MECHANISM OF PORE WATER PRESSURE AND GROUNDWATER FLUCTUATION IN SLOPE STABILITY UNDER HEAVY RAINFALL CONDITION

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ABSTRAK

Dalam kajian ini, model berasaskan fizikal telah digunakan dalam kerja ini untuk mengenal pasti pengaruh intensiti hujan yang berlebihan terhadap kestabilan cerun. Melombong pasir dari kawasan perlombongan di Kampung Kuala Trong, Taiping, Perak, adalah tanah yang digunakan dalam pemodelan fizikal. Parameter tanah yang membawa kepada kegagalan cerun dicirikan. Keamatan hujan ekstrem terpilih adalah berdasarkan penggunaan langsung. Daripada keamatan hujan yang dikenal pasti, Kandungan Air Isipadu dan Sedutan Matrik boleh diukur menggunakan model fizikal. Simulasi dijalankan dalam 2 kes dan parameter yang berbeza. Tempoh hujan simulasi ialah 6 jam. Trend keseluruhan ukuran sedutan matrik dalam setiap kes meningkat dengan beberapa pengecualian tensiometer yang menunjukkan nilai menurun. Selepas simulasi hujan berhenti, sedutan matrik menurun dengan cepat dan kekal bertakung diikuti dengan penurunan yang ketara dengan ketara. Bagi kandungan air isipadu, terdapat peningkatan yang sama dalam aliran semasa simulasi hujan. Walau bagaimanapun, terdapat perbezaan dari segi permulaan dan pertambahan kandungan air bagi bahagian cerun yang berbeza. bagi bahagian bawah cerun, kandungan air awal adalah jauh lebih tinggi iaitu pada 24 - 26 % dan semasa simulasi hujan ia meningkat sehingga 30 - 33 %. Manakala bagi bahagian atas adalah pada 20 -22 % dengan sedikit kenaikan semasa simulasi hujan iaitu meningkat kepada 23 - 26 %. Untuk semua kes, tiada kegagalan berlaku tetapi masih terdapat sedikit pergerakan tanah di cerun. Analisis berangka dilakukan untuk memodelkan kes dalam perisian GeoStudio. Untuk melihat faktor keselamatan dan menunjukkan peningkatan intensiti hujan akan menjejaskan faktor keselamatan kestabilan cerun.

ABSTRACT

In this study, physical-based model was used in this work to identify the influence of excessive rainfall intensity on the stability of a slope. Mining sand from a mining region in Kampung Kuala Trong, Taiping, Perak, is the soil used in the physical modelling. The parameter of the soil that lead to slope failure are characterized. Selected extreme rainfall intensity is based on direct adoption. From the identified rainfall intensity, Volumetric Water Content and Matric Suction can be measured using the physical model. The simulation is conducted in a 2 different cases and parameter. The duration of the simulated rainfall is 6-hour. The overall trend of the matric suction measurement in each case is increasing with a few exceptions of tensiometer that shows decreasing value. After the rain simulation stopped, the matric suction decreased rapidly and remain stagnant follow by a significant dropping significantly. For the volumetric water content, there is a similar increase in the trend during the rainfall simulation. However, there is difference in term of initial and increment of water content for different part of the slope. for the lower part of the slope, the initial water content is much higher which at 24 - 26 % and during the rainfall simulation it increase up to 30 - 33 %. While for the upper part are at 20 -22 % with a slight increment during the rainfall simulation which is increase to 23 - 26 %. For all cases there is no failure had been occurred but there are still have slightly soil movement of the slope. Numerical analysis is done to model the cases in GeoStudio software. To see the factor of safety and it shows that the increased in rainfall intensity would affect the factor of safety of the slope stability.

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LIST OF ABBREVIATIONS

AASTHO	American Association of State Highway and Transportation Officials
AEV	Air Entry
AF	Adjustment Factor
FEM	Finite Element Method
FOS	Factor Of Safety
LEM	Limit Equilibrium Method
LL	Liquid Limit
MC	Moisture Content
NEM	North East Monsoon
PI	Plasticity Index
PWP	Pore Water Pressure
SHC	Saturated Hydraulic Conductivity
SWCC	Soil-Water Characteristic Curve
SWM	South West Monsoon
TDR	Time Domain Reflectometer
TSM	Tensiometer
USCS	Unified Soil Classification System
VMC	Volumetric Water Content

LIST OF SYMBOLS

c	Cohesion
φ	Friction Angle
i	Gradient of Total Hydraulic Head.
k	Hydraulic Conductivity
S	Saturation
°	Slope Angle
q	Specific Discharge
G_S	Specific Gravity

CHAPTER 1

INTRODUCTION

1.1 Background

According to Directive 20 of the Malaysian National Security Council (MNSC) from 2003, the definition of a disaster is "a complicated emergency scenario that will result in the loss of lives, damage to property and the environment, and disrupt local social and economic activities" (Shaluf and Ahmadun, 2006). There are two different kinds of disasters: natural disasters and man-made disasters. Floods, landslides, and mudslides are all examples of natural disasters, which are catastrophic events that are caused by natural forces that are beyond the control of man. One of the natural disasters that is most likely to occur is a landslide, and it has been claimed that both the number of landslides and the number of injuries has increased between 1993 and 2019. (Majid, 2020). The movement downslope of a mass of rock, rubble, or dirt is what is referred to as a landslide. Gravity is the force responsible for this sort of mass wasting, which can be described as any downward movement of soil and rock. Thus, leading to changes in the morphology of slopes, as well as movement of groundwater, seepage, and earthquakes.

1.1.1 Climate in Malaysia

Malaysia is hot and humid all year due to its proximity to the equator and location in the tropical climate of Southeast Asia. Unlike other countries located far from the equator, Malaysia only has two seasons which are wet and dry. Southeast Monsoon (May-September) and Northeast Monsoon (October-November) are the two monsoon wind seasons in Malaysia (November-March). In comparison to the Southwest Monsoon, the Northeast Monsoon brings more rain. Several landslides have occurred during monsoon season as a result of excessive rainfall of up to 700 mm per month.

1.1.2 Rainfall-Induced Slope Failure

Slope failures occur when significant amounts of soil fall down a slope due to gravity. It happens when the slope's shear stress is greater than its shear strength. Slope failures continue to be popular from year after year in Malaysia. According to a Malaysian sectoral report, 49 landslides occurred, with 88 percent of them occurring on man-made slopes (JKR, 2009a, 2009b). Most of the landslides that have occurred in Malaysia's hilly areas have been triggered by slope cutting for development purposes. As a result, a combination of poor design and construction errors, geological factors, and inadequate maintenance contribute to the occurrence of landslides. Landslides have become more common during the monsoon season as a result of heavy rainfall, resulting in rainfall-induced slope failure(Mukhlisin et al., 2015).

Collapses on slopes caused by rainfall typically take the form of a shallow slope failure with slip surfaces that are parallel to the slope surface. The groundwater table will rise as a result of rainwater infiltrating the pores of the soil, which will lead to an increase in the soil's water content. This will be resulting in an increase in pore-water pressure and, as a direct consequence, a reduction in effective stress. Therefore, the shear strength of the soil and its capacity to sustain loading are both reduced. The soil mass will slip, and the slope will fail when the shear strength mobilised at a crucial slip surface is no longer sufficient to withstand the shear stress (Chen et al., 2004). Changes in rainfall patterns may impact flux boundary conditions such as infiltration and evapotranspiration, resulting in changes in soil water pressure.

1.2 Problem Statement

Extreme rainfall intensity has a variety of adverse consequences on the soil. One of the positive impacts is that the soil becomes fertile. However, too much rain can erode the soil's strength which leading to landslides. The focus of this research is to determine how extreme rainfall intensity can affect the ground condition in terms of rainfall intensity, pore water pressure, groundwater condition, and other factors when a slope fails.

The characterisation of rainfall in cases of slope failure caused by rainfall varies according to the cases that are considered to have the most significant contributing element. The antecedent rainfall, the precedent rainfall, the duration it precipitated, and the amount of rain that fell are the controlling factors that produce slope failure caused by rainfall (Mukhlisin et al., 2015). However, research conducted by Kristo and colleagues in 2017 found that the variance in the intensity of rainfall has a substantial association with the stability of slopes. The increasing trend of rainfall intensity has been demonstrating a nearly linear association with the decline in the slope's stability. This relationship has been showing itself more and more as time goes on. In addition to this, the process by which the slope fails can change depending on the amount of rainfall that has occurred (Tohari et al., 2007). Therefore, the pore water pressure and groundwater fluctuation of the rainfall intensity would be causing distinct failure mechanisms, and there would be a certain prognosis of a linear relationship between increasing rainfall intensity and the decline of slope stabilities.

1.3 Objectives

To pursue the aim, the consequent objectives of this research were as follows.

1. To determine the parameter of the soil that lead to slope failure under unsaturated condition.
2. To assess the changes in groundwater level and pore water pressure during heavy rainfall in physical model.

3. To evaluate the changes in slope stability under unsaturated condition using limit equilibrium method.

1.4 Scope of Work and Limitations

In the context of this study, the primary focus of the work is on developing a physical model of the slope stability that is subjected to rainfall intensity. In the physical modelling, the rainfall intensity that was utilised was 60 mm/hr and 80 mm/hr, and the slope inclination that was used was 40 degree. It will have two cases to conduct, and it will only use a few measurement tools to collect the results. Aside from that, it focused on numerical analysis utilising the GeoStudio software, in which the same rainfall intensities and slope inclinations would be used.

There are several limitations in order to do this study. Firstly, the 2 mm sand sieve size need to handle carefully from mix with other size. If the sand mix with other soil it will disturb the result and reduce the result's accuracy. Other than that, tensiometer need to calibrate properly which need remove all the bubble inside the tensiometer to make sure the result accurate. It is also heavy work load that because need to handle the huge amount of sand.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Concerns have been raised about the impact that human activities may be having on the climate system as a result of an observed rise in both the frequency and intensity of extreme rainfall events. It is generally agreed in the study that one of the most significant effects of global warming will be an increase in the frequency as well as the intensity of extreme rainfall events. (Cheng et al. 2012). Extreme precipitation over a short period of time or consistent precipitation over a long period of time can commonly be the root cause of devastating floods, creating potentially dangerous conditions. The Peninsular Malaysia region is subject to unpredictable rainstorms that can cause extensive property damage and run up repair bills in the millions of Malaysian ringgits. The increased severity of rainfall in recent years is likely to blame for the recent uptick in the lot of incidents of massive flooding, including both flash floods and landslides. As a result of land development and other human activities, natural disasters such as landslides and other types of ground movement-related losses are becoming more severe. According to Mokhtar (2006), rainfall and the activities associated with storm water are the primary causes of slope collapse and landslides at a number of sites in the development of Malaysian hillside areas. Annual rainfall in Malaysia can be as high as 4500 mm (Rahman, 2017). This, along with year-round high temperatures, results in strong chemical weathering and the production of thick residual soil profiles that can exceed 100 metres in depth in some spots. Landslides are one of Malaysia's most destructive natural catastrophes due to the combination of these climate and geological variables, as well as other causative elements (Bujang et al., 2008).

The most common type of slope failure which cause by extreme rainfall are called as rainfall-induced slope failure. Rainwater infiltrates into the unsaturated zone of the soil slope, reducing matric suction and, as a result, soil shear strength, resulting in slope failures (Rahimi et al., 2011). According to (Zhang et al., 2005) the stability of a soil slope during a downpour is affected by both hydraulic and shear strength qualities of unsaturated soils. Uncertainties in hydraulic property parameters for unsaturated soils and their consequences on slope reliability under rainy conditions are vital to understand.

2.2 Rainfall-Induced Slope Failure

Rainwater has been recognised as one of the primary reasons for slope failures in locations that receive a significant amount of annual precipitation. The stability of slopes is a significant aspect of management, and it is typically the factor that is either the most important safety concern or the most essential component of many civil engineering projects (Azmi et al., 2019). According to Rahimi et al. (2011), slope collapse is a type of natural disaster that can take place in a number of different locations throughout the world. Rainfall is the most well-known source of this disaster, particularly in tropical regions where the temperature is hot and humid. Rainfall is the most common cause of this disaster. The effect of rainfall on the triggering of slope collapses is mainly linked to the loss of matric suction as the wetting front advances from the ground surface or the rise in the ground water table within the slope. It's also possible that both processes happen at the same time. Rainfall-induced slope failures are widespread in tropical places with residual soils, such as Singapore.(Kristo et al., 2017)

Occasionally, rainfall triggered slope failures result in debris that travels a great distance on the sloping land underneath the source of the waste (Dai et al., 1999). The increase in pore water pressure that results from infiltration and near-surface flow causes the stress path to move almost horizontally until it comes into contact with a failure envelope, which ultimately leads to the collapse of the slope. When the soil is loose condition, a debris flow can be mobilised, and when significant shear stresses are present, a rapid loss of strength can occur, which is connected with an undrained collapse (Renaud *et al.*, no date). In the literature, the mechanism by which a rain-induced slide might transform into a debris flow is not well understood. In order to model the transition from slide to flow, geo-mechanical modelling should be used that incorporates existing findings about strain-softening soils (Potts et al., 1997). Furthermore, additional experimental studies are required in order to verify the hypothetical failure mechanisms and provide a rational approach to analysing rainfall-induced landslides in both the failure and post-failure stages. (Zhang et al., 2011)

2.2.1 Rainfall Characteristic

The ratio of the total amount of rain that falls during a certain period (measured in terms of rainfall depth) to the amount of time that the given period lasts is the definition of rainfall intensity. It is typically written as millimetres per hour (mm/h), which is an abbreviation for the depth units per unit time.

2.2.2 Rainfall Infiltration

Infiltration is the term given to the process by which water travels from the surface of the soil down into the subsoil below. The gravitational force and the capillary action of the soil particles work together to direct this movement. The surface of the earth is the very first point at which water makes contact with the earth.

In the event that there is a moisture deficit in the soil, the infiltrated water will first come into contact with it. After that, the excess water will continue to flow vertically downward until it reaches the groundwater table as a source of replenishment water. It is a measure of how quickly the soil can take in water from precipitation or irrigation. The rate is reduced as the soil goes from being partially wet to being entirely saturated as the infiltration process continues. If the amount of precipitation that falls in a certain time period is more than the amount of water that can be absorbed by the soil in that time period, runoff is likely to occur.(Abdullahi and Garba, 2016)

As rainfall infiltrates the slope, the level of slope safety changes. It causes a rise in pore-water pressure. There is no conventional slope design methodology that takes into account the impacts of rainfall infiltration at this time. The surface water table condition is suggested in the present slope design specification to prevent slope failures in the event of rainfall. However, unless the slope is highly permeable and has an originally high water-table, the surface water-table state is irrelevant to the current situation, in which just the surface of the slope becomes saturated. If the infiltrated rainfall reaches the critical depth, the slope will fail. The majority of these failures are shallow or surface type. As a result, the matric suction and water content inside the slopes have been identified as the most essential soil variables directly associated to the slope's instability in this form of collapse (Lee et al., 2009)

It is believed that rainwater infiltration is the cause of slope failure because it reduces the matric suction in unsaturated soils, resulting in a decrease in the soil's shear strength. Because of this, having a grasp of the groundwater regime is essential for determining the stability of slopes and for predicting conditions on slopes that are likely to be affected by landslides caused by water infiltration. In addition, once the present condition of the subsoil has been evaluated, the stability conditions of the slope may be estimated with the use of a simple infinite slope model, which will deliver continually updated information regarding the slope's current level of safety (Pirone et al., 2015)

2.2.3 Changes in Groundwater Level

From Abdullahi and Garba, 2016 research paper state that groundwater is the term used to describe water that is located deep within the earth. When water seeps or infiltrates into the ground as a result of precipitation or melting snow, the process starts. The amount of water that seeps into the ground varies dramatically from one region to the next since there are so many different types of land surfaces. Groundwater has been shown to be the cleanest kind of water in the world, and it also offers humanity countless natural resources at the most affordable prices. It continuously moves over a long distance in the aquifers through the pore spaces in the rock and the rock cracks. In this study, monthly measurements of the water table's fluctuation were taken, and the results of the analysis revealed that both rainfall runoff and infiltration play a role in the process of recharging the water table. According to the findings of this research project, the variation in the level of groundwater is strongly dependent on the pattern of rainfall. Also demonstrates that there is a downward trend in the water table when it rains decreasingly until it starts to rain heavily again.

One of the causes that can cause slope failure is a rise in groundwater level in the slope due to heavy rainfall. As the groundwater level rises, the pore water pressure rises, reducing the soil's shear resistance. In order to evaluate the changes in groundwater level, it is necessary to first estimate the distribution of pore water pressure in the slope and then conduct an unsaturated-saturated seepage flow analysis. In the end, stability analysis was utilized to assess the degree of variation in the factor of safety for the slope based on the results of the seepage flow. (Ng et al., 2020)

2.2.4 Unsaturated Zone

The formation of residual soils, which are frequently seen in unsaturated circumstances, is a result of the tropical climate (Rahimi et al., 2011). Rainwater infiltrates into the unsaturated zone of the soil slope, reducing matric suction and, as a result, soil shear strength, resulting in slope failures (L. L. Zhang et al., 2011). Suction decrease and associated volumetric collapse may be implicated in the failure process in unsaturated loose soils (Olivares and Picarelli, 2003). Localized transient pore water pressures caused by specific hydraulic boundary conditions could also serve as a trigger for the shift from slide to flow. Static liquefaction is unlikely to occur if the soil is unsaturated and the depth to bedrock is large, according to experimental findings from centrifuge model experiments (Zhang et al., 2011)

2.2.5 Soil Water Characteristic Curve (SWCC)

The relationship between soil water suction and soil water content is represented by the soil-water characteristic curve (SWCC). Gravimetric water content is the most common kind of water content utilized when soil water suction is first determined. However, volumetric water content is the most generally used type of water content when it is published (Houston et al., 1999)(Zapata *et al.*, no date). The degree of saturation, S, is occasionally employed as a water content indicator for the SWCC. The matric suction is commonly employed for the SWCC, but total suction is occasionally used as well. Unsaturated soils' shear strength, volume change, and fluid flow properties are all affected by the SWCC.

To estimate soil suction for use in calculating the state variable, the SWCC is frequently used with the water content. As a result of the uncertainty in the SWCC relationship, there is a wide range of predictions for unsaturated soil behavior. Suction is not commonly studied in geotechnical laboratories or in the field, despite its well-known relevance (Zapata *et al.*, no date). As part of the current study, a review of practice in the United States revealed that only around 20% of commercial geotechnical laboratories do suction measurements on a regular basis (Zapata, C., 1999).

Several approaches for estimating the SWCC have already been proposed based on (Fredlund et al., 2002). The following are three broad groups of estimate techniques:

(i) Statistical estimates of water contents at various soil suctions (Gupta and Larson 1979),

(ii) Estimation of soil parameters for an algebraic function describing the SWCC (Rawls and Brakensiek 1985, 1989; Vereecken et al. 1989; Scheinost et al. 1997), and

(iii) Physico-empirical models in which the grain-size distribution curve is used in the prediction of the SWCC data (Arya and Paris 1981; Arya et al. 1999; Tyler and Wheatcraft 1989; Fredlund et al. 1997).

The physical meaning of SWCC characteristics can be applied as equation parameters. SWCCs are represented on an arithmetic scale in terms of degree of saturation, S. There have been proposed flexible mathematical representations for both unimodal and bimodal soil-water characteristic curves. Unimodal SWCC is designed for materials with a normal grain size distribution, whereas Bimodal SWCC is designed for materials with a gap-graded size distribution **(**Fredlund et al., 2004). The proposed equations are defined by physical characteristics that are not related to the geometric aspects of the SWCC in any way. The suggested equations' fitting capability was demonstrated using parametric analyses and fitting to experimental data sets, with good results.

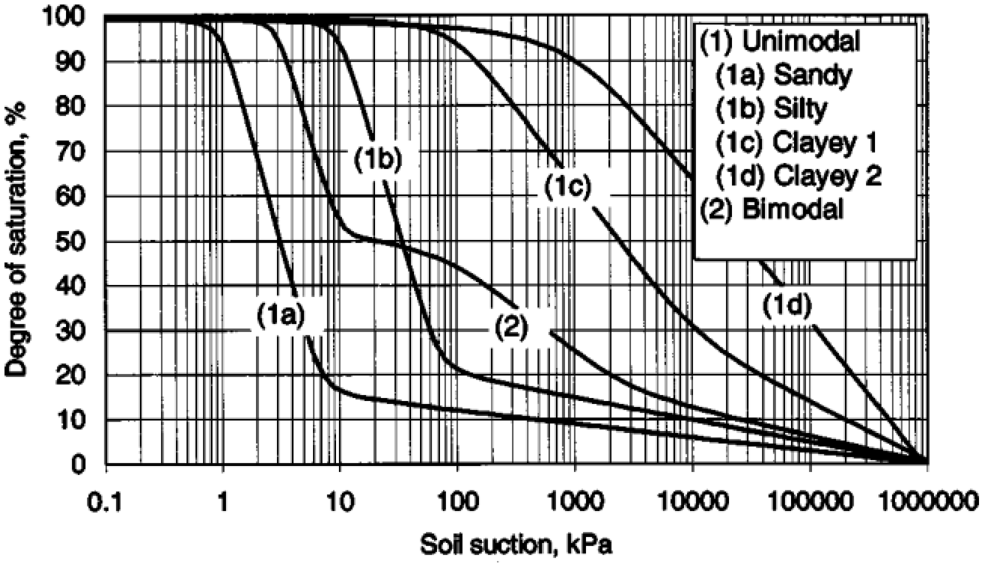

Figure 2.1: Soil-water characteristic curves conceptualizations for various soil textures. (Gitirana Jr and Fredlund, no date)

2.3 Physical Modelling

A physical model is used to represent and regulate the parameter and characterise the variable when determining slope stability. It's utilised to recreate the site's state in a controlled setting, ensuring the outcome. In previous studies, a few different types of slope physical models were used. To study the failure mechanism, (Chueasamat *et al.*, 2018) conducted experimental testing utilising slope models. Take et al. (2004), Kaneko et al. (2010), and Kohgo et al. (2011) used physical 1g slope models in their experiments, while Take et al. (2004), Kaneko et al. (2010), and Kohgo et al. (2011) used centrifuge slope models. During the 1g slope failure experimental tests, Yagi and Yatabe (1987) observed the PWPs, displacements, and shear strains. A series of experimental tests utilising 1g physical slope models were done to evaluate the effect of the surface sand layer density and rainfall intensity on slope failure due to rainfall. The structure of the 1g slope model was comparable to that of typical natural slopes that are prone to failure, with a permeable residual layer on top of a rather hard foundation. The physical slope model in this study consists of a hard-packed silt (DL clay) foundation and a surface sand

(Kasumigaura sand) layer. During the experimental testing, both negative and positive pore water pressures, as well as slope displacements, were measured. Depending on the rainfall intensity and the density of the surface sand layer, two forms of failure were observed: surface sliding failure and retrogressive failure. The slope failure mechanism, the behaviour of pore water pressures (PWP), and the slope displacements have all been observed through experimental tests utilising physical models.

Rainfall is a major contributor to slope failures all throughout the world (Wu et al., 2015). The purpose of this paper is to describe a series of physical tests that were carried out to replicate rain-induced slope failures. The tests looked at two scenarios: (1) rainwater penetration into the slope and (2) simulated rainfall-induced slope failures with varying initial conditions. Slope deformation and failures were recorded, and the experimental results were used to interpret possible processes. The slope model experiments were designed to investigate the mechanisms of rainfall infiltration and slope failure, as well as the effects of various factors on landslides. It was investigated and tested how elements such as soil moisture, pore-water pressure, and matric suction in the slope affected landslide formation during rainfall. The rainfall test began after the model slope was completed, with a given rainfall intensity. During the rainfall test, the pore-water pressures and water contents in the model slope were automatically recorded. Rainfall intensity has a significant impact on slope seepage characteristics of slope collapse, according to model experiments. The loss of matric suction and the advance of the wetting front might cause slope failures (Zhang et al. 2011; Li et al. 2013). In worn soils, the suction range of the wetting front has a considerable impact on slope stability (Kim et al. 2004). The crucial rainfall pattern is determined in part by the ratio of rainfall intensity to soil saturation permeability (Lee et al., 2009)

2.3.1 Slope Geometry

The occurrence of flow slides is also influenced by slope geometry. Therefore, one of the parameters to consider in the physical modelling of the effect of rainfall on slope stability is the slope inclination angle. From Egeli and Pulat, 2011 studies, if the degree of relative compaction increases, the Factor of Safety (FOS) for the slope stability increases. Small slope angles, such as = 15°, have a smaller increase (i.e. the average line's slope is flatter than tan = 0.8), whereas higher slope angles, such as = 25°, have a larger increase (i.e. the average line's slope is steeper than tan = 1.05). It should be noticed that at the upper end of the slope, all 35° slope models have failed due to translational failure. When FOS 1, all 35° slopes failed due to translational failure, with reported motions ranging from 3–5 cm. When FOS > 1 for the other slopes (15°, 25°), no failures were found. Besides, FOS increase with increasing relative degrees of compaction (in percent) and reduced with increasing slope angle (in °) for all slopes studied. As a result, the lowest angle needed to show the slope failure during physical modelling is 35 degrees.

2.4 Numerical Analysis in GeoStudio

With the advancement of numerical methods and digital computers, the validity of limit equilibrium methods has steadily gained attention. In several research, stress-strain relationships have been successfully applied to the investigation of slope stability. However, in the study of slope stability, the use of determinants of safety against local failures has received little attention. The authors describe a local minimal factor-of-safety method for slope stability analysis in this work. An alternate way to studying slope stability is to examine the soil stress-strain relationship in conjunction with the failure criterion. Various assumptions of the limit equilibrium solutions, such as the location and geometry of the slip surface, constant shear stress distribution along an assumed surface, and nature of side forces between slices, are not required with the suggested method (Huang and Yamasaki, no date). There is a few software programmed that use different mathematical methods to solve difficult calculations in slope stability and seepage analysis. Although the Finite Element Method (FEM) or Numerical Analysis is the most widely used, there are a few other methods such as the Limit Equilibrium Method (LEM), Limit Analysis, Probabilistic Method, Variation Method, and others. (Batali and Andreea, 2016)

2.4.1 Numerical using GeoStudio

According to (Raj and Sengupta, 2014) study, GEO-STUDIO 2007 is used as an element program. There are seven modules in the program. The first three modules, known as SEEP/W, SLOPE/W, and SIGMA/W, are used to investigate the Malda embankment's behavior. In numerical analyses, the soil embankment is discretized using typical two-dimensional quadrilateral and triangular elements. For embankment soil, a relationship between soil–water content and matric suction is established. It is then used in coupled evaluations of seepage and slope stability to estimate the embankment's performance under various rainfall intensities and durations. The FE code Geo-Studio is used to run the numerical simulations.

The initial conditions of the pore-water pressures are derived by transient seepage analysis using the SEEP/W program before the embankment stability analyses. The transient analysis result is then transferred into the stability analysis model. Under a certain intensity and period of rainfall, the negative pore-water pressure distribution within the embankment is computed. A steady state analysis is performed before the transient seepage study to achieve a hydrostatic condition within the embankment and foundation. The infiltration rate is calculated by dividing the amount of rainfall in an event by the whole duration of the rainfall event and then applied to the slope boundary as a surface flux in transient assessments. The SEEP/W transient analysis programmed is based on the assumption that water flows through both saturated and unsaturated soil according to Darcy's law, which states:

$$q = ki \tag{2.1}$$

where,

q = specific discharge

k = hydraulic conductivity

i = gradient of total hydraulic head.

Water flow across unsaturated material is also regulated by Darcy's law. The sole difference is that in unsaturated flow, hydraulic conductivity no longer remains constant, but varies with changes in water content and, indirectly, with variations in pore-water pressure. When suction pressures occur or pore-water pressures are negative, the SLOPE/W programme considers unsaturated shear strength conditions. The GeoStudio tool allows to model the increase in shear strength caused by soil suction in two different methods. The numerical analyses predict that suction pressure has a significant impact on the stability of an embankment slope. With the lowering of soil suction, the slope may become potentially unstable. Suction pressure in the soil drops during rain infiltration, and thus the effective shear strength of a slope diminishes, lowering the factor of safety (Raj & Sengupta, 2014)

CHAPTER 3

METHODOLOGY

3.1 Overview

Using physical based modelling and numerical analysis, this study focused on the impact of extreme rainfall intensity on unsaturated slope stability. The procedures for data analysis, physical modelling analysis, and numerical analysis of rainfall-induced slope failure due excessive rainfall intensity are described in this chapter. The method that would be used to determine the effect of extreme rainfall intensity on the slope would be physical modelling. The physical modelling simulations would be done with various slope angles and rainfall intensities. During the simulation, measurements of volumetric water content and matric suction would be used in the numerical analysis of slope stability. Furthermore, soil characterisation tests such as particle size distribution, soil water characteristic curve, direct shear test, and permeability test will be used to evaluate soil characteristics in the numerical analysis. The numerical analysis will be used to determine seepage qualities and slope stability. It's also to draw a comparison between the results of the physical modelling. Figure 3.1 shows a flowchart outlining the steps involved in this study.

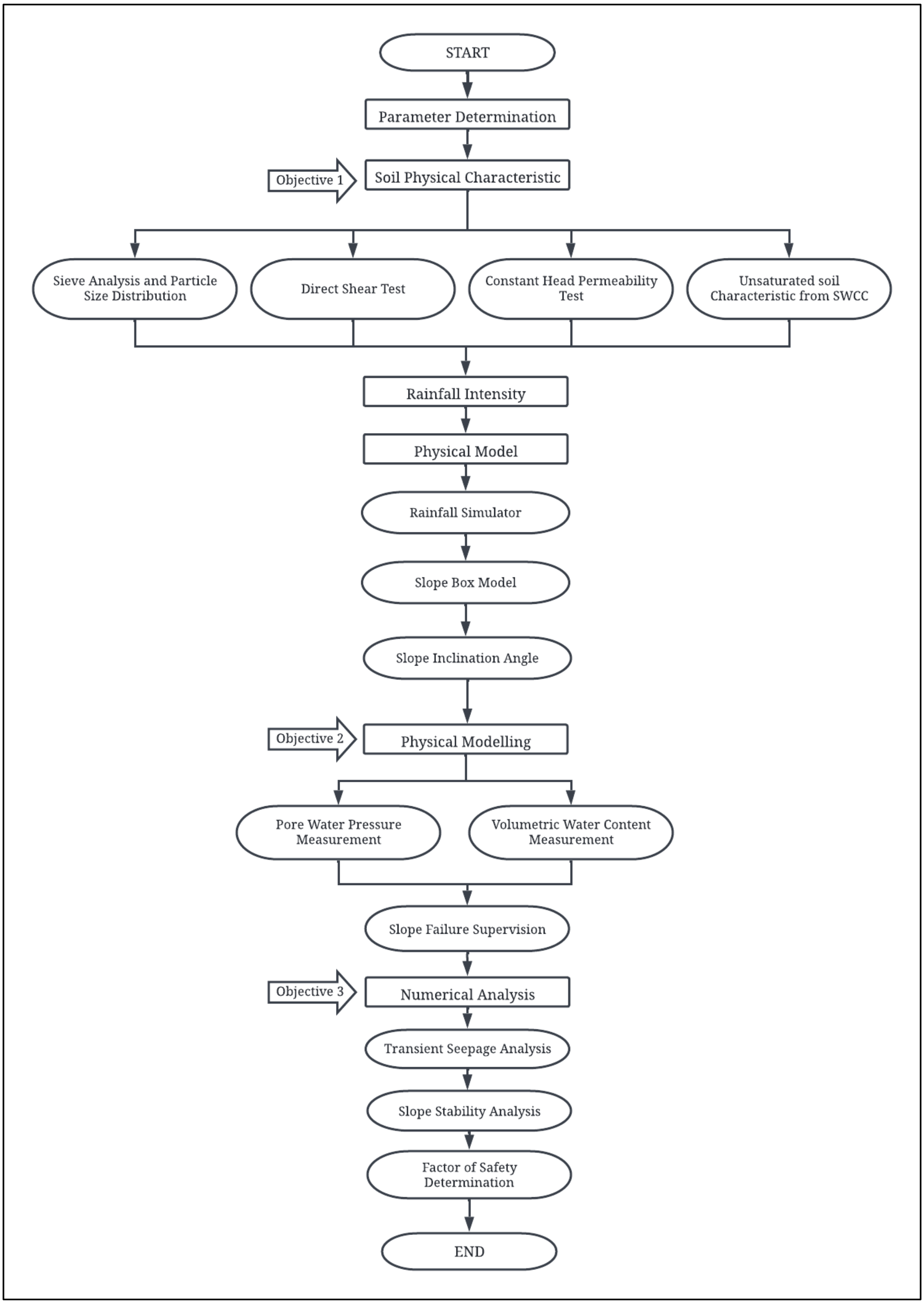

Figure 3.1: Research process in flowchart

3.2 Soil Physical Characterization

Mining sand from a mining region in Kampung Kuala Trong, Taiping, Perak, is the soil used in the physical modelling. As a disturbed sample, a sample is taken at 0.5 metre depth from the surface of the soil. Only the sand that passes the 3.35 mm sieve and retains at the 2 mm sieve is used in the model. All of the data about the soil's physical characteristics originates by this source (Azmi et al., 2019). A number of soil physical characterization tests must be carried out in order to determine the soil's physical characteristics.

Physical Characterization test:

- Particle Size Distribution
- Soil Water Characteristic Curve
- Permeability Test (Constant Head Permeability Test)
- Direct Shear Test

3.2.1 Particle Size Distribution

The term "particle size distribution" refers to an index (means of expression) that indicates which particle sizes are present in what proportions (relative particle amount as a percentage of total particle amount) in the sample particle group to be assessed. The particle distribution or sieve analysis allow others to perceive the soil properties depending on the content of the given mass proportion. The engineering property of the soil is usually governed by the most dominating or highest by mass proportion. Cleaning a 2 mm sand sample is the first step in the sieve analysis process. The sample is washed to remove silt and clay particles, then the sand samples are dry for 24 hours and a 2 kg sample is weighed. After that, the sand sample is sieved using the following sieve sizes: 14 mm, 10 mm, 6.3 mm, 5 mm, 3.35 mm, 2 mm, 1.18 mm, 600 µm, 425 µm, 300 µm, 212 µm, 150 µm, 63 µm, and pan accordingly. The sieve then will be place on the automatic shaking for approximately 15 minutes. Every sieve's retained material was weighed.

3.2.2 Soil Water Characteristic Curve (SWCC)

The relationship between matric suction and water content is known as the soil water characteristic curve (SWCC). It is used to estimate soil water storage and determine the hydraulic and mechanical behaviour of unsaturated soils (M Azmi et al 2019). The matric suction and volumetric water content are the state variables in the SWCC. The SWCC could give unsaturated soil characteristics such as unsaturated shear strength and unsaturated soil permeability. The Fredlund-Xing-Huang equation is used in Geostudio software to estimate the hydraulic function. For estimating the unsaturated permeability function, the Fredlund–Xing–Huang permeability function provides a flexible integration technique (F. Zhang and Fredlund, no date). The SWCC is significant in numerical seepage and slope stability analysis. From the Geostudio the estimated SWCC and hydraulic conductivity function for this research is shown in Figure 3.2 and Figure 3.3 respectively.

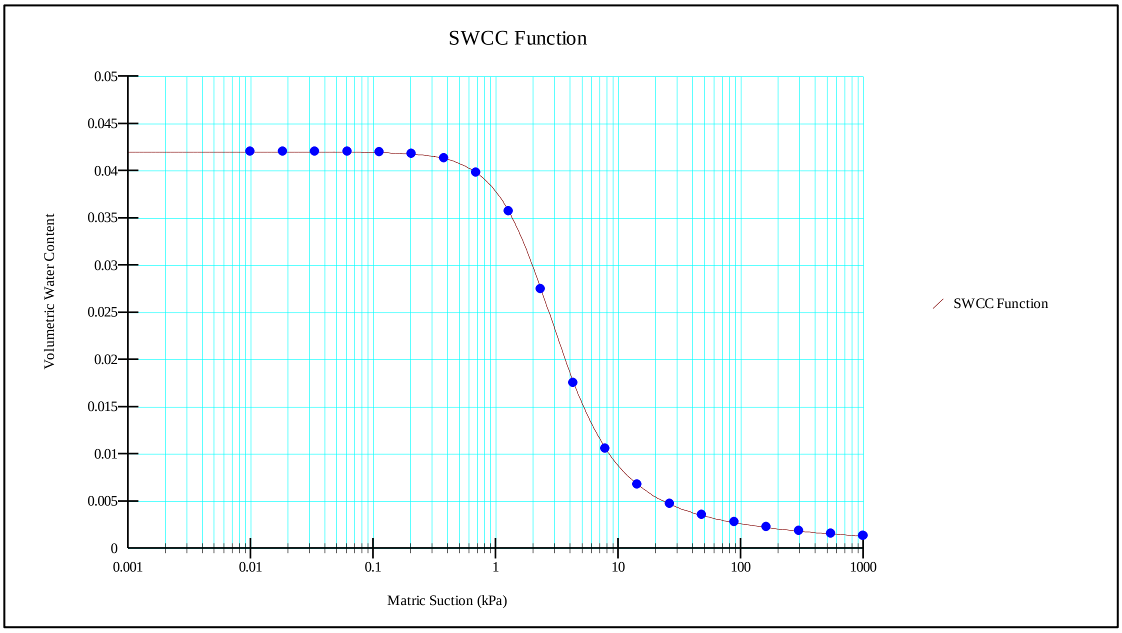

Figure 3.2: Estimated SWCC used for Numerical Analysis in GeoStudio

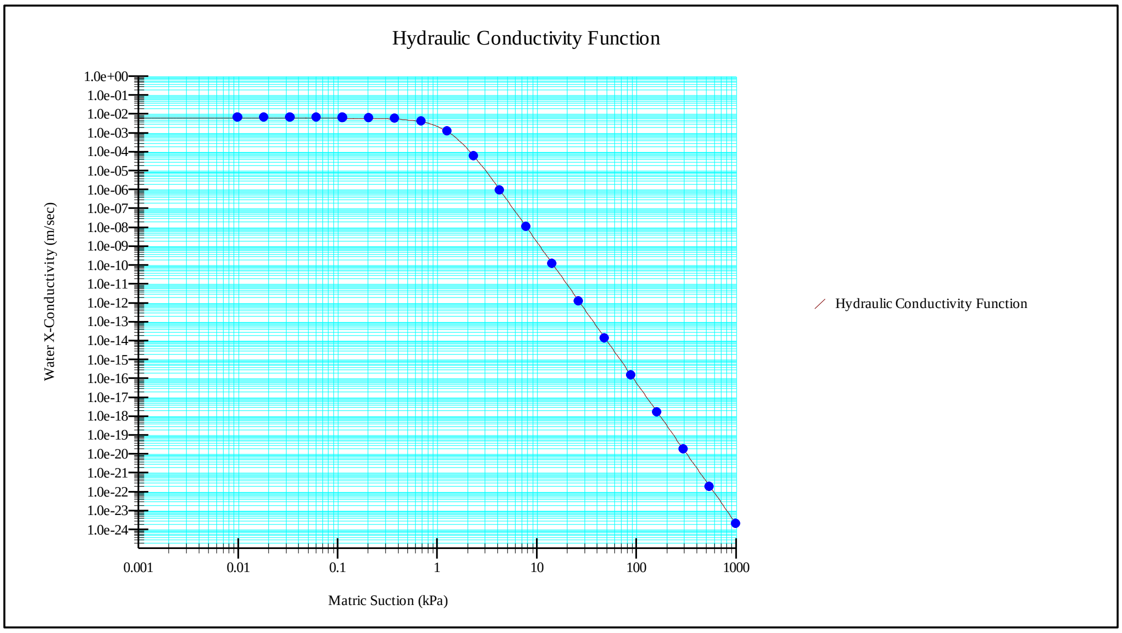

Figure 3.3: Estimated Hydraulic Conductivity Function in GeoStudio

3.2.3 Permeability Test

The rate at which water moves through soil materials is referred to as the hydraulic conductivity or permeability of the soil. Water can easily pass through soil gaps, but other elements including the hydraulic gradient, soil type, texture, and particle size distribution also have an impact on permeability. Testing for soil permeability is done either using a falling head test or a constant head test. Constant head test describes a device that maintains the same relative elevation of the water column's top (head pressure) over the sample during the test. A variety of soil types, including sand and gravel, as well as clay, can be tested using this device. While the Falling Head Test permits the head to shrink when water penetrates into the sample, resulting in a reduced total pressure during the test. In most cases, the falling head technique can be utilised with just the finest-grained soils. The Constant Head Test would be utilised for this investigation because sands were used as the sample.

The saturated coarse-grained soil k coefficient of hydraulic conductivity is measured using the constant head permeability test. An assessment of a soil's ability to transfer water when subjected to a hydraulic gradient is known as its hydraulic conductivity (K). Saturated soil pores allow water to pass through them easily. Coarser-grained soils have higher hydraulic conductivity at high volumetric moisture content levels, while finer-grained soils have lower hydraulic conductivity. Coarse-grained soils lose hydraulic conductivity more quickly than fine-grained soils as moisture content decreases. Soil and fluid characteristics both influence saturated hydraulic conductivity (SHC). The soil pore geometry, fluid viscosity, and density all play a significant role. The constant head permeability test has the advantage of being a simple and direct test to perform. Small-scale measurements of the hydraulic conductivity k of coarse-grained soils are only possible using this method. This test typically measures k values between 10−1 to 10−6 m/s.

The test will be test used 2 mm of dry sand and tested for 3 set of the test. Firstly, start by preparing the apparatus and measure the length and diameter of the specimen to get the area of the specimen. Then weigh the permeameter cell and permeameter cell with the soil. Then the test can be tested and record the H1, H2 and time collection for 5 times to get the average. This test is tested for 3 times with the same sample to get the average of the k value in order to increase the accuracy of the result.

3.2.4 Direct Shear Test

In contrast to other materials, such as concrete or metals, failure in soils typically takes place on a particular surface (shear plane). Failure takes place whenever the shear stress, which is acting parallel to that surface, is greater than the shear strength. When a body is subjected to shear stress, the resulting deformation is referred to as shear strain. This phrase is used to describe the deformation. In direct shear tests, the amount of shear strain is measured by determining the displacement that occurs between the two parts of the soil specimen. The shear strength of a soil can be evaluated with the help of a direct shear test, which consists of forcing the soil to shear at a consistent rate along a horizontal line of weakness.

The cohesion (c) and friction angle (φ) are two important strength metrics that can be determined by doing a direct shear test. Figure 3.5 shows the results as a relationship between shear strength and the amount of effective normal stress. Additionally, there are a few benefits to adopting direct shear strength. The testing technique is simple, the specimens are small, and practically any soil type may be analyzed, making it a useful tool for researchers. The sample that used in this test is 2 mm of dry sand and this test also tested for three times using the same sample in order to get the best result.

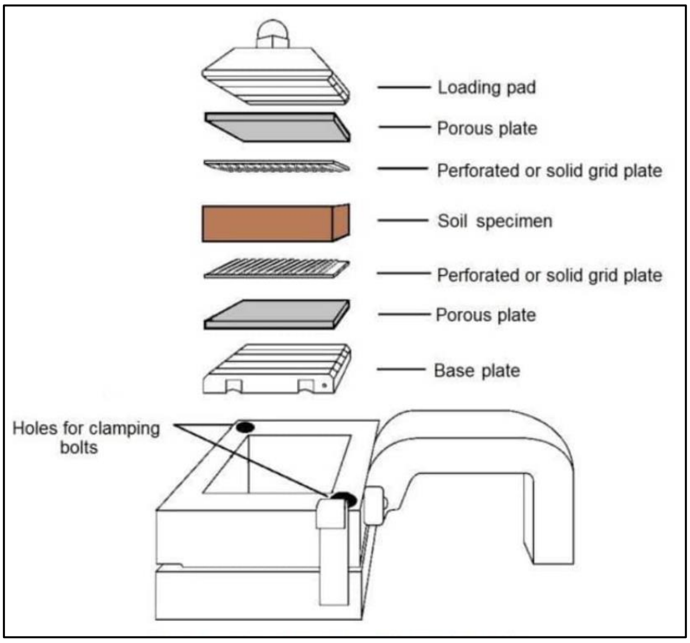

Figure 3.4: Shear Box (Vjtech.co.uk, 2018)

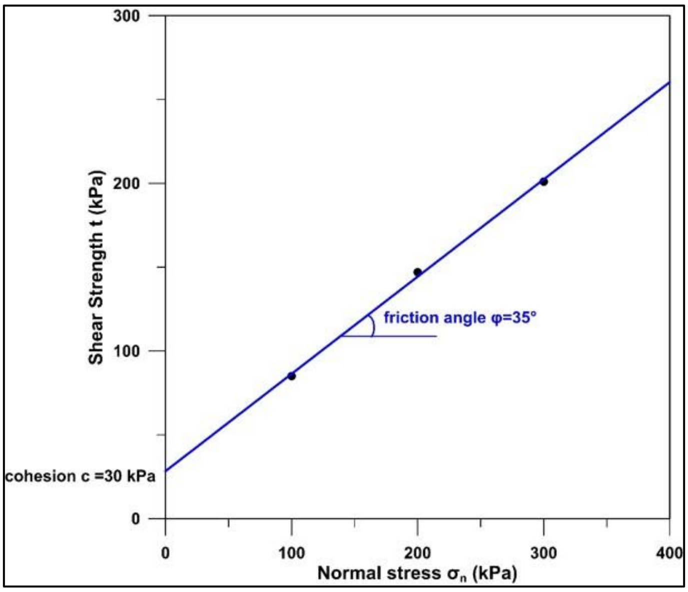

Figure 3.5: Relationship between shear strength and the amount of effective normal stress (Geoengineer.org, 2014)

3.3 Physical Model

A physical model is created and constructed to simulate the rainfall and sand slope model in the laboratory. The model box, water circulation system, and rainfall simulator are the main setup of the physical model created.

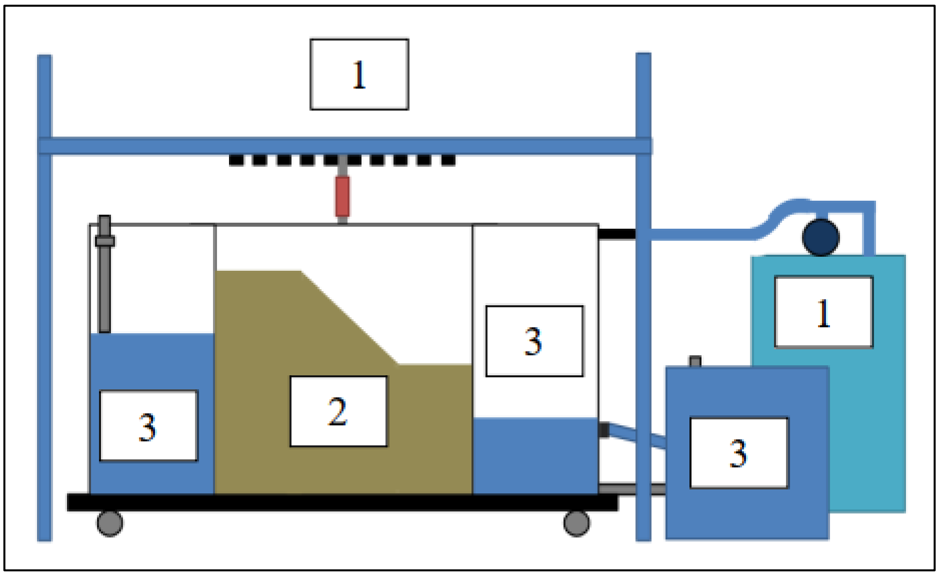

Figure 3.6: (1) Rainfall Simulator, (2) Sand Slope Model, (3) Water Circulation System