate the soil erosion. A proper collection tank is needed because the sieve is too small and the runoff is rapid.

2) The laboratory sprinkler model should be equipped with more small tips tensiometers to further study the water wetting front behavior during water infiltration.

3) It is recommended that in future a more flexible and adjustable water pump is used so that infiltration tests can be carried out in relation with various intensities of water being sprinkled onto the soil surface.

4) It is recommended that an automatic data acquisition system be fixed to the sprinkler model so that the infiltration test can be carried out for a longer duration.

6.2.3 RECOMMENDATION ON SLOPE STABILITY STUDIES

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

1) Most of the slope failures in Malaysia are rainfall-induced failure. Water infiltration and water seepage analysis should be considered during slope stability analysis in order to obtained a more accurate design.

2) During the seepage analysis, the water infiltration rates should be incorporated according to the weathering grades because with different combination of infiltration rates, it may cause perch water tables that may cause instability to slope (Subramaniam, 1996).

3) Grass is a better surface cover because it can reduce soil erosion tremendously. For any long-term slopes, it is recommended that they should be covered with grass. Artificial cover can be used but it is suggested that installation is carried out under close supervision (If the artificial cover were not installed properly, erosion can still take place under the cover).

4) Since infiltration rate increases with the length of slopes, it is recommended that slopes shall be divided into berms with proper berm drains to reduce water infiltration on slopes during rainfall.

5) For filled slopes, close supervision is needed to achieve the optimum dry density. The higher the density, the lower the porosity or void ratio and this directly reduce the water infiltration.

6) During construction, any soil bedding exposed on slopes that has very high infiltration rates should be covered to stop rainwater from infiltrating the slope. Weep holes is needed to drain water from the slopes.

7) Slopes should be checked and maintained periodically to make sure of the followings: -

   a) Grass is growing well - The grass on slopes should be maintained well because decayed roots of any dead grass or vegetation could form an abnormal water passage in soil. Combination of different vegetation (with different nutrients needs) is recommended on slopes. The vegetation mentioned should be self sustained by taking and providing nutrients to others on slopes. Deforesting should also be prevented near any slopes for the same reason.

   b) No cracks on berm drains - water can infiltrate easily through the cracks because during rainstorms, water is collected in the berm drain. Tension cracks also needs to be taken care of because it also increases the water infiltration.

c) Gully and piping - Gully, piping etc., should be repaired because all these will increase water infiltration and cause instability to slopes.

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LIST
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- “Parametric Studies of Slope Stability in Unsaturated Residual Soils” 13th South East Asian Geotechnical Conference, Taipei, Taiwan.

- Suction, Rainfall and Slope Stability”, the 7th JSPS-VCC Seminar on integrated Engineering”, Kuala Lumpur.

- “Water infiltration on Slopes”, The International Conference in Civil Engineering 1999 - World Engineering Congress, Kuala Lumpur.

- “Perched Water Table Consideration on Slope Stability”, The International Conference in Civil Engineering 1999 - World Engineering Congress, Kuala Lumpur.

- Soil Water Characteristics for Unsaturated Residual Soils”, The International Conference in Civil Engineering 1999 - World Engineering Congress, Kuala Lumpur.

- “Effects of Perched Water Table on Slope Stability in Unsaturated Residual Soils”, International Symposium on Slope Stability Engineering, Geotechnical and Geo-environmental Aspect, ISShikoku ’99, Matsuyama

Japan.

- “Suction and Infiltration Characteristics on Slope of Highly Heterogonous Residual Soil” Young Geotechnical Engineer Conference 2000, Southampton, United Kingdom. (Malaysia National Nominee and Southeast Asia Delegates).

- “The Role of Suction of Partially Saturated Residual Soils on Slope Stability” Malaysian Science and Technology Congress 2000.