

Application of Multi-Walled Carbon Nanotubes in Slope Stabilization

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Declaration

I hereby affirm that the thesis titled "Application of multi-walled carbon nanotubes in slope stabilization" is an original work of mine, and that all citations and quotations have been properly cited. I certify that, this proposal has not been previously submitted to any university or any other national or international institution, in its entirety or in part.

ABSTRACT

Landslides are a common phenomenon that every year causes economic and human losses around the world. It emerges in various geographical places worldwide because of diverse natural circumstances and triggering mechanisms, including precipitation, seismic events, and anthropogenic interventions. In the conventional methods, slopes are stabilized using different methods including application of lime, cement, and fly ash. However, each of these materials has their own shortages. In this study, the application of multi-walled carbon nanotubes (MWCNT) is investigated for slope stabilization. Extensive tests are conducted in the laboratory to obtain the index properties, compaction, soil water characteristics curve and unsaturated permeability of the soil for both scenarios of soil with and without MWCNT. Liquid limit and plastic limit of soil stabilized with MWCNT increased compared to soil without multi-walled carbon nanotubes and plasticity index decreased. The result from SWCC demonstrates that saturated volumetric water content and air entry value of the soil with MWCNT has increased compared to soil without MWCNT. The result from unsaturated permeability test demonstrated that the unsaturated permeability of soil stabilized with MWCNT has decreased.

Different sets of numerical analysis were conducted using Seep/W and Slope/W to analyze the seepage and safety factor of slope with and without MWCNTs. The result from Seep/W analysis shows that the pore water pressure (PWP) in the slope without carbon nanotube is lower than PWP in the slope with MWCNT in the surface area. Moreover, it shows that the PWP in the surface area is increasing by passage of time during the rainy period and it is decreasing as the raining period stops. The result from slope /W analysis shows that factor of safety (FoS) of slopes without MWCNT. However, the FoS of slope MWCNT declines rapidly and with a high rate, while the FoS of slope with MWCNT only change slightly and remains safe compared to non-stabilized slope.

Keywords: Carbon Nanotubes, Slope Stability, Unsaturated Soil, Seepage Analysis.

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Chapter 1 – Introduction

1.1. Overview

Landslides are a prevalent occurrence worldwide, characterized by the downhill movement of substantial quantities of earth, rock, and debris. This phenomenon happens when the shear stress within a slope surpasses its shear strength (Kristo et. Al, 2017). Landslides emerge in various geographical places worldwide as a result of diverse natural circumstances and triggering mechanisms, including precipitation, seismic events, and anthropogenic interventions. These phenomena are classified as natural hazards, namely geo hazards, due to their capacity to inflict significant harm (Schuster and Highland, 2007). These environmental processes are accountable for causing numerous fatalities and injuries annually, as well as substantial financial losses amounting to billions of dollars. Indirect damages entail persistent financial impact and displacement of populations over an extended period of time (Petley, 2012). Hence, a thorough knowledge of the mechanisms involved in landslides, is a fundamental necessity for various preventive efforts, spanning from land-use planning to the implementation of technical solutions and civil protection measures.

The potential consequences of climate change and its associated increase in rainfall have significantly heightened the vulnerability to slope collapses, as emphasized by Rahardjo et al. (2012). From the factors that trigger landslides, precipitation stands out prominently. The rainfall infiltration into the ground, momentarily increase the ground water table, resulting in undermining slope factor of safety (Guzzetti et al., 2022). The occurrence of mass movements at varying depths can be influenced by the strength and frequency of rainfall, as well as the interplay between absorption and drainage processes (Guzzetti et al., 2022). Therefore, slope stabilization is very important to decrease the potential financial and human losses.

The main goal of implementing slope stabilization is to increase the safety factor of slopes or at least keep the safety factor in the existing condition during the current and future environmental scenarios. The future scenario on the slope might involve typical ground water table variation due to precipitation, and snow melting (Cornforth, 2005). The slope stabilization can be categorized into two main categories: decreasing the active forces that currently act on the slope and trigger landslide; and increasing the strength of soil which forms the material of slope (Fall et al., 2018). Depending on the situation, specialist may consider any of the approaches to increase the safety factor. In some scenarios, a combination of both of these approaches can be considered to keep the slope safety in the existing condition or increase factor of safety. To improve the soil condition in order to increase the slope stability, different methods such as drainage of surface and subsurface water, removing weak

layer of soils, building retaining walls and supportive structures, stabilization of the soil in the site to heighten the shear strength is implemented (Abramson et al., 2002).

Increasing the strength of the soil in a slope is an effective approach for stability of slope. In research by Rahardjo et al. (2013), the influence of using Secudrain and recycled crushed concrete were explored for slope protection. The study revealed that the application of Secudrain and crushed concrete increased the safety factor of slope because it has worked as an impediment for water infiltration into the ground. In another research by Rahardjo et al. (2018), the application of *C. crista* was explored for slope stabilization. The result shown that the vegetation works as a protective layer for slope stabilization. Vegetation and root reinforcement is a good method for slope stabilization. (Schwarz et al., 2010). The efficiency of slope stability depends on various factors like slope angle, soil cohesion, friction angle, and height of slope (Steinacher et al., 2009).

Considering the review in the previous articles, vegetation and roots are efficient materials for slope stability. Research findings shows that adding carbon nanotubes in the soil, positively affects growth of some of the plant's roots, seeds and overall height (Khodakovskaya et al., 2009; Mondal et al., 2011). Moreover, Correia et al. (2015) shown that application of carbon nanotubes in the soil is heightening the shear strength of the soil significantly. Therefore, it seems that application of carbon nanotubes will enhance the safety factor of slope directly by heightening the soil shear strength and indirectly by helping the vegetation available on the surface of slope to grow and help the slope stability. However, it is worth mentioning that no prior research has been conducted to explore the application of carbon nanotubes for slope protection. Therefore, this article is exploring the application of carbon nanotubes for slope stabilisation.

1.2. Hypothesis

Application of multi-walled carbon nanotubes (MWCNTs) for slope stabilization is an effective approach. It is increasing the slope's factor of safety by preventing water infiltration into the slope and increasing the shear strength of the soil and indirectly by promoting vegetation growth on the slope surface.

1.3. Research Objectives

The primary objective of this study is to examine the impact of multi-walled carbon nanotubes on slope stability.

1.4. Scope of works

- Experiments in the laboratory on the MWCNT stabilized soil.
- To obtain the MWCNT stabilized soil's index properties.
- To acquire data on the soil-water characteristic curve (SWCC) and permeability, of MWCNT stabilized soil and subsequently compare these findings with those of soil that hasn't undergone stabilization.
- To conduct numerical analysis on slope stabilized with MWCNTs.

Chapter 2. Literature Review

2.1. Unsaturated soil mechanics

A crucial area of geotechnical engineering is unsaturated soil mechanics, and it studies the properties of soils under negative pore water pressure. Or an unsaturated soil can be termed as a soil comprising three phases, including solid particles, water, and air, where the pressure of the water is negative relative to air pressure. (Fredlund and Rahardjo., 1993). In addition to the air, liquid, and solid states, Fredlund and Morgenstern (1997) introduced a fourth phase specifically for unsaturated soil -contractile skin. The contractile skin, often referred to as the contractile layer, affects the mechanical properties of the soil by bringing soil particles closer together using surface tension, similar to an elastic membrane. Atmospheric pore-air pressure (u_a) is commonly used as a reference value in the field. It serves as a basis for two distinct stress state variables: net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). These variables are commonly utilized in practical applications to distinguish between the impacts of normal stress and variations in pore-water pressure (u_w), especially the net normal stress is the difference between the total normal stress (σ) and the pore-air pressure (Rahardjo et al., 2019). Matric suction is the difference between the pore-water pressure and the pore-air pressure, expressed as a negative number. Fluctuations in matric suction result in changes in the moisture level of soil. Consequently, the water flow properties of unsaturated soil are affected by the diminished water-filled gaps between solid particles (Wijaya and Leong, 2016). Changes in matric suction have a direct impact on the permeability of unsaturated soil, which is known as the permeability function.

The soil–water characteristic curve (SWCC) is a tool that describes the variation of water content in the soil versus the different suction corresponding to the water content. There are three methods to represent the relationship between soil water content and suction, which includes gravimetric water content, volumetric water content (θ), or degree of saturation (S) on a logarithmic scale. In these graphs, the vertical axes show the gravimetric water content, volumetric water content or degree of saturation and the horizontal axes show the suction (Fredlund, 2006). The minimum, value for suction to be considered is a number close to zero that usually 0.1 is considered the lowest value for suction and the highest value for suction is one million which means the water content is equal to zero in this suction. The value of parameters in the vertical axes ranges from zero to one or from zero to 100%. The SWCC variables include saturated water content, air entry value, inflection point and residual water content.

Saturated water content is the point at which the soil is fully saturated and represents the maximum amount of water which the soil can hold. The air entry value (AEV) is also an important variable of SWCC, and it represents the point at which air is starting to enter the soil and water starts to decrease from the soil (Brooks and Corey, 1966). It is also the point where soil starts to transition from saturated condition to unsaturated condition. The inflection point represents the point where the SWCC curve is changing from steeper slope to a gentler slope.

2.2. Carbon Nanotubes

2.2.1. General Information

In recent decades, nanotechnology has experienced extensive investigation, that resulted in the emergence of numerous new materials and nanostructures. These materials have totally different characteristics compared to material with larger scales, presenting new possibilities for different applications in different industries. Among all the discovered nanomaterials, carbon nano materials have attracted more interests because of its unique and remarkable characteristics such as high aspect ratio, and high tensile strength and low density (Qiu and Yang, 2017). The more recent studies have demonstrated that the carbon nano materials production technology is developing as well as its application and usage across different industries are expanding.

For the first time, Iijima, (1991) introduced the carbon nanotubes in 1991; and ever since, researchers from different industries including chemistry, physics, electrical engineering, civil engineering, medical and many other fields started to investigate the characteristics of carbon nanotubes and its application in their fields. Carbon nanotubes, are nanostructures with one dimensional shape and made from carbon. The nanostructures can be visualized as cylindrical tubes formed by wrapping graphitic sheets around themselves (Breuer and Sundararaj, 2004). The tubes exhibit sp²-hybridized carbon, with all of the other atoms of carbon being connected to three other atoms on the xy plane.

Carbon nanotubes are divided into two categories: the single-walled carbon nanotube (SWCNT) and the multiwalled carbon nanotube (MWCNT). SWCNTs are made of a graphene sheet that is wrapped up into a single tube, while MWCNTs are made up of numerous concentric nanotubes that encircle one another (Gooding, 2005).

To define the unit cell of carbon nanotubes, a chiral vector $C_h = n_{a1} + m_{a2}$ can be used and this vector can be combined with a variety graphene base vector combination. Graphene which is building of block of carbon nanotubes can be described using this formula and how it is rolled to make the carbon nanotubes. Therefore, the orientation in the graphite sheet plane and the diameter of the nanotube may

be obtained from a couple of integers (n, m) that represent the type of nanotube (Louie, 2001). All SWCNTs exhibit metallic properties. SWCNTs with a diameter of 5 nanometers (nm), are semiconductors with a very small energy gap. On the other hand, all other MWCNTs are semiconductors with an energy gap that is inversely proportional to their diameter (Baughman et al., 2002). The electrical characteristics of MWCNTs can closely resemble those of SWCNTs.

The exceptional features of carbon nanotubes have caused their widespread recognition as groundbreaking nanomaterials in the field of nanotechnology. In scholarly discussions, these materials are occasionally recognized as the leading nanomaterials. The widespread utilization of this material is motivated by its remarkable thermal and electrical conductivity, as well as its unmatched strength, which makes it highly prevalent in the fields of electronics and superconductivity (Ozin and Arsenault, 2005; Marx and Barth, 2008).

To synthesize carbon nanotubes, different approaches are available. Selecting the desired method relies on different factors including the quality of carbon nanomaterial needed, the budget and timing and many other factors. The two most popular methods are discharge method and chemical vapor disposition method (CVD). Synthesizing carbon nanotubes via CVD requires heating in a furnace the catalyst material and running a gas of hydrocarbon through a reactor tube for a specific time period. Catalytic nanoparticles are nanostructures that are generally supported by high surface area nanostructures called alumina. (Dai, 2001). Usually, this nanostructure acts as seeds to initiate the nanotube formation.

Synthesizing carbon nanomaterials by discharge method requires creating an electric arc between two graphite electrodes in a desired environment. This procedure generates high temperature that results in vaporizing the graphite and condensing it as carbon nanotubes. Using this method, we can obtain both SWCNT and MWCNT (El-Khatib et al, 2018).

2.2.2. Application of MWCNT in soil stabilization

The rapid growth of urbanization and industrialization in the recent decades has given rise to the challenge of stabilizing soil for a sustainable structure and sustainable environment. Several traditional methods exist for soil stabilization including using cement, lime, fly ash and other traditional methods. These methods might be able to satisfy the soil stability purpose, but also generate many environmental problems and contribute to the pollution of environment. Hence, it is essential to actively pursue alternate materials that can mitigate these concerns. Nanomaterials are now being contemplated as a prospective resolution owing to the progressions in nanotechnology and the

integration of multiple disciplines. Nevertheless, the utilization of nanotechnology in the domain of geotechnical and geological engineering remains predominantly at the preliminary stage, with only a restricted number of applications observed thus far. (Huang and Wang, 2016).

Arabania et al. (2012) blended 0.05-0.2% MWCNTs by weight of the soil with clayey sand in the soil improvement sector. When compared to the original clayey soil, the soil's compressive strength increased significantly with 0.2% MWCNTs. This shows that even tiny quantities of MWCNTs can have a significant impact on improving soil compressive strength. Moreover, MWCNTs enhance cohesion while reducing the friction angle between grains of soil. However, some researchers are worried that application of carbon nanotubes into the soil might negatively affect the environment. Lu et al., (2005) and Li et al., (2013) have investigated the utilization of carbon nanotubes for absorbing water contamination. The study revealed that MWCNT can be effective in absorbing water pollution. This effectiveness is attributed to the nanoscale voids available in the MWCNT structures and significant surface area of multi-walled carbon nanotubes. In a similar study conducted by Johansen et al. (2008) and Tong et al. (2007), it was found that multi-walled carbon nanotubes have a negligible effect on the water microbes.

Some researchers have explored the applicability of MWCNTs on soil shear strength. Correia et al. (2021) study objective is discovering the critical parameters that influence the behavior of stabilized soil after the multi walled carbon nanotube is added to the soil. To conduct the test, he mixed the carbon nanotubes into the soil with and without surfactant solution. In the method which he mixed the soil with surfactant, he added surfactant in the water and mixed it with carbon nanotubes. To get a homogenous solution, he exposed the solution for ultrasonication for a 20 minutes. The research finding revealed that when the carbon nanotubes were mixed with soil after dispersing them in the surfactant solution, the mechanical properties of soil increased significantly compared to carbon nanotubes without surfactant. Correia et al. (2021) found that the concentration of MWCNTs does not seem to be an important consideration, and similar benefits can be achieved with a lower concentration.

The quality of surfactant is very important in soil stabilization with carbon nanotubes. This is because a small amount of surfactant molecules increases the adsorption capability of carbon nanotubes, soil, and other binders. Consequently, they facilitate improved dispersion without impeding cementitious reactions.

To sum up, the application of nanotechnology in geotechnical engineering promises solutions to the challenges. Novel solutions are needed because traditional methods like cement and chemical grouts are inefficient and have detrimental effects on the environment. Studies conducted by the authors cited in this review, demonstrate that incorporating carbon nanotubes into soil can significantly enhance soil compressive strength and mechanical behavior, therefore it seems promising to the conventional

2.2.3. Application of MWCNTs on plants growth

One of the present-day challenges to farming practices can be tackled by combining it to nanotechnology. The recent field in research found out that it is possible to use carbon nanotubes to improve the growth of plants and other agricultural products. As illustrated by a study, Khodakoovskaya et al. (2009), the introduction of MWCNT has proved to be yielding a higher germination rate in comparison with the seeds that were without MWCNT. Thus, relying on this investigation, Mondal and his research teams (Mondal et al., 2011) conducted a research that focused on the positive impact of using MWCNTs with a diameter ranging from 30 nm on the growth of mustard seeds known as *Brassica juncea*.

The findings of the research indicate that MWCNTs have the potential to go deep down the outer layers of mustard seeds and penetrate the root tissues of the plant cells. This suggests that with the help of nanotechnology, there is a rich possibility for improving the growth of plants and other agricultural products. Due to the penetration effect of nanotechnology on the seeds, the moisture level within the seed cells and an enhanced level of water absorption within the plant's tissues occurred.

According to Lahiani et al. (2013), a faster seed promotion process is possible without resulting in any damage to the overall development of the plant. This study used MWCNT on several different crop seeds such as soybean, barely, and corn and employed two differing methods such as seed coating and agar growth media and noticed a quicker growth of seeds. Therefore, implying that MWCNTs are capable of modulating the functions of aquaporin; a significant part of water transport is found in the cellular structure of plant cells. A research conducted by Hu et al. (2021) examined the impact of different quantities of MWCNTs on the breakdown process of nitrogen and carbon in maize. Their study aimed at understanding the mechanism of MWCNTs at the molecular level in plants. They found that a 100 mg/L of MWCNTs enhanced the growth of plants at roots and also had an impact on the length of the seed. Furthermore, it was found that with the help of 100 mg/L of MWCNTs, it is possible to have the level of chlorophyll expanded, transpiration improved, as well as the conductance of stomata cells elevated.

Water soluble carbon nanotubes were utilized by Tripathi et al. (2010) to see if it was possible to expedite the growth mechanism of Cicer arietinum plants. The research had positive results as those plants that were treated with 6.0 mg/mL of CNTs showed a higher growth rate in the roots, stems, branches, and almost all parts of it. Another study conducted by Canas et al. (2008) examined the impact of SWCNTs on carrots, cucumber, cabbage, lettuce, onion, and tomato. Onion and cucumber upon exposure to nanotubes showed longer and thick roots. Thus, these studies can be collectively emphasized to highlight the usefulness and safety of utilizing carbon nanotubes in agricultural fields to enhance the development and growth of plants.

Generally, in the field of agricultural nanotechnology, the use of carbon nanotubes to increase plant growth is highly beneficial. Various sources of research after their thorough reviews have witnessed the usefulness of using nanotubes on different levels of plant growths and nourishment, highlighting the benefits in agriculture including improved germination, water absorption, regulated aquaporin activities and expedition of root growth.

2.3. Seepage and stability analysis.

According to (Yu, 2023), slope stability is a significant concern in the arenas of civil engineering, water management, road and railway building. Slope failure is an event that can lead to catastrophes like landslides and other structural destruction. There are a few variables that have the potential to disturb the safety of a slope comprising its geometry, soil characteristics, groundwater levels, and external stresses. Engineers make use of several unique techniques including limit equilibrium and numerical modeling methods to evaluate the safety of slopes (Tanh et al., 2014). These approaches benefit in the evaluation of the equilibrium between the weakening forces applied on the slope and the repelling forces present within it.

In the process of stability of slope analysis, it is very important to consider the presence of water because it can considerably change the stability of a given slope. Therefore, in the context seepage analysis is very relevant. Seepage is a procedure by which water infiltrates through deposit significantly affecting the stability of a slope (Kovas, 2011).

Various computer software applications have been developed, and this has enabled smooth performance of complex calculations and effective replications by the simple use of inputs and data. Compared to observations conducted in the field, there are less chances for errors and more detailed analysis is possible through various computer software. In this research, Slope/W is used for analyzing stability of slope. Slope/W is usually used in geotechnical engineering to analyze safety of slopes and

embankments (Abbas et al., 2018). The software allows the users to input the soil properties and slope geometry and the boundary condition. It calculates the factor of safety of slope and indicates whether the slope is stable or not (Harshith, 2020). SEEP/W is a numerical software can be used to manage and analyze the seepage of water in the homogenous and non-homogenous soil (Mohammed et al., 2006). SEEP/W is a computer-aided design (CAD) software that use finite element analysis for analyzing ground water flow and seepage. Moreover, it has the capability to address a wide range of problems, from saturated steady state concerns to unsaturated and time dependent analysis problems.

Chapter 3 - Applicable theories.

3.1. SWCC

The Soil-water characteristic curve (SWCC) is an important concept in geotechnical engineering. It is describing the correlation between soil water content and suction under different circumstances. It is important for different applications, including slope stability analysis, ground water flow modeling and foundation design.

To obtain the SWCC curve, different methods exist. The SWCC can be directly obtained in situ or in the laboratory by taking soil samples into the lab. The procedure is that scattered data from experiments is obtained which need to be best fitted. Several formulas have been developed for best fitting the curve. In this research, the soil is bi modal, and the equation developed by Satyanaga et al. (2013) is used for fitting.

$$\theta_w = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \times \left[\theta_r + \left\{ (\theta_{s1} - \theta_{s2}) \left(1 - \operatorname{erfc} \left(\frac{\ln\left(\frac{\psi_{a1} - \psi}{\psi_{a1} - \psi_{m1}}\right)}{s1} \right) \right) \right\} + \left\{ (\theta_{s2} - \theta_r) \left(1 - \operatorname{erfc} \left(\frac{\ln\left(\frac{\psi_{a2} - \psi}{\psi_{a2} - \psi_{m2}}\right)}{s2} \right) \right) \right\} \right] \quad (3.1)$$

In this equation,

θ_w = volumetric water content

ψ = Suction obtained from experiment

ψ_r = Suction at residual point

θ_r = residual point volumetric water content

θ_{s1} = Saturated volumetric water content in sub-curve 1

θ_{s2} = Saturated volumetric water content at sub-curve 2

ψ_{a1} = AEV1 parameter

ψ_{a2} = AEV2 parameter

ψ_{m1} = Suction parameter at inflection point 1

ψ_{m1} = Suction parameter at inflection point 2

ψ_m = matric suction at inflection point

S1 = standard deviation 1

S2 = standard deviation 2

3.2. Unsaturated Permeability

To find the slope stability under different conditions, another factor that is required is the unsaturated permeability of the soil. unsaturated permeability describes the capacity of a soil to convey water under conditions in which the soil is not completely saturated. Unsaturated permeability takes into account scenarios in which air and water coexist within the soil matrix. Having a solid understanding of unsaturated permeability is absolutely necessary for a variety of engineering applications, such as slope stability analysis, foundation design, and environmental research.

In the saturated condition, Darcy's law (Criag, 2004) is applied. The formula can be written as follow:

$$q = Aki \quad (3.2)$$

In this equation:

q = water volume that flows per time unit

A = the cross-sectional area of soil which water flows through

k = coefficient of permeability

i = hydraulic gradient

However, in unsaturated permeability, the permeability of soil is varying with variation in soil suction. Since obtaining unsaturated permeability is very challenging, theoretical calculations are made to obtain the unsaturated permeability of soil. Therefore, in this research, the statistical method is employed to obtain the unsaturated permeability of soil with the help of SWCC data (Fredlund and Rahardjo, 1993) The k_w is obtained with the help of SWCC data using the following formula:

$$k_w(\theta)_i = \frac{k_s}{k_{sc}} A_d \sum_{j=i}^m [(2j + 1 - 2i)(u_a - u_w)_j^{-2}], \quad i = 1, 2, \dots, m \quad (3.3)$$

Where:

$k_w(\theta)_i$ = Permeability coefficient

i = Interval number

j = The count from i to m

A_d = Adjusting factor

k_{sc} = Computed saturated coefficient

3.3. Unsaturated Shear Strength

During numerical analysis in the slope stability, unsaturated shear strength is an important factor. Unfortunately, the time limit during the master thesis is not enough to complete two sets of unsaturated shear strength. Therefore, the typical values for unsaturated shear strength of the soil are considered from literature.

To obtain the unsaturated shear strength of soil, several mathematical equations are proposed. However, most proposed equations are applicable for unimodal soil. The recent mathematical model proposed by Satyanaga et al. (2022) is used to obtain the bimodal unsaturated shear strength from SWCC and unsaturated permeability curves. The formula proposed by Satyanaga et al (2022) can be written as follow:

For the suction between AEV1 and AEV2:

$$\tau = c' + [(\sigma - u_a) + AEV1] \tan \phi' + [(u_a - u_w) - AEV1] b_1 \theta k_1 \tan \phi' \quad (3.4)$$

$$k_1 = [\log (u_a - u_w) - \log AEV1] y \quad (3.5)$$

$$b_1 = -0.245 \{ \ln [S1 (Ip + 4.4)] \}^2 + 2.114 \{ \ln [s_1 (Ip + 4.4)] \} - 3.522 \quad (3.6)$$

$S1$ = Parameter of standard deviation 1

For suction less than higher than AEV2:

$$\tau = c + (\sigma - u_a) \tan \phi' + AEV2 \tan \phi b_2 + [e \times (u_a - u_w) - (0.2 + \text{fines}) \times AEV2] b_2 \theta k_2 \tan \phi' \quad (3.7)$$

$$k_2 = [\log (u_a - u_w) - \log AEV2] y \quad (3.8)$$

$$b_2 = -0.245 \{ \ln [S2 (Ip + 4.4)] \}^2 + 2.114 \{ \ln [S_2 (Ip + 4.4)] \} - 3.522 \quad (3.9)$$

$$y = 0.502 l(Ip + 2.7) - 0.387 \quad (3.10)$$

In the equations, the AEV1 and AEV2 are the air entry values, $(u_a - u_w)$ is the matric suction. These parameters can be obtained from the SWCC. The variables are cohesion (C'), Friction angle (ϕ') and Effective Angle of Internal Friction (ϕ^b).

Chapter 4 - Research methodology

In order to achieve credible and reliable findings, a highly systematic methodology needs to be used while examining the application of multi-walled carbon nanotubes (MWCNTs) in the protection of slopes. In this chapter, a detailed study methodology used in the study to evaluate soil engineering properties and analyze the collected data. The study uses soil combination, which comprises 80 % Kaolin (K), 20 % Sand (S), and 0.2 % MWCNT. Therefore, in this study the term sand-kaolin(80k20s) is used for the soil without carbon nanotubes and the term 80K20S + 0.2MWCNT is used for the soil with 0.2 percent multi-walled carbon nanotubes admixture.

There is not much information about the effect of size of carbon nanotubes on mechanical properties of the soil. However, in research conducted by (Gao et al., 2020), it was demonstrated that carbon nanotubes with 40-60nm diameter is the optimum size for getting the optimum strength of cement-based materials. The measurement of CNTs used in this study ranges 50 to 90 nm in diameter and more than 95% pure carbon (Sigma -aldrich Co., 2023). Cetyl trimethylammonium bromide (CTAB) is used as a surfactant to increase the dispersion of multi-walled carbon nanotubes (Sigma -aldrich Co. 2023).

To understand how carbon nanotubes and soil interact, it is very important to choose the materials for the reason that soil engineering features can be easily determined by it. The mixture of soil went through many tests, such as Proctor methods, which measured the features of its compaction. Atterberg limit test was used to determine plasticity limits, and grain size distribution was to examine the size distribution of soil. Finally, a specific gravity test was used to measure the density of soil. These tests are necessary and provide very important information regarding the mechanical and hydraulic characteristics of the soil.

After determining the index characteristics, subsequent experimental works were conducted on the soil-water characteristic curve (SWCC). Two samples were generated for testing: one consisting of 80K20S (a soil mixture without carbon nanotubes) and the other consisting of 80K20S+0.2%MWCNT. The SWCC tests play a crucial role in comprehending the water retention behavior of soil under various suction situations, offering significant information for later research. Afterward the information regarding unsaturated permeability is obtained using Hyprop for the saturated point and the graph was obtained using statistical data. Since the triaxial test is very time consuming and is not possible to obtain the unsaturated shear strength result within the time span of this research, the data is obtained from typical soil types with the same soil classification. The

numerical study is undertaken using GeoStudio software, a robust tool in geotechnical engineering that enables the simulation of complex interactions within soil systems.

4.1. Laboratory Testing

4.1.1. Compaction

The compaction test is a laboratory method used to determine the maximum dry density of a soil and its corresponding moisture content. Research by the California Highway Department from 1928 to 1929 revealed that the main reason behind the failure of roads is uneven compaction, resulting in inadequate capacity of the subgrade soil. To tackle this issue in practical terms, a significant advancement happened in the 1920s and early 1930s. These include the establishment of Proctor compaction curves (Proctor, 1933) for compaction specification and the introduction of the California Bearing Ratio (Croney, 1991). These two experiments have been employed in the laboratory to find the relationship between the moisture content (w) and dry density of a particular soil with a certain gross energy input. The energy is exerted by compacting moist layers into a cylindrical mold using a hammer. A compaction curve demonstrates the relationship between the dry density and moisture content. This curve exhibits a parabolic shape that is inverted and is utilized to ascertain the maximum dry density and the corresponding optimal moisture content for a given energy input.

The experiments were conducted following standard proctor method test in accordance with the guidelines outlined in ASTM D698-12(2012). For this experiment, a mold with a volume of 939.7 cm³ and a hammer weighing 2.5 kg were used. The soil was carefully arranged in the mold, forming three distinct levels. Each layer was then subjected to compaction using 25 hammer blows. This process repeated for different soil samples with different water content. Subsequently, three specimens were extracted from each sample of compaction and subjected to the process of drying in an oven in order to determine their respective moisture content. After the soil samples are dried in the oven for 24 hrs., the specimens are weighted, and the result is recorded in a book sheet. The obtaining data is later used to extract the graph of dry density vs the compaction of the soil. The test procedure is shown in Figure 4.1.

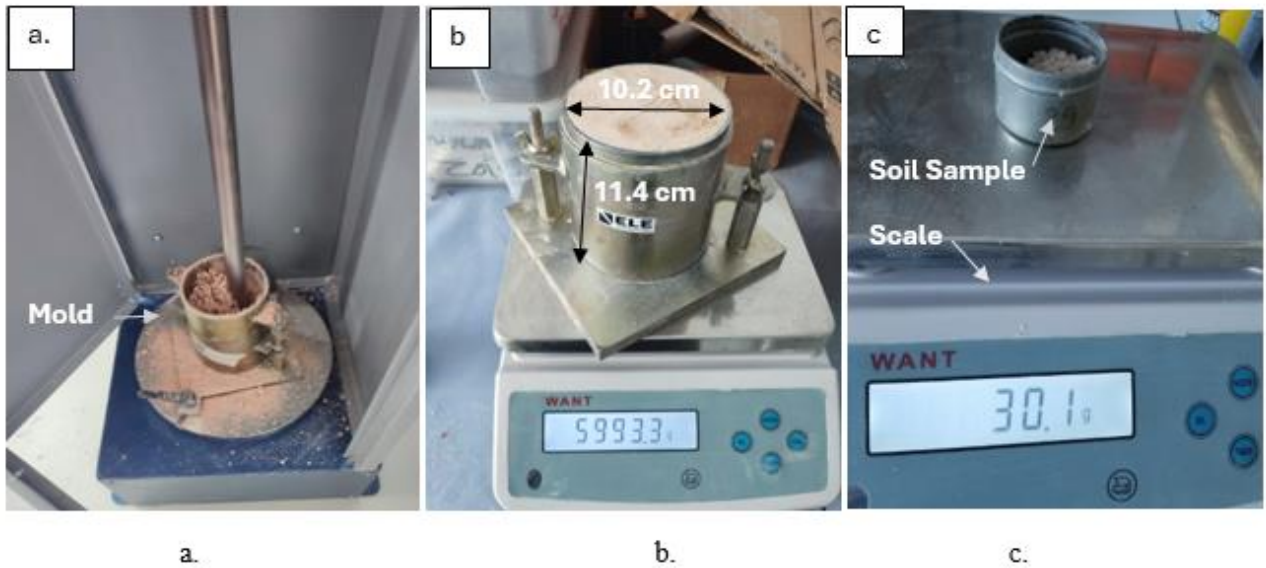


Figure 4. 1 a. Compacting the soil. b. Weighing the compacted mold c. Weighing the samples.

4.1.2. Scanning Electron Microscope Analysis

Scanning Electron Microscope (SEM) tests are used in various scientific fields and many industries for analyzing the structure and composite of the materials. The SEM provides magnified images of the materials. In this research, the SEM technique is utilized as an essential investigative instrument, providing qualitative information regarding the materials that are being examined. The effectiveness of the dispersal method applied to MWCNTs in the soil is confirmed through the utilization of SEM. The SEM imaging is conducted following (Mirzababaei & Yasrobi, 2007). In this procedure the MWCNT mixed soil sample is fixed on the microscope prop and covered with a few angstroms of gold and then placed in the SEM chamber for taking image. This method is completed via high resolution pictures in addition to information on the primary arrangements of the element.

For preparing the MWCNT, the following method is used:

- The surfactant (70% percent of MWCNT) is solubilized in the water and mixed using magnetic stirrer for 20 minutes.
- The carbon nanotube (0.2%) of soil weight is prepared and then added in the solution that is already prepared.
- The mixed solution of MWCNT and surfactant is then mixed using ultra sonication bath for one hour.

- During the ultra-sonication, ice is introduced into the ultra-sonication bath to prevent temperature increase more than 30° C.
- The MWCNT preparation technique is illustrated in the figure 4.2.

During the ultra-sonication process, it is vital to bring ice into the ultra-sonication wash as a defensive mechanism to keep the temperature below 30°C. In order to assure the steadiness of the MWCNT distribution and avoid any possible variations in the features of the nanotubes produced by extreme heat, the maintenance of controlled temperature is of the utmost importance. In the present research, there is one primary structure to be focused on while using the SEM examination. The evaluation of the longitudinal organization of MWCNTs in the soil, checking if the dispersal practice attains a constant dissemination over the soil matrix.

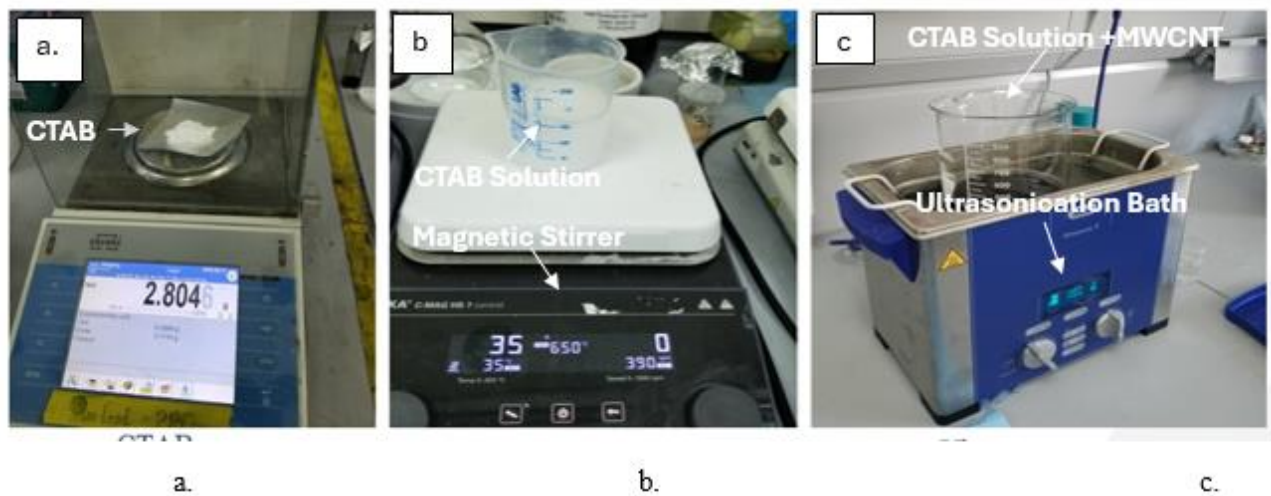


Figure 4. 2 a. Weighing CTAB b. Solving CTAB in Water by Magnetic Stirrer c. Ultrasonication

4.1.3. Atterberg Limit test

The Atterberg limit test includes plastic limit (PL), liquid limit (LL), and plasticity index test, which are very common tests in geotechnical engineering. The LL is the minimum water content of the soil that is behaving like liquid. The PL refers to the amount of water in the soil at which the shift from plastic to brittle behavior occurs (O' Kelly, 2016). The Atterberg limit test in this test is conducted following ASTM D4318-17, (2017). In this test the cone penetration test has been applied to determine the liquid limit according to the ASTM D4318-17, (2017) standard. The test is repeated many times to obtain the cone penetration about 20mm and a trend line is drawn to obtain the exact penetration in the soil with different moisture content. Then the samples are dried in the oven for 24

hours to find the dry mass of soil and calculate the water content. The plastic limit is obtained the hand rolling method as it is the most prevalent and accepted method. The diameter of the soil samples was considered about 3mm and the samples were dried to find the water content. The experimental procedure is depicted in Figure 4.3.

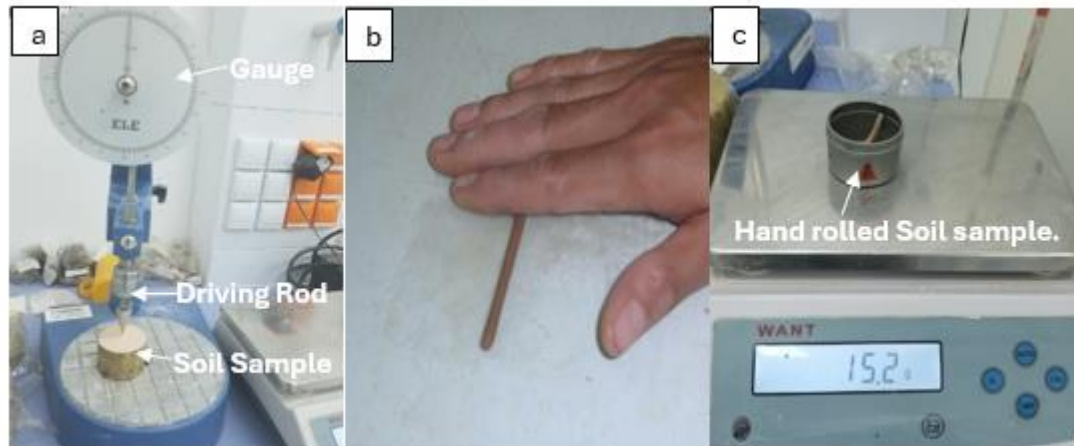


Figure 4. 3 a. Cone Penetration Test Apparatus b. Hand Rolling Plastic Limit c. Weighing Sample

4.1.4. Grain Size distribution.

Grain size distribution (GSD) is an important test which is utilized to assess physical features of soil to be considered when dealing with scientific concerns. For grain size distribution, there have been plenty of advanced techniques developed so far, such as X-ray microtomography, laser diffractometry, SEM, and mass-spectrometry of secondary ions.

The GSD test is performed according to the ASTM D6913M-17(2017) using laser granulometry apparatus, which is also known as laser diffraction, to distribute grain sized soil (Pye & Blott, 2004). Laser diffraction is a mechanism that is based on modern and effective technology to evaluate the sizes of particles in soils. The method involved in this technique is through the use of laser light that is made to pass through soil containing transparent objects spread out in a liquid media. The angles and intensity of the scattered light can be detected via a detector, which is important in the determination of the distributed sizes of particles. When the laser beam hits the suspended soil, it comes in contact with soil particles, which are scattered in various directions. The particles that are small in size have the greater potential to scatter light at wider angles as compared to the bigger particles, and the size of the particles is in direct proportion with the intensity of light. Laser

granulometry makes use of Mie theory and Fraunhofer diffraction theory, both of which are mathematical techniques in the translation of scattering patterns to a distribution of particle sizes.

One of the positive things about laser granulometry compared to sieving is that it is rapid and very effective in providing analysis. In this method, there is accurate precision that can be achieved constantly. In addition, the non-invasive nature of laser granulometry also enables other tests and analyses to be done on the same sample. The device is depicted in Figure 4.4.

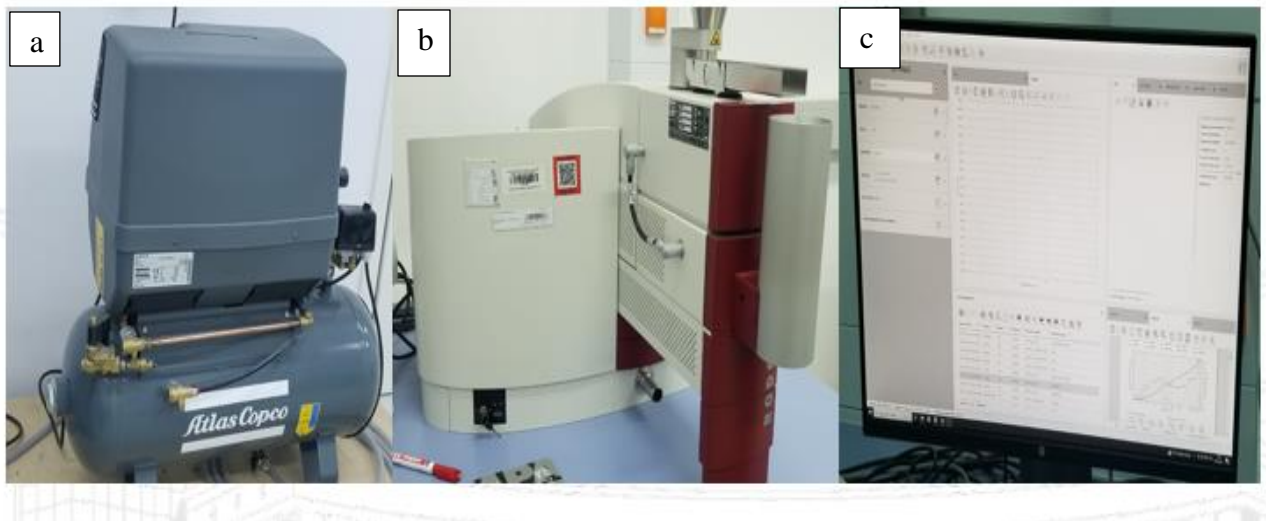


Figure 4. 4 a. sample dispersion unit b. laser granulometry c. Software

4.1.5. Specific Gravity Test.

A vital factor in many geotechnical and civil engineering applications is soil specific gravity. For the computation of void ratios, porosities, and other volume relationships necessary for geotechnical studies, specific gravity is important. The test is performed according to ASTM D854 14(2014). For determining the specific gravity of soil in this test, volumetric flask method is used. In this method, the necessary amount of soil is prepared and weight is recorded. The flask is filled with water and until the mark on the flask. Then the flask is shaken so that any bubble in the flask is removed and then it is degassed. To find the soil's specific gravity, divide the mass of the dry soil by the difference between the flask's and the water's volumes. Later on, specific gravity can be used to define bulk density, dry density, and water content with ease.

4.1.6. Soil Water Characteristic Curve (SWCC)

The soil-water characteristic curve (SWCC) is a tool that describes the correlation of soil and suction. Its graph is drawn on logarithmic scale. SWCC with the help of degree of saturation (S-SWCC) is one of three potential representations used to calculate volume change of soil. It is acknowledged that S-SWCC is equivalent to the distribution of pore-size. However, S-SWCC is often used to characterize the probability of random pore linkages (Zhai et al., 2015), because the degree of saturation is determined by the region within the pore-suction distribution function.

The air-entry value (AEV), that depends on suction and represents the point of water draining from the biggest pores of soil, is an important component of the SWCC in the context of unsaturated soil mechanics (Brooks and Corey, 1966). Or, AEV can be described as the suction that ruptures the meniscus due to the surface tension of water within the largest pores (Fredlund and Xing, 1994). The AEV was shown to be dependent on the particle size distribution of soils. A higher percentage of fine particles reduces intra-particle pore spaces among soil particles, resulting in an enhanced AEV (Aung et al., 2001). In contrast, residual suction relates to the level of suction at which water evacuation from the soil does not appreciably increase.

The obtaining of the SWCC needs the utilization of advanced laboratory techniques. The behavior of unsaturated soil is significantly influenced by the SWCC (Satyanaga et al., 2017). The SWCC curve is obtained through the use of the Hyprop and WP4C instruments. The Hyprop test was conducted according to the following procedures:

- The soil was compacted into three layers within the Hyprop ring and subsequently submerged in water for a period of three days to achieve full saturation.
- The process of degassing the sensor unit and ceramic shaft was carried out utilizing the Refill unit. Distilled water is employed for the process of degassing.
- The sensor unit of Hyprop was saturated using for 24 hours to completely saturate.
- Afterward, the sensor unit and ceramic shaft were installed to check if it is properly working.
- Once the soil, sensor unit, and ceramic shafts have been saturated, the equipment is constructed and linked to a computer to quantify the soil suctions at varying levels of water content.
- After the test was done, the soil is kept in the stove for 24 hours to find the water content in the sample.

- Hypop is only capable of obtaining suction until 100 Kpa, because it is utilizing 1 bar small tip tensiometer that is capable of measuring suction only until 100 KPa, the remaining part were obtained using the WP4C which is able to obtain suction up to 1000000 KPa.

The integration of Hypop and WP4C proves to be an optimal pairing due to their shared capacity for detecting soil sucking through the utilization of sensors.

For the WP4C, almost the same procedure was conducted. The soil sample was prepared into the WP4C ring and compacted. Then the measurement continued until the final suction were read by the machine. The WP4C uses chilled hygrometer method to measure soil suction. The device consists of a infrared thermometer, sealed chamber, a fan and mirror. When soil sample is locked in the device, moisture of the soil specimen appears on the mirror which is equal to the dew point. The specimen temperature and dew point are used to calculate pressure above the specimen. The methodology for Hyprop and WP4C is depicted in Figure 4.5.

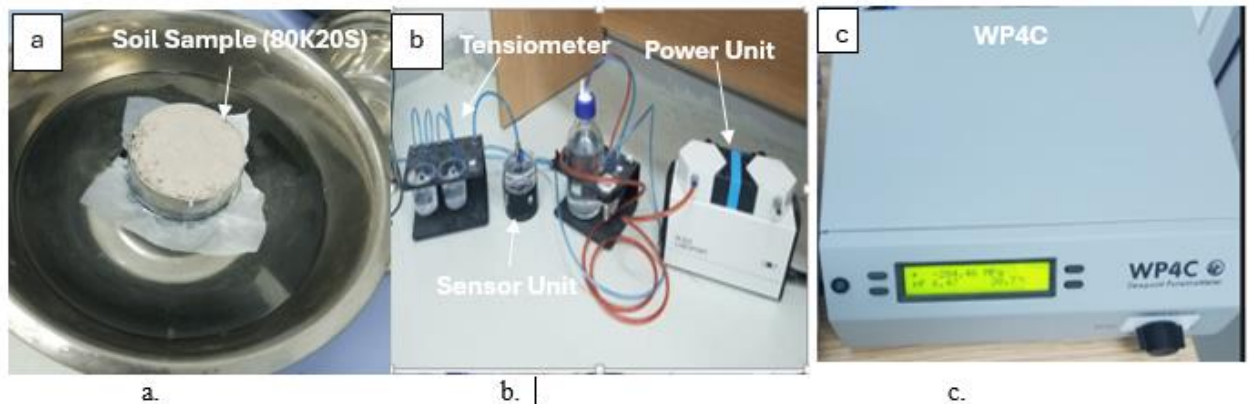


Figure 4. 5 Soil specimen saturation b. tensiometer saturation c. WP4C

4.1.7 Unsaturated Permeability

Unsaturated permeability provides information about the movement of water in soils that are not entirely saturated. Unlike saturated circumstances, which fill all soil voids with water, unsaturated conditions have a mix of air and water in the soil cavities. Understanding unsaturated permeability is critical for many geotechnical applications, such as slope stability analysis, foundation design, and environmental engineering. Water flows between the liquid and gas phases in unsaturated soils. Unsaturated permeability is regulated by soil texture, pore size distribution, suction, and saturation level. Suction, also known as matric suction, is a measurement of the attractive forces that hold water

in soil against gravity. As suction increases, soil water content drops, affecting unsaturated permeability.

In real life, computer models and simulations are often used to figure out the unsaturated permeability of soils. People often use different equations to show how water moves through grounds that are not saturated. When figuring out how stable a slope is, the unsaturated permeability of the soil is very important. Especially in places where the soil isn't fully saturated, rain or changes in the amount of water in the soil can have a big effect on how stable slopes are. Knowing how water moves through soils that aren't wet helps engineers figure out how likely it is that a slope will fail and take the right steps to stabilize it. The unsaturated permeability of soil in this test is obtained using statistical data and the

4.2. Numerical Analysis

The assessment of slope stabilized with multi-walled carbon nanotubes (MWCNTs) through numerical analysis comprises the application of finite element analysis to assess the success of integrating MWCNTs into soil or slope materials with the aim of increasing stability and reducing the likelihood of slope failures. The numerical studies in this study will be conducted utilizing the GeoStudio program. Specifically, the SEEP/W module will be employed for seepage analysis, while the SLOPE/W module will be utilized for slope stability analysis. When conducting slope safety analysis, it is important to consider variations in height and angle of slope. This scenario is considered for both slopes with and without carbon nanotubes. Moreover, In the numerical analysis, the time interval considered will be 24 hours with the first 12 days raining based on the Kazakhstan raining (Sharipov et al., 2023).

The obtain the unsaturated shear strength of the soil is very challenging and time consumable. Considering the time limit and shortage of available devices in the laboratory, I have used typical shear strength values in this thesis.

Table 4. 1 Numerical Analysis Geometry Summary

No of Trials	Slope Height(m)	Slope Angle(deg)
1	10	27
2	10	35
3	10	45
4	10	60
5	20	27
6	20	35
7	20	45

4.2.1. Seepage analysis using Seep/W

Seepage analysis is very important for analyzing slope stability. This analysis checks the movement of water through earth structures and soils. SEEP/W is a resilient software that is very beneficial in seepage analysis which utilizes finite element method to study seepage conditions in soils in numerous geotechnical circumstances. A thorough illustration of groundwater flow and possible problems connected with seepage can be studied by this analysis

SEEP/W is used widely in conditions that involve the investigation of seepage through structures and dams. Engineers apply a variety of factors to imitate and seepage routes, movement speeds, and pore pressure inside the software. These elements encompass soil characteristics, boundary conditions, and water table elevations. The process of seepage analysis involves a number of important phases. Beginning from defining the exact geometric features of the soil arrangement and ascribing material properties to distinct covering layers. Then, boundary conditions are quantified, including water table elevations and inflow/outflow settings. SEEP/W produces a distinct network to divide the soil structure giving the users a flexibility to adjust analysis parameters considering time-dependent factors and both steady-state and transient conditions.

This study has explored the slope seepage for different slope angle and different height. The analysis consider two sets of slopes, one without carbon nanotubes and another slope with 0.5m layer of soil that is stabilized with carbon nanotubes. The analysis are done on the slope with 10m and 20m height and degree of inclination 27, 35, 45 and 60 degrees for each height. The numerical model for seepage analysis is illustrated in Figure 4.6.

In a comprehensive simulation, pore water pressure, flow rates, and seepage paths are addressed by SEEP/W. Engineers can obtain information concerning the performance of seepage by studying results obtained through contour plots, flow nets, and graphs, The SEEP/W analyses use the unstable seepage equation that Fredlund et al. (2012) proposed. The expression of this equation is as follows:

$$\frac{d}{dx}(K_w \frac{dhw}{dx}) + \frac{d}{dy}(K_w \frac{dhw}{dy}) = m_2^w \rho_w g \frac{dhw}{dt} \quad 4.1$$

In this equation

dx, dy is the x and y dimension (m).

m_2^w is the storage of water modulus.

hw = hydraulic head (m).

K_w = coefficient of permeability (m/s).

dt = time derivative (s).

ρ_w = water density (kg/m^3)

g = gravitational acceleration (m/s^2)

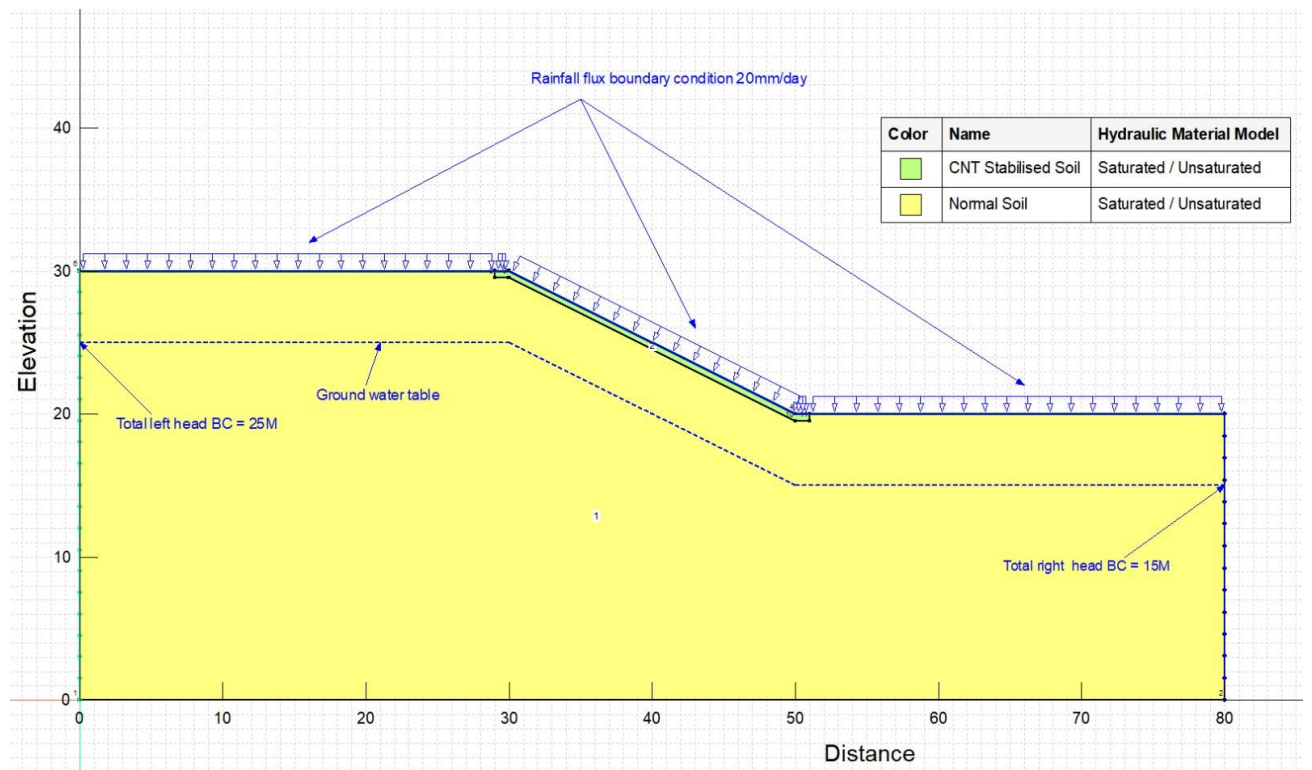


Figure 4. 6 Figure Numerical model for seepage analysis 10m 27deg

4.2.2. Slope stability analysis using Slope/W

To facilitate the simulation and assessment of various factors that influence slope stability, an engineering software known as the SLOPE/W is used which consists of finite elements. One of the primary goals of slope stability analysis is the identification of critical factor of safety and assessing the possibility of slope failure. The consideration of factors like external stresses, groundwater conditions, soil properties, and slope geometry, SLOPE/W gives engineers an adaptable structure for making wise decisions in designing and constructing slopes.

The workflow for slope stability analysis utilizing Slope/W comprises a number of critical stages. By inputting geometric information such as slope angles and soil stratification, engineers allocate material properties to each layer, including cohesion, internal friction angle, and soil unit weight. Boundary conditions are established to include external burdens, water table elevations, and drainage systems. By accommodating both saturated and unsaturated conditions, the software enables a comprehensive examination of the behavior of slopes. In the subsequent numerical simulation conducted in Slope/W, critical slide surfaces, factors of safety, and deformations are computed. Utilizing visualization tools, including safety factor maps, contour plots, and graphs, facilitates the understanding of slope behavior. This study explored the slope safety factor for different slope angle and different height. The analysis consider two sets of slopes, one with carbon nanotubes and another slope with 0.5m layer of soil that is stabilized with carbon nanotubes. The numerical model is illustrated in Fig 4.7.

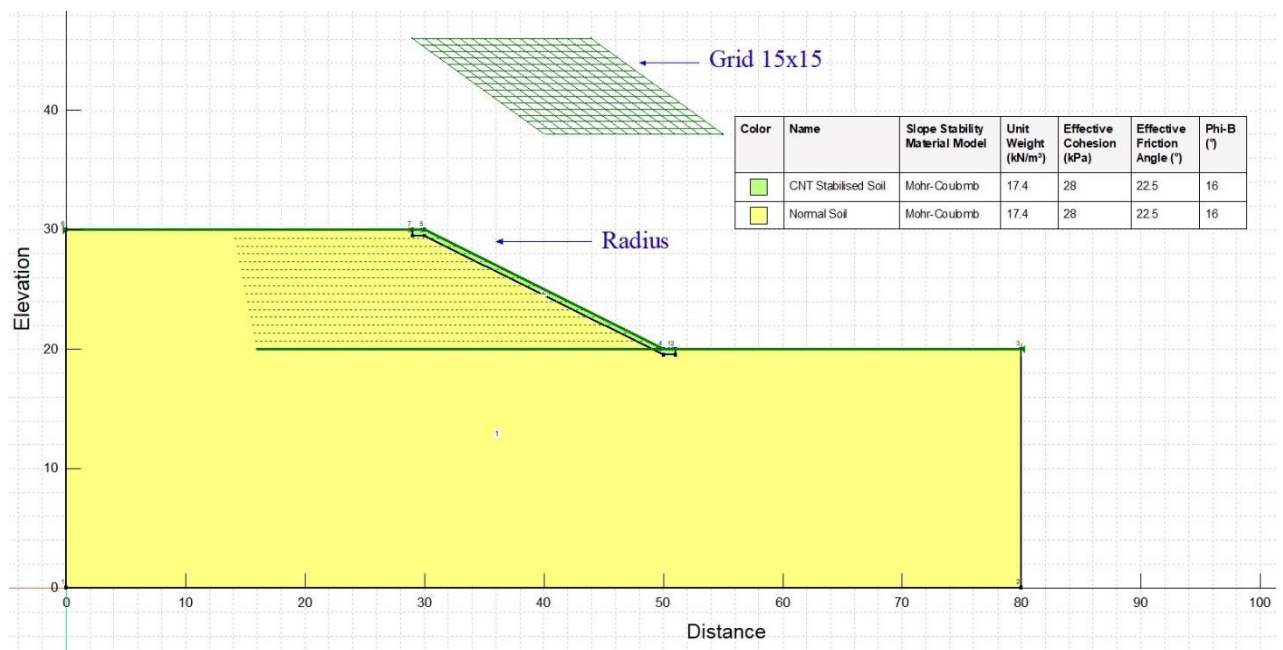


Figure 4. 7 Numerical Model for Slope Stability Analysis 10m 27 deg

Chapter 5 - Results

5.1. Experimental Results

5.1.1. Proctor Method Compaction

The compaction tests were performed following standard proctor method to acquire the maximum dry density and its corresponding water content. Figure 5.1 illustrates the correlation between the moisture content and compacted density of the soil. The graph illustrates that the soil's maximum dry density is 1.71 g/cm^3 , whereas the corresponding water content at this maximum dry density is 18.5 percent

The compaction curve obtained for the soil, which indicates that the ideal moisture content is 18.5% and the dried density is 1.71 g/cm^3 , offers crucial information regarding the compaction properties of the soil. The maximum dry density signifies the utmost dry unit weight that can be attained by the soil when compacted according to the given conditions. The dry density of soil is an important factor that affects the soil's strength, bearing capacity, and general stability. The OMC value is the ideal amount of water needed to ensure effective compaction by striking a balance between providing sufficient lubrication for soil particles and avoiding an excessive amount of water that could hinder the compaction process.

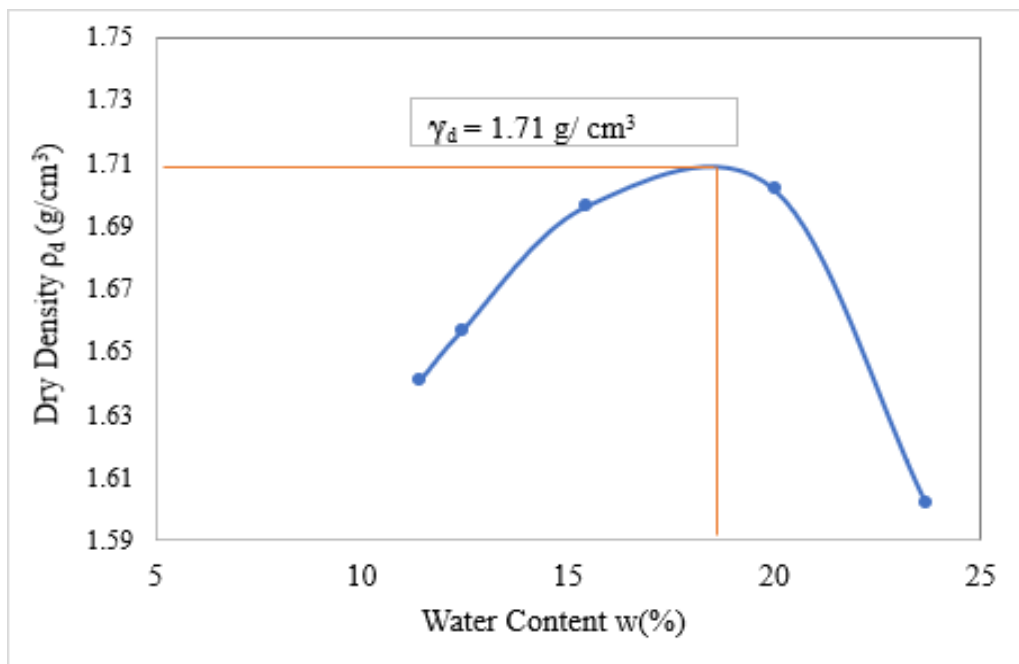


Figure 5. 1 Compaction Curve

5.1.2. SEM Result

The SEM tests conducted on the CNT stabilized demonstrate that the carbon nanotube in the soil is dispersed. The picture a has taken with 5000 magnification and the picture b with 10000 magnifications. The result from the analysis shows that agglomeration in the carbon nanotubes has not happened. It could be due to the fact that CTAB prevents carbon nanotubes from agglomeration and helps MWCNT to effectively disperse into the soil. However, the carbon nanotube in some areas have not distributed homogeneously. This indicates that a longer time should be spent for mixing carbon nanotube solution with the soil. The SEM pictures are illustrated in the Figure5.2.

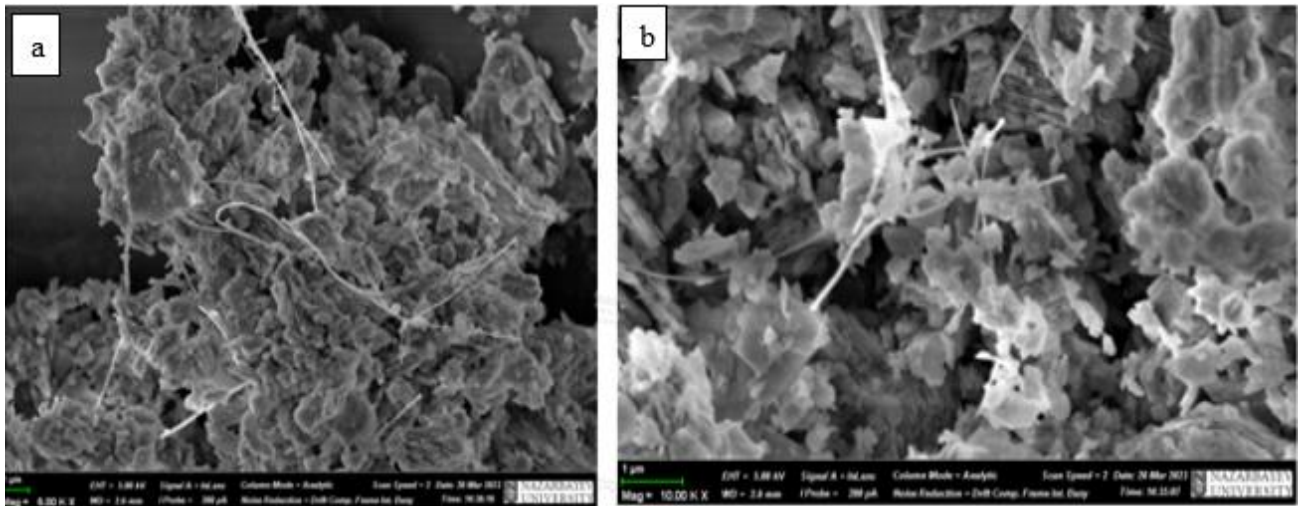


Figure 5. 2 SEM Analysis Result

5.1.3. Atterberg Limit Test

The result of Atterberg limit conducted on the soil sample containing 80 percent kaolin and 20 percent sand vs the same soil combined with 0.2% MWCNTs are listed below. The results illustrate that adding even a small percent of MWCNT can increase the LL and PL and decrease the plasticity index of the soil. The observed alteration in Atterberg limits indicates that the incorporation of MWCNTs, even in minute quantities, has potentially impacted the consistency of the soil. This, in turn, may result in modifications to the soil's engineering behavior, shear strength, and overall geotechnical properties. The identified discrepancies emphasize the necessity for a thorough comprehension of the ways in which nanomaterials, such as MWCNTs, can intricately alter the fundamental characteristics of soil, which are vital for a wide range of construction and geotechnical uses.

Table 5. 1 Index properties of soil vs MWCNT stabilized soil

Index Properties	80K20S	80k20s+0.2% MWCNT
Liquid Limit	36%	40%
Plastic Limit	23.2%	28.7%
Plasticity index	12.8	11.3
Dry Density, Mg/m ³	1.71	1.73
% Sand	20%	20%
% Silt	80%	80%
MWCNT	-	0.2%
USCS Classification	CL	CL

5.1.4. Grain Size Distribution

Grain distribution tests are essential analyses used in many different fields, especially geotechnical engineering, to evaluate the distribution of grain sizes in a sample. These tests offer insightful information on the physical properties of grains, information that can have important applications. In this research, the test is conducted using laser granulometry and the result is shown in Figure.5.3.

Based on the analysis, the soil diameters range from 3.2 mm to 0.005mm. The largest part, which is coarse sand has a range of 2 to 3.2mm, the medium sand is 0.425mm to 2 mm, the fine sand is 0.075mm to 0.425mm. From 0.005mm to 0.075mm is silty clay. Overall, the combined soil has 20% sand and 80 percent silty clay.

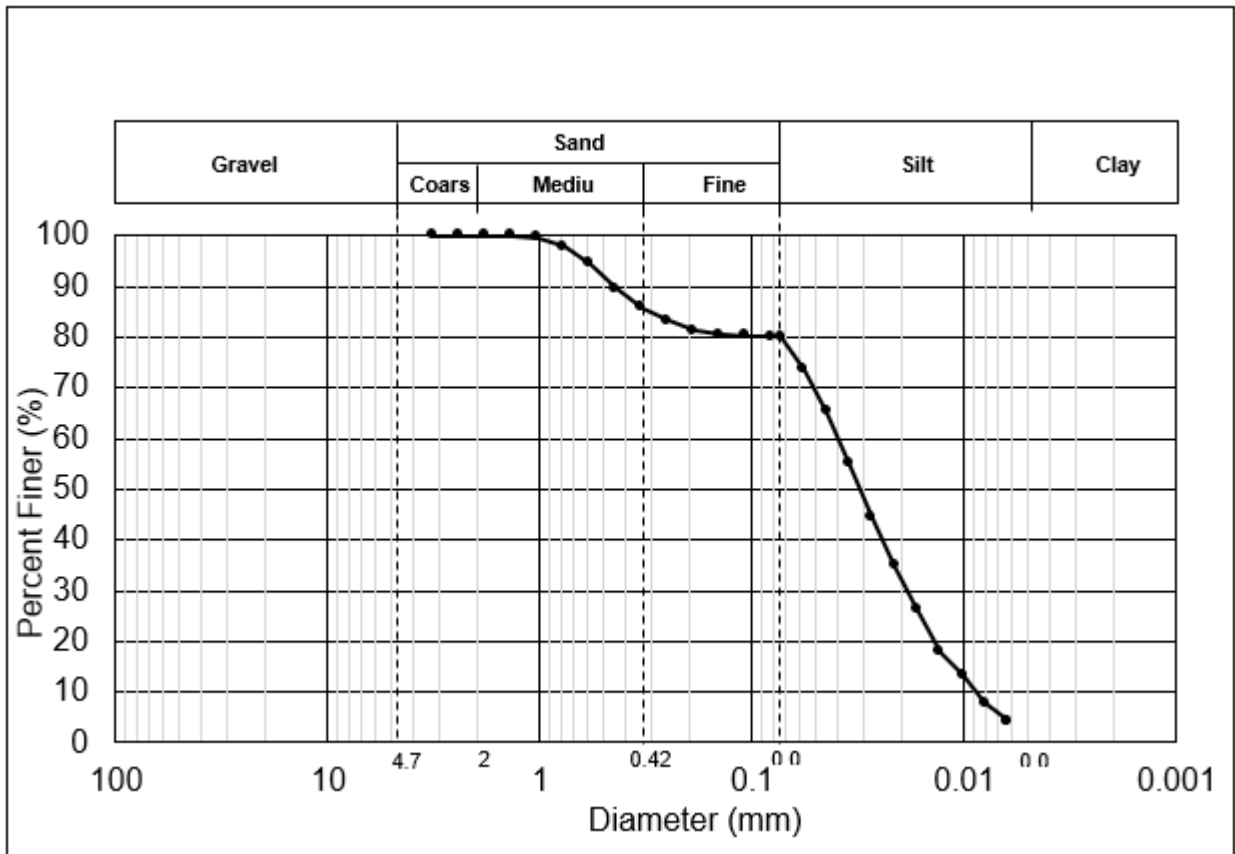


Figure 5. 3 Grain Size Distribution Curve

Table 5. 2 particle size of the soil

Diameter	Size(mm)
D60	0.04
D30	0.02
D10	0.0085

$$Cu = \frac{D60}{D10} = 4.7$$

$$Cc = \frac{(D30)^2}{D10 * D60} = 1.17$$

Based on the results obtained from Cu, the soil is poorly graded. The Cu which is more than one indicates that the soil has more of peaked curve which is more common in poorly graded soils.

5.1.5. SWCC

The SWCC represents the correlation between the soil and its matric suction. Understanding this curve is crucial to comprehending how water is taken in and released by the soil in various situations.

To get the SWCC curve, a combination of Hyprop and WP4C is used. The Hyprop are good at obtaining the small suctions until 100 kPa while WP4C is accurate in measuring higher suctions ranging from 500 Kpa up to 1000000 Kpa. Therefore, a combination has been used to get an accurate result. Scattered data were obtained from laboratory testing and then it was best fitted using Satyanaga et al. (2017) equation.

The outcomes of the experimental study show that the SWCC exhibits bimodal behavior and that the bimodal best fitting parameters should be used to best fit the graph of the SWCC. All the physical parameters of the SWCC are shown in Table 5.3. with regard to the saturated and residual volumetric water content, residual suction, and air entry values of one and two, which are determined using the best-fitting formula by (Satyanaga et al., 2017).

The result show that the volumetric water content of the soil stabilized with carbon nanotube has increased compared to soil without carbon nanotubes. The saturated water content for the soil without carbon nanotube is 0.47, while the saturated water content for the soil with carbon nanotube is 0.5. This can be attributed to the high surface area of MWCNT. Similarly, the air entry value for the soil with carbon nanotube is 9 and the air entry value for the soil without carbon nanotube is 5. The suction at second air entry value for the bare soil is 1160 while it has increased to 1537 for the soil with carbon nanotube. A higher air entry value indicate that the soil with MWCNT has a higher potential to attain the water and it needs more pressure to drain the water from the soil. The SWCC graph is shown in figure 5.4

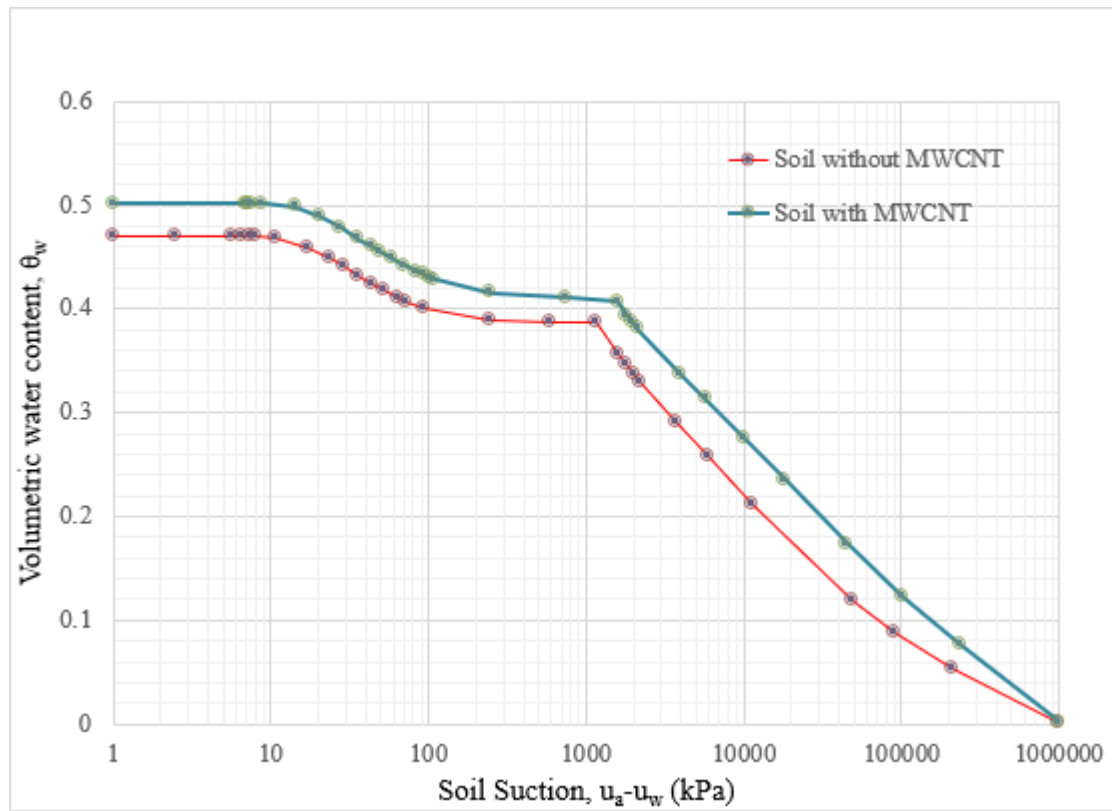


Figure 5. 4 SWCC

Table 5. 3 Best fitting parameters

SWCC parameters	Symbol	Soil without MWCNT	Soil with MWCNT
Saturated Volumetric Water Content 1	θ_{s1}	0.47	0.5
Suction at AEV1 (kPa)	Ψ_{a1}	5	9
Suction at inflection point 1 (kPa)	Ψ_{m1}	39.54	47
Saturated Volumetric Water Content 2	θ_{s2}	0.38	0.41
Suction at AEV2 (kPa)	Ψ_{a2}	1160	1537
Suction at inflection point 2 (kPa)	Ψ_{m2}	14994	18034

5.1.6. Permeability

The term "unsaturated permeability" describes the soil's capacity to carry water through its pore spaces when it is not completely saturated. In unsaturated conditions, the pore in the soil holds both water and air, and the suction affects the flow of water. To obtain the unsaturated permeability, the soil saturated permeability was obtained using Hyprop. Since Hyprop is only capable of obtaining the permeability data until 100 kPa, the unsaturated permeability of the soil were obtained using statistical data. The result for permeability of the soil is shown in figure 5.5.

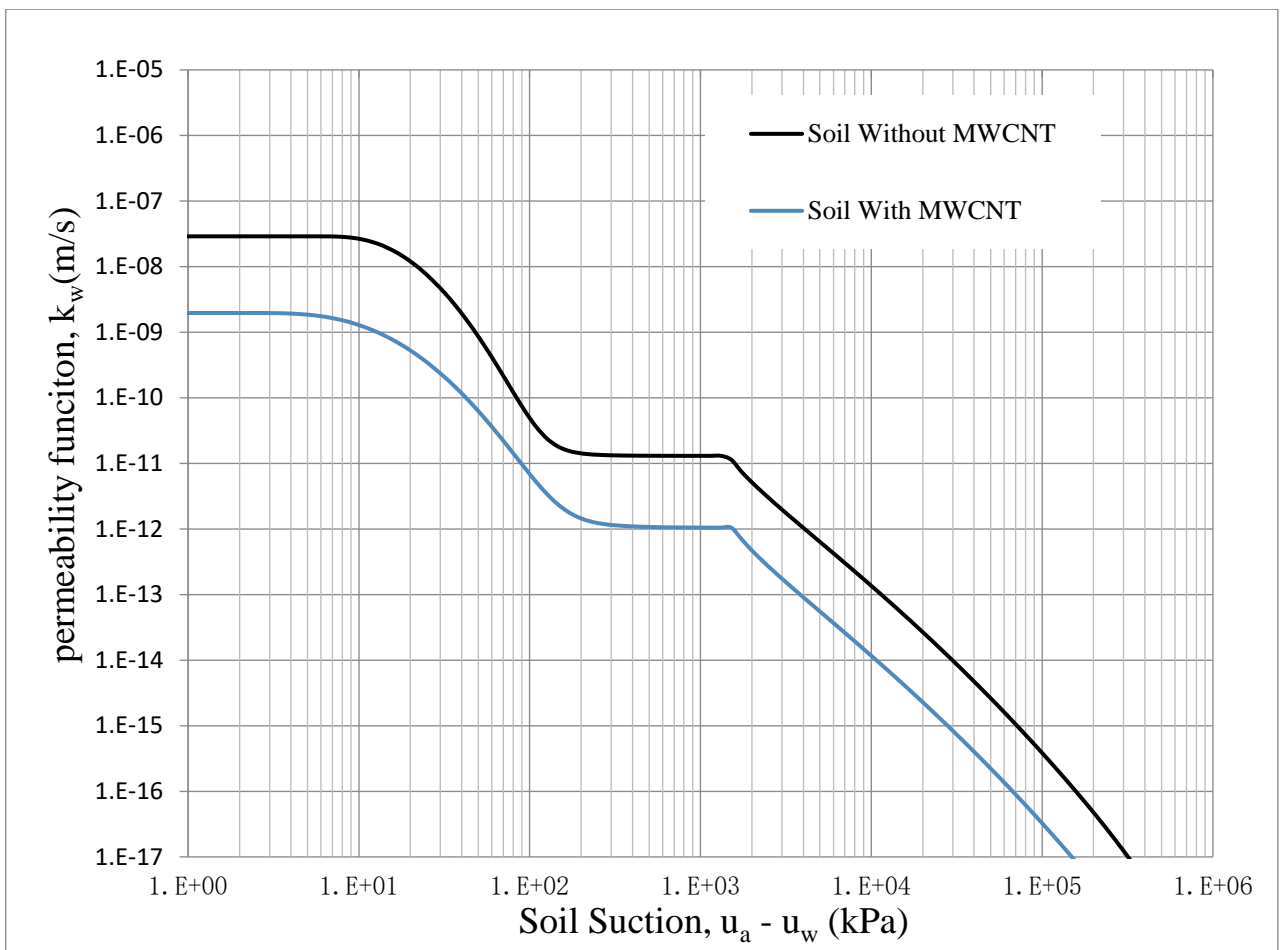


Figure 5. 5 Unsaturated Permeability

As seen in the graph, the result shows the unsaturated permeability of soil with carbon nanotube is lower. The Saturated permeability of soil without MWCNT is 3×10^{-8} , while the saturated permeability of soil with carbon nanotube is 2×10^{-9} m/s. The reduction in permeability of the soil could be attributed to the fact that carbon nanotube has the potential of affecting soils pores and connectivity of the soil. Since the CNT has very small particles, it can fill the voids in the soil and decrease the flow of water into the soil.

5.1.7 Unsaturated Shear Strength

Since obtaining unsaturated shear strength is very challenging and time consuming, I have used typical value for unsaturated shear strength from the literature. According to the USCS soil classification, the soil is classified as CL type. Therefore, I have used the data from the article Nam

et al. (2011) which has the same soil classification. The unsaturated shear strength of the soil is listed in table 5.4.

Table 5. 4 Unsaturated shear strength parameters

Description	Symbol	Value	Unit
Cohesion	c'	28	KPa
Friction Angle	ϕ'	22.5	degree
Unit Weight	γ	17.4	kN/m ³
Phb	ϕ^b	16	degree

5.2. -Seepage and Slope Stability Result

The analysis demonstrates that the factor of safety of slopes without carbon nanotubes and slopes with carbon nanotubes are similar at the beginning. After the passage of time, the factor of safety decreases in both slopes but the rate is very high in the slope without carbon nanotubes.

The analysis result of Seepage analysis using SEEP/W demonstrated in figure 5.6a, 5.6b and 5.7a, 5.7b. The result of pore water pressure (PWP) for slope 10m height and 27 degrees as an example indicates that application of MWCNT on the slope has affected the PWP within the slope. The PWP within the slope in the first 4 days is almost the same for the higher depth, for both slopes, but it is higher in the slope surface for slope without carbon nanotubes. For instance, the PWP in the height of 5 m in the 4th day for slope without MWCNT and slope with MWCNT is 140.5 and 140.49 kPa, respectively and it is -7.21 and -7.22 kPa respectively in the height of 21 m. It shows that more water has infiltrated into the surface of slope without carbon nanotubes. As time passes, the difference in PWP within the slope is increasing. The PWP in 20th day of analysis within the 5 m height of slope without and with MWCNT is 156.9 kPa and 145.8 kPa respectively. The PWP within the height of 21m in this time frame is 9.85 kPa and -7.22 kPa. This comparison illustrates that more and more water is seeping into the slope without MWCNT and the stabilized layer acts as a barrier for water infiltration and decrease the water seepage into the soil. The result from all case studies shows a similar result. PWP in slope without MWCNT is higher compared to slope stabilized with MWCNT. The pore water pressure in the slope with carbon nanotube is lower because MWCNT is decreasing the permeability, as it is also shown in the slope stability analysis.

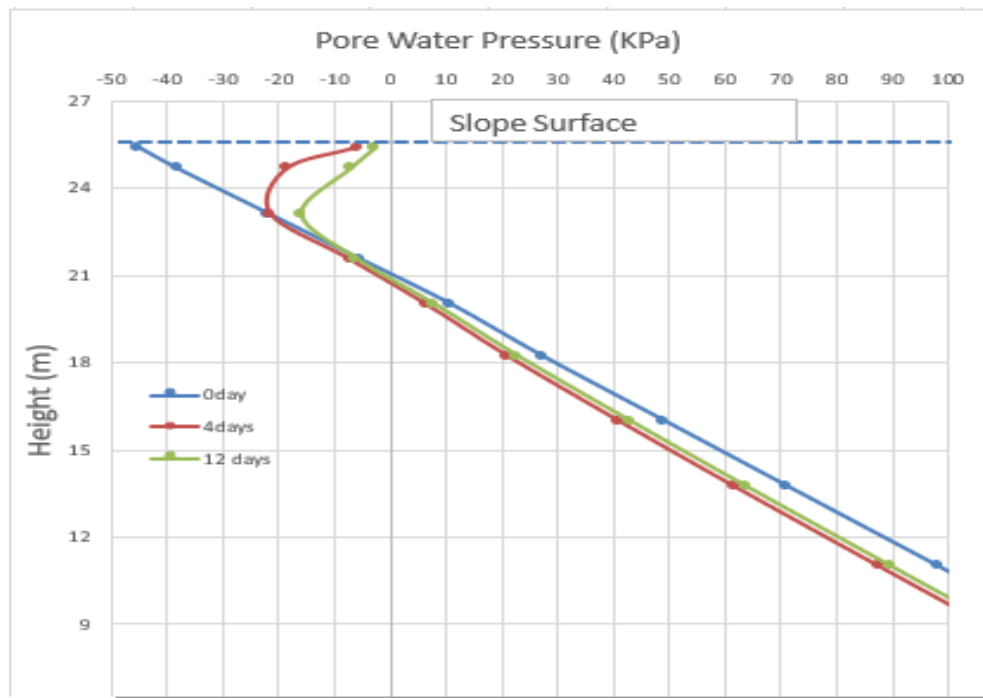


Figure 5. 6a Pore water pressure for the normal slope 10m 27 deg – Wet Period

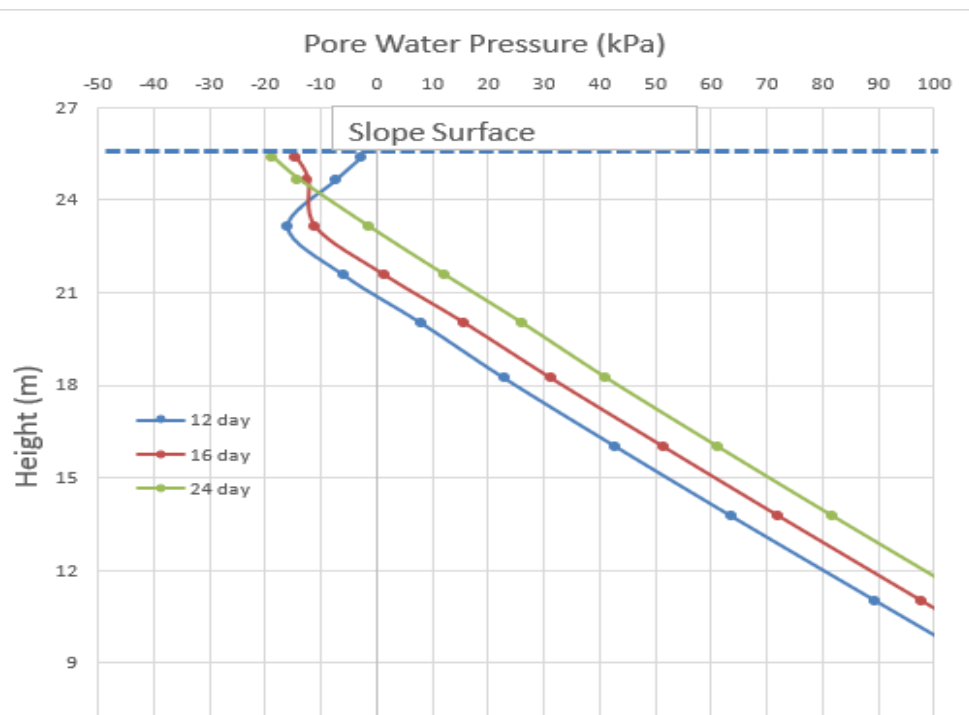


Figure 5. 7b Pore water pressure for the normal slope 10m 27 deg – Dry Period

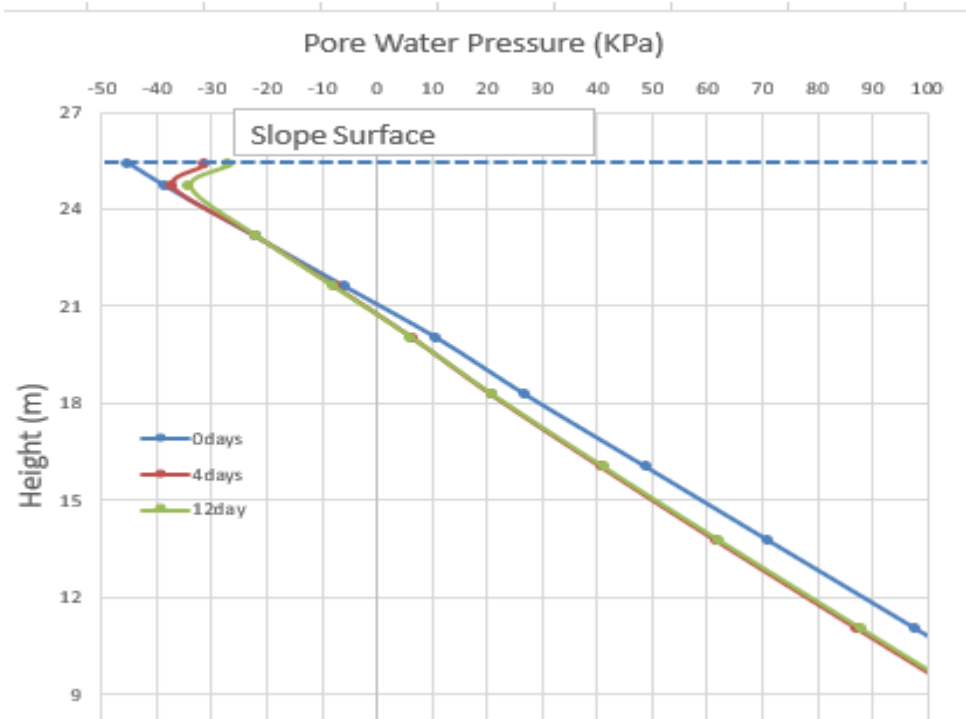


Figure 5. 8a Pore water pressure for the MWCNT stabilized slope 10m 27 deg – Wet Period

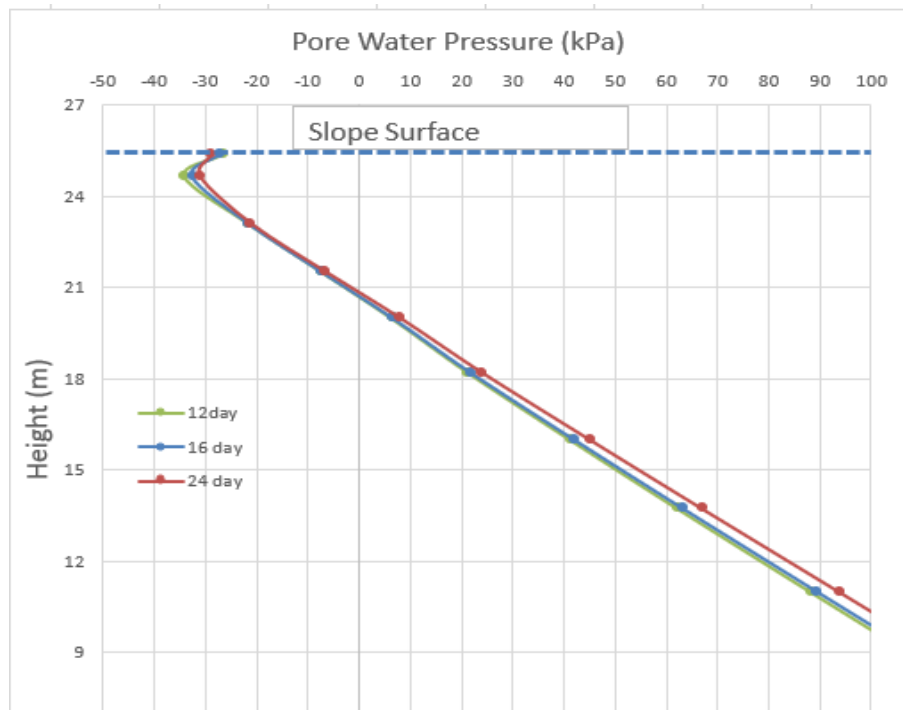


Figure 5. 9b Pore water pressure for the MWCNT stabilized slope 10m 27 deg – Dry Period

The result from Slope/W demonstrates the safety factor of slope. In the slope with 10m height and 27-degree angle, it shows that the FoS for both slopes are 2.66 at the beginning. The FoS starts declining,

because rainfall is infiltrating into the soil and undermines the strength of soil, as a result, it decreases the safety factor of slope. However, the FoS inclination in bare slope decreases faster than slope protected with 50cm layer of carbon nanotubes. The FoS at the end of raining period for bare slope is 2.59 which has decreased about 0.07 units, while the MWCNT stabilized slope decreased to 2.64 which has decreased about 0.03 units in safety factor. Comparing the results, the safety factor of bare slope has decreased about two times higher rates. The factor of safety for MWCNT stabilized slope remained almost constant after the raining period while the safety factor of slope without carbon nanotubes decreased to 2.36. The result of this analysis is demonstrated in fig. 5.8.

As the slope inclination has increased, the factor of safety decreased in both slopes with and without MWCNTs. However, the slope behaves the same; at the beginning the slope's safety factor is the same for both slopes and it decreases with higher rate in slope without MWCNT. As it is shown in figure 5.9, the FoS in slope with 10m height and 35-degree inclination is 2.28 at the beginning for both scenarios of with and without MWCNT. Comparing the result with slope of 10m height and 27-degree angle, it has significantly decreased. The factor of safety for the raining period for bare slope has decreased to 2.21 and for MWCNT stabilized slope it has decreased to 2.26. Again, the decreasing rate for slope without carbon nanotube is more than two times higher. The factor of safety at the end of drying period after 24 days, has decreased significantly for soil without carbon nanotubes, while it has only slightly changed for MWCNT stabilized slope.

The factor of safety for slope with the geometry of 10m height and 45-degree inclination has decreased to 1.9 for the beginning of the period for both slopes with and without MWCNTs. However, it has decreased to 1.64 for the slope without carbon nanotubes and it has decreased to 1.84 for slope stabilized with MWCNT. The FoS for slopes with 10m height and 60-degree inclination has dropped to 1.86 for the initial stage and it has dramatically decreased for the first 4 days, compared to slopes with lower inclination. Then it dropped to 1.74 for the stabilized slope and 1.6 for the normal slope. The analysis result using slope/W is shown in figure 5.10 and 5.11.

To affirm the result of the MWCNT on slope stabilization, analysis is performed on different slope height and angles. The result from slopes with 20m height and different angles are shown in figures 5.12 – 5.14. The factor of safety for slope with the 20m height and 27 m angle is 1.62 at the beginning for both cases of with and without carbon nanotubes. But over time, the safety factor of slope without carbon nanotube has decreased to 1.41 after 24 days while the safety factor of slope with carbon nanotube has changed only slightly, decreasing to 1.6. From the analysis, we can observe that with

the increment of slope height, the safety factor of slope is decreasing, even if the slope angle remains the same.

Similarly with the slope angle 35 degree and height 20m, the initial factor of safety is 1.34 for both slopes of with and without carbon nanotubes. its FoS for slope without carbon nanotubes becomes 1.14 which shows a huge inclination. But the FoS for slope with carbon nanotubes remains almost the same, with a slight change to 1.3 at the end of analysis period, which is 24days. However, the factor of safety of slope with 45-degree angle and 20m height fall below one, which is not recommended in the real life. Its factor of safety is 0.98 at the beginning and it decreases 0.87 for bare slope and 0.9 for MWCNT stabilized slope. The factor of safety for slope should be more than 1, which in the 60 degrees, this condition is not satisfied. Therefore, the slope is not stable.

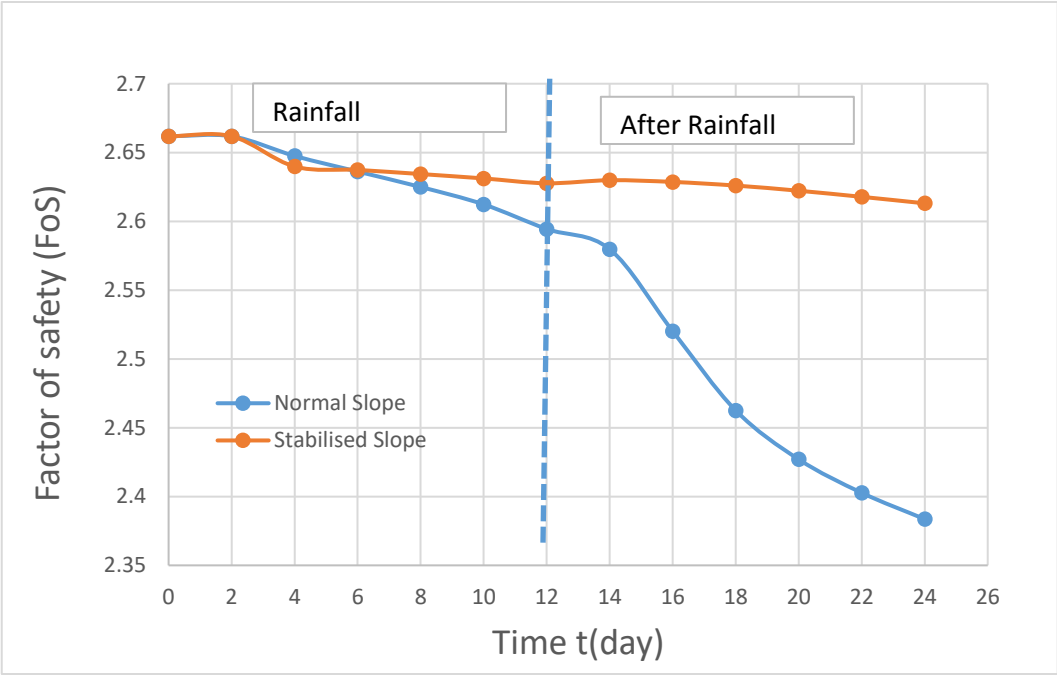


Figure 5. 10 Factor of safety of slope (10m 27deg)

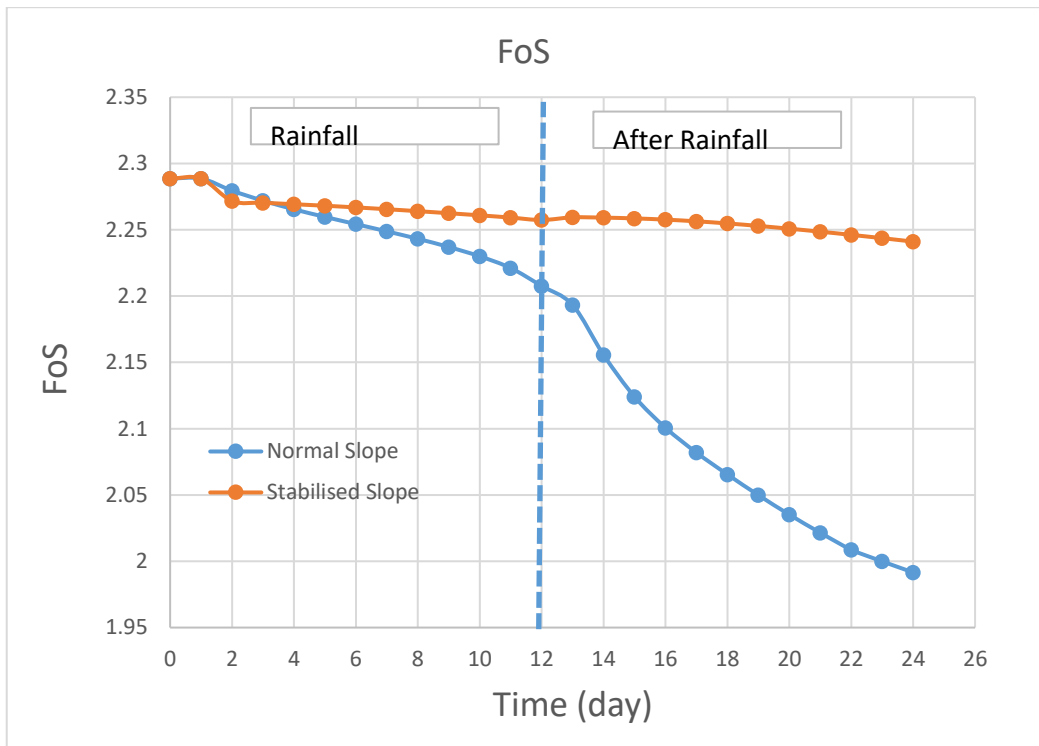


Figure 5. 11 Factor of safety of slope (10m 35deg)

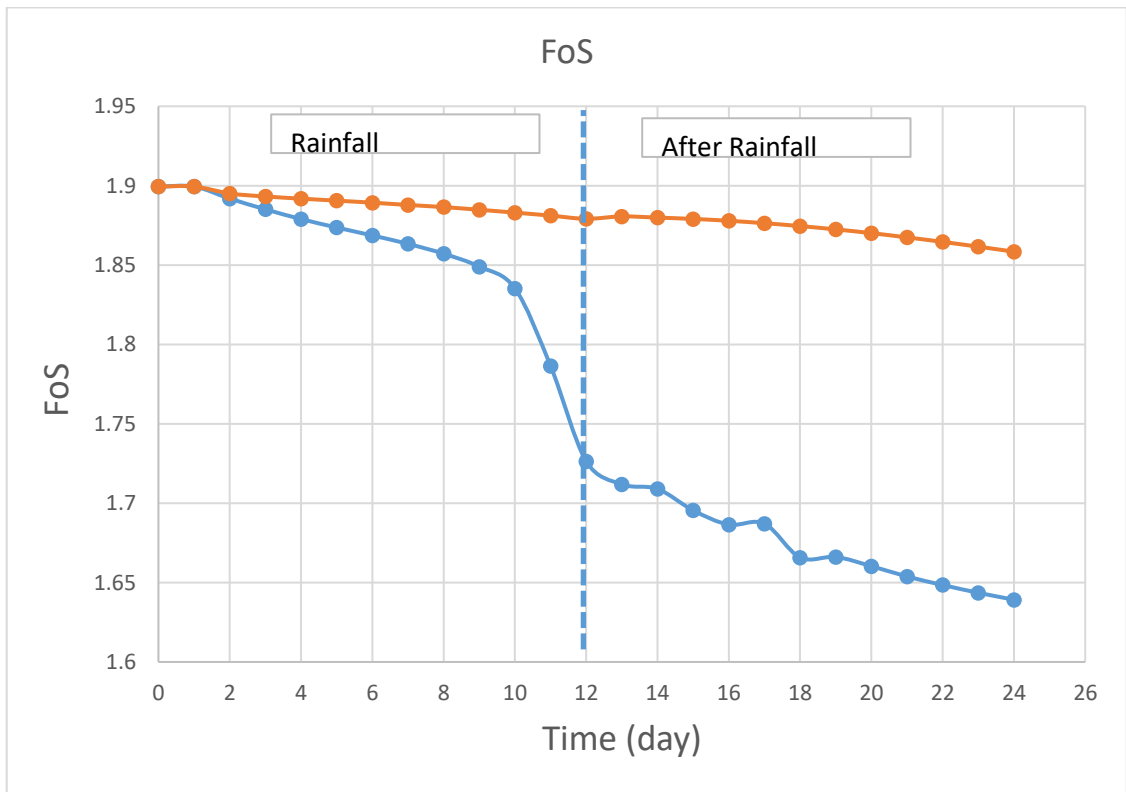


Figure 5. 12 Factor of safety of slope (10m 45deg)

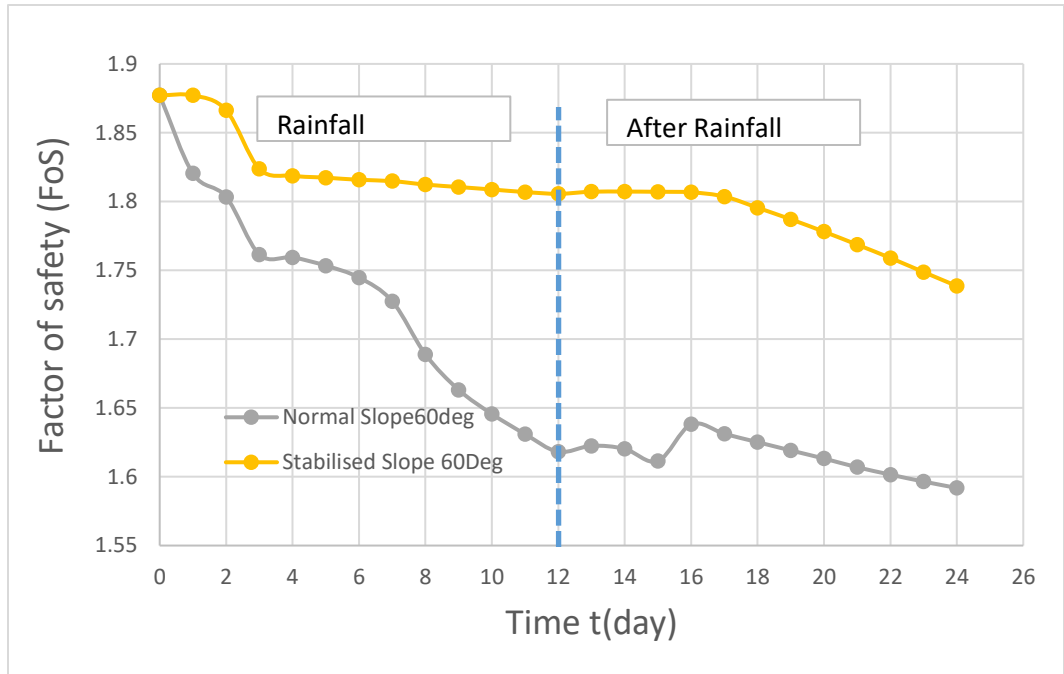


Figure 5. 13 Factor of safety of slope (10m 60deg)

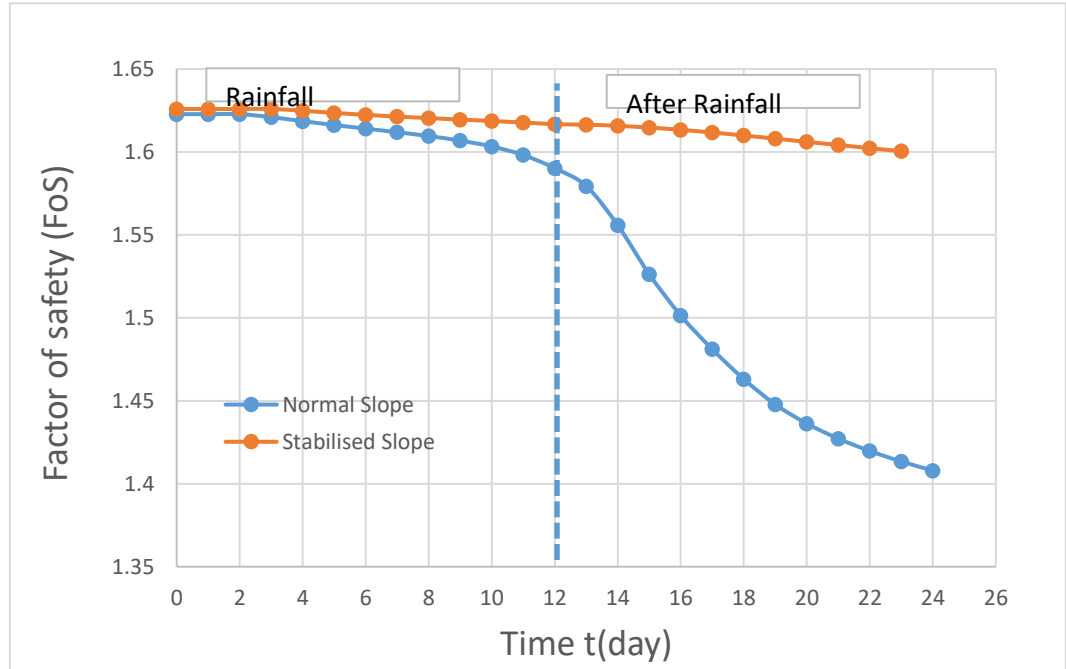


Figure 5. 14 Factor of safety of slope (20m 27deg)

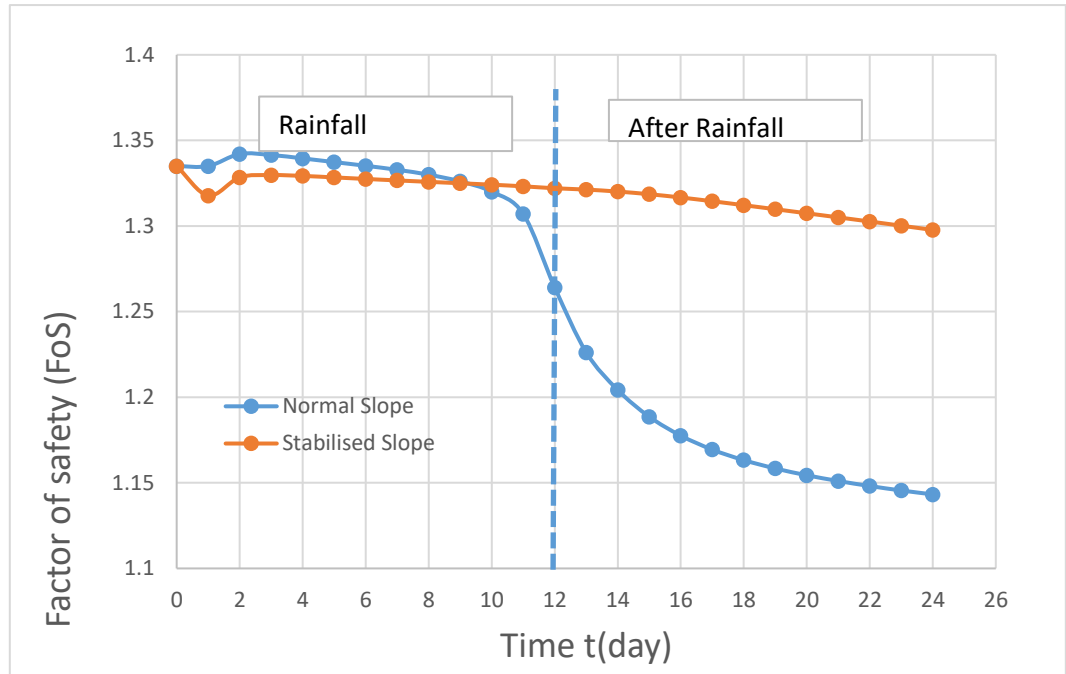


Figure 5. 15 Factor of safety of slope (20m 35deg)

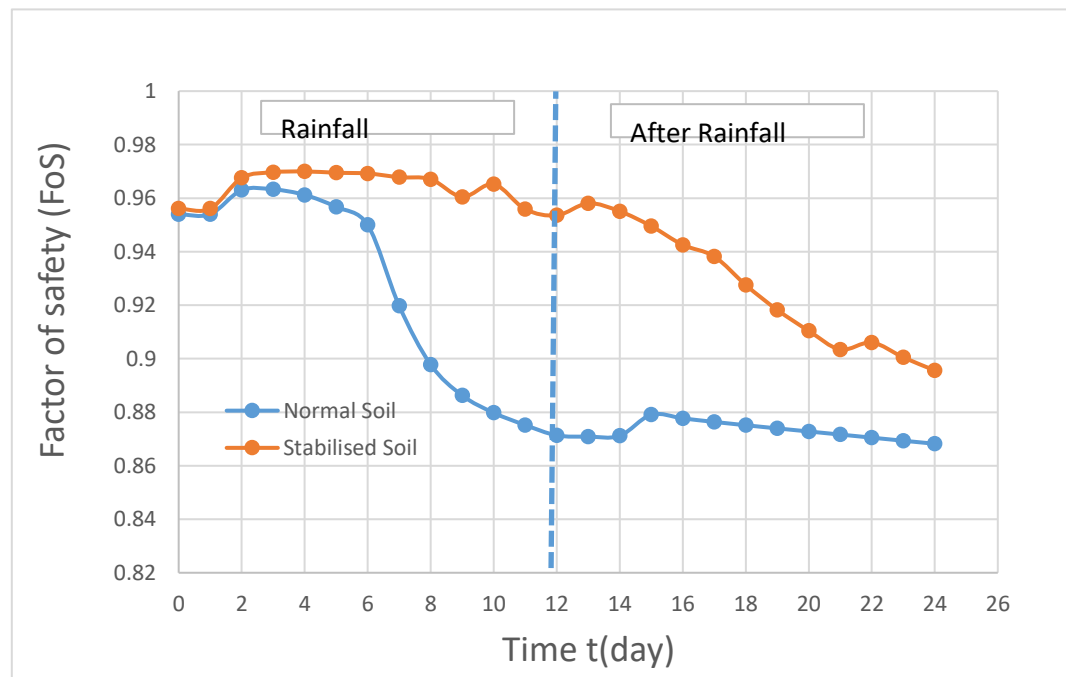


Figure 5. 16 Factor of safety of slope (20m 45deg)

Chapter 6 - Discussion

The results from numerical analysis and laboratory tests are very intriguing. This chapter has discussed the result thoroughly and the application of carbon nanotube for slope stabilization.

The result from numerical analysis demonstrates that the factor of safety of a slope without carbon nanotube starts to decrease dramatically during the raining period. The result from seepage analysis shown that the PWP is greater at the surface area of slope without MWCNT because it is easier for water to infiltrate into the soil. The analysis demonstrates that the pore water pressure increases in respect to depth. This could be attributed to the water table and water seepage during the rainy period. Therefore, the safety of slopes decreases for the whole analysis period. On the other hand, when 50 cm of the slope is covered with MWCNT stabilized soil, the factor of safety undergoes only slight changes. This is because carbon nanotube is acting as a barrier to decrease water infiltration, as a result the pore water pressure in the slope with MWCNT is lower. The initial pore water pressure (PWP) is nearly identical for the higher depth in both slopes during the first four days. However, the PWP is greater at the surface of the slope lacking carbon nanotubes. As an example, the pore water pressure (PWP) at a height of 5 meters on the 4th day is 140.5 kPa for the slope without MWCNT and 140.49 kPa for the slope with MWCNT. Similarly, at a height of 21 meters, the PWP is -7.21 kPa for the slope without MWCNT and -7.22 kPa for the slope with MWCNT. Evidence indicates that a greater amount of water has penetrated the surface of the slope in the absence of carbon nanotubes. Over time, the disparity in pore water pressure (PWP) within the slope is growing. The pore water pressure (PWP) on the 20th day of study at a height of 5 meters on the slope is 156.9 kilopascals without MWCNT and 145.8 kilopascals with MWCNT. The PWP, or pore water pressure, reaches a maximum of 9.85 kPa and a minimum of -7.22 kPa within the 21-meter height during this time period. This comparison demonstrates that the absence of MWCNT results in an increased amount of water permeating into the slope. Conversely, the presence of the stabilized layer works as a barrier, preventing water penetration and reducing water seepage into the soil. Therefore, it indicates that carbon nanotubes can be used as a slope protector in situations where the slope is in good condition, but rain infiltration could jeopardize its safety. In this scenario, carbon nanotubes can work as a preventive layer for water infiltration which helps to maintain the slope's factor of safety and stability.

The affect that carbon nanotube has in keeping the factor of safety of slope could be attributed to its nanostructure that fills the voids in the soil and decrease infiltration into the soil, as a result the factor of safety of soil remain the same or only slightly decrease. Moreover, SEM results show that the carbon nanotubes are making interconnect network within the soil particle which result in higher

strength for the soil. As was found by Arabania et al., (2012), mixing 0.2% carbon nanotubes with soil can significantly increase the shear strength of soil. Increment in soil shear strength results in higher stability for slopes. Even though the shear strength parameters are not calculated in this research, and only typical and similar values are considered for both soils, the slope stability of soil showed significant improvements. Considering the finding by Arabania, and numerical analysis in this research, carbon nanotubes can improve FOS of slopes even with a higher rate, by keying in the real shear strength parameters from laboratory.

It is worth mentioning that application of carbon nanotubes for slope stabilization is resulting in keeping the slope stability under existing conditions, but its effectiveness depends on several factors including the type of soil, concentration of carbon nanotubes, the thickness soil layer that needs to be stabilized, rainfall concentration, and ground water table. Moreover, the environmental concern regarding the application of carbon nanotubes should also be considered and investigated.

The summary of absolute factors of safety of different slope height an angle is demonstrated in the table 6.1. and illustrated in figure 6.1. The chart of absolute safety factor for different slope geometry shows that MWCNT has increased the safety factor in all cases. The FoS of slopes for slope with 10m height and 27deg, 35deg, 45 deg and 60 deg has increased 9.6%, 12%, 13% and 6.7% respectively. The FoS of slope with 20m height and 27 deg, 35 deg and 60 deg has increased by 11%, 13% and 3.2%.

Table 6. 1 Factor of Safety of Slopes

Slope Properties	FoS of Normal Slope	FoS of CNT stabilized slope
10m 27deg	2.384	2.613
10m 35deg	1.992	2.242
10m 45deg	1.639	1.858
10m 60deg	1.491	1.591
20m 27deg	1.408	1.572
20m 35deg	1.143	1.298
20m 45deg	0.868	0.896

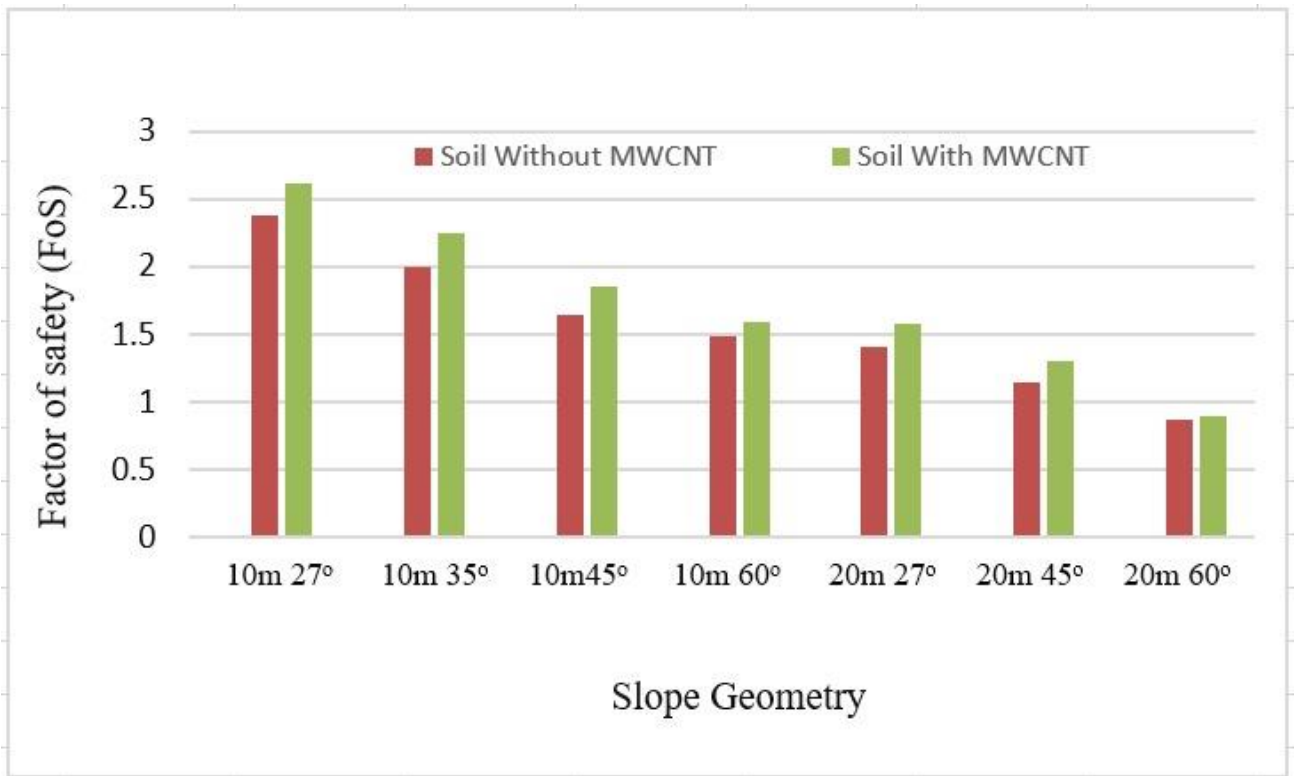


Figure 6. 1Factor of Safety Vs Slope Geometry

Chapter 7: Conclusion

In this chapter, the result from laboratory tests and numerical analysis is outlined. According to the results obtained, multi walled carbon nanotube (MWCNTs) are affecting the soil characteristics, which result in affecting the safety factor of slopes. The result from index properties shows that adding carbon nanotubes into soil increases liquid limit, plastic limit and decreases the plasticity index of the soil.

1. The SWCC result demonstrates that adding carbon nanotubes into the soil is increasing the air entry value of soil, indicating it is helping the soil to prevent excessive water infiltration and help the slope to remain under existing conditions.
2. The permeability function demonstrates that soil mixed with carbon nanotube has lower permeability. It helps the slope to be more stable because it prevents excessive water infiltration.
3. The result from numerical analysis indicates that application of carbon nanotubes helps the slope stability to remain under the existing condition. Comparison between the slope with and without carbon nanotubes for all slope angle and height, demonstrates that the slopes factor of safety for the beginning of period is the same for both scenarios of MWCNT stabilized slope and slope without carbon nanotubes. The result for the first period shows that the FoS are decreasing because of the water infiltration. However, after the rainfall, the FoS of slope without carbon nanotubes decrease dramatically, while the MWCNT stabilized slopes FoS only change slightly.
4. The result from numerical analysis shows that slopes factor of safety is decreasing with increment in slope's inclination and height. The FoS of slope with the geometry of 27-degree inclination and 10m height, for the beginning of the period $t = 0$, is 2.66 for both scenarios of slope with and without carbon nanotubes. At the end of the period, the safety factor of slope without MWCNTs decreases to 2.39 and FoS of slope with MWCNTs changes only slightly, showing 2.63. As the slope inclination increased to 35, 45 and 60 degrees, the factor of safety decreased to 2.28, 1.9, 1.84 respectively. Similarly, as the height of the slope increased to 20m, the FoS of slopes decreased to 1.62, 1.34, 0.98 for the inclinations of 27, 35 and 45 degrees.

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APPENDIX A

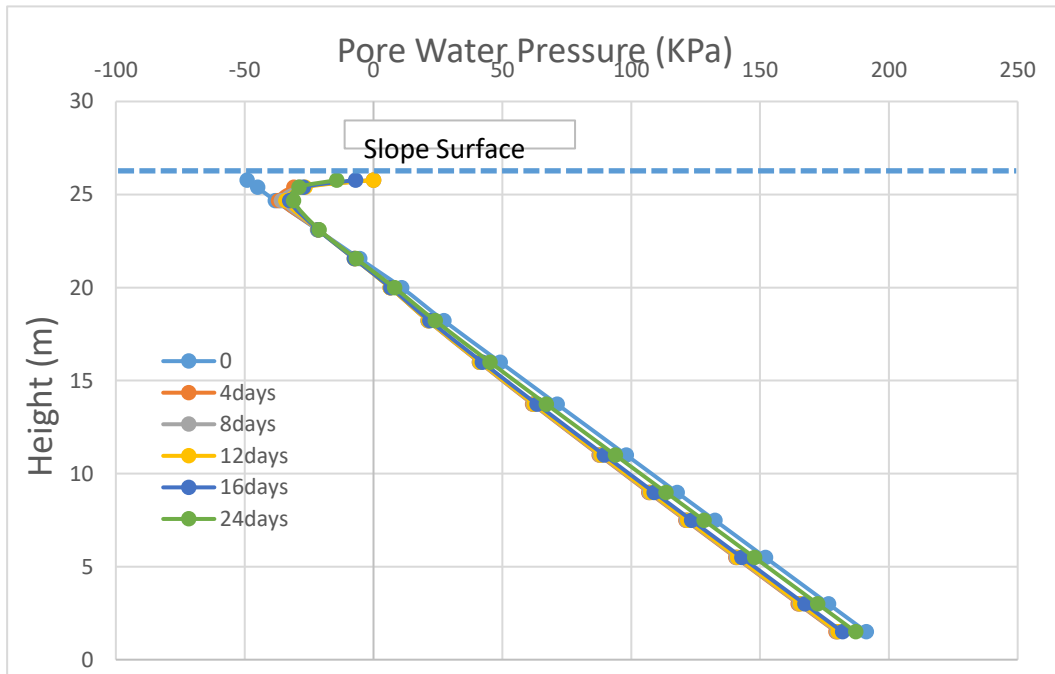
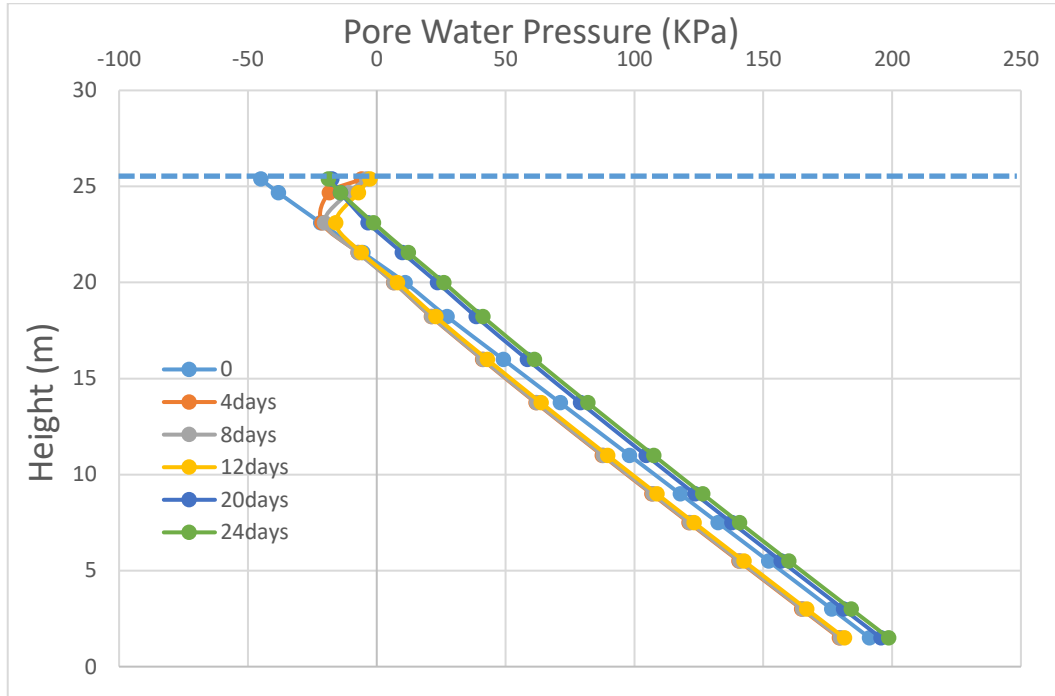


Figure A1. Pore water pressure for the normal slope 10m 27 deg

Figure A3. Pore water pressure for the CNT stabilized slope 10m 27 deg

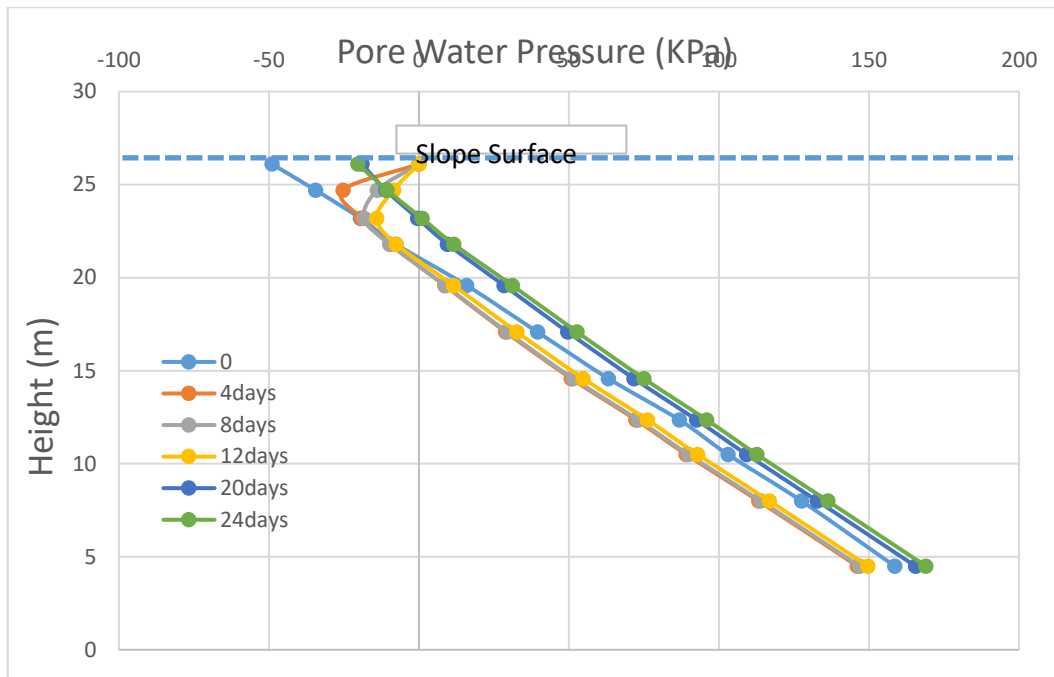


Figure A3. Pore water pressure for the normal slope 10m 35 deg

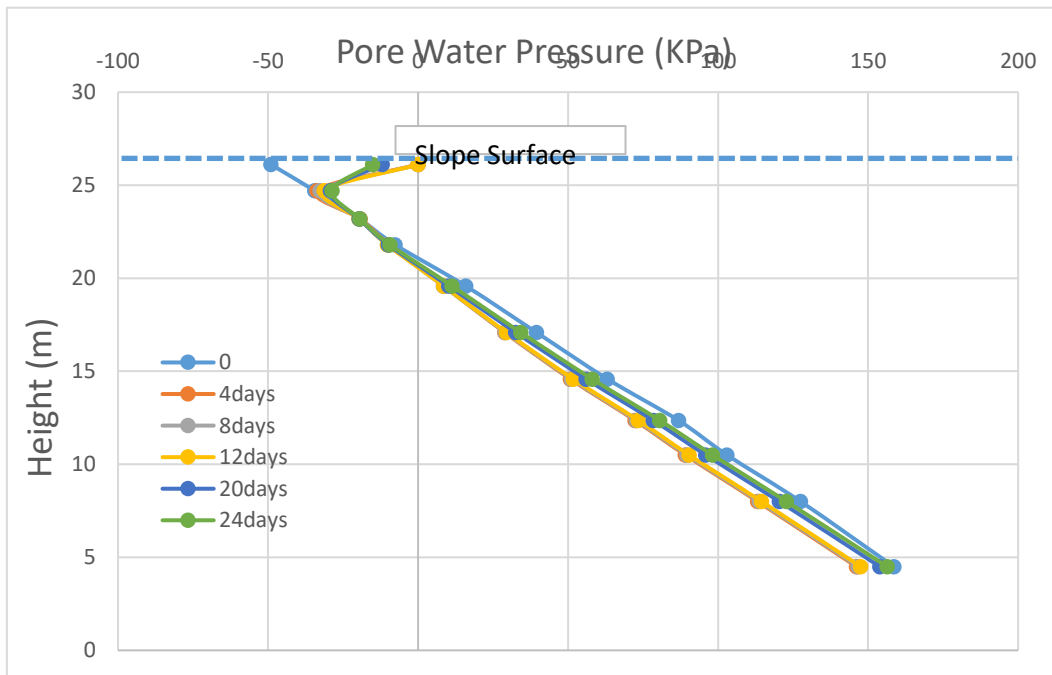


Figure A4. Pore water pressure for the CNT stabilized slope 10m 35 deg

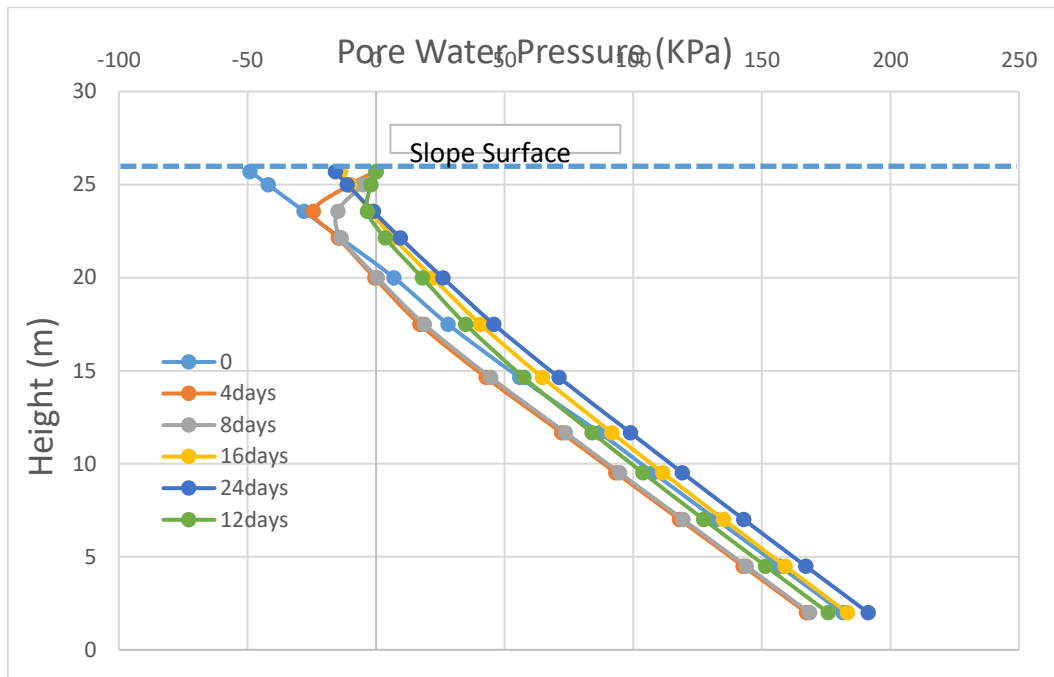


Figure A5. Pore water pressure for the normal slope 10m 45 deg

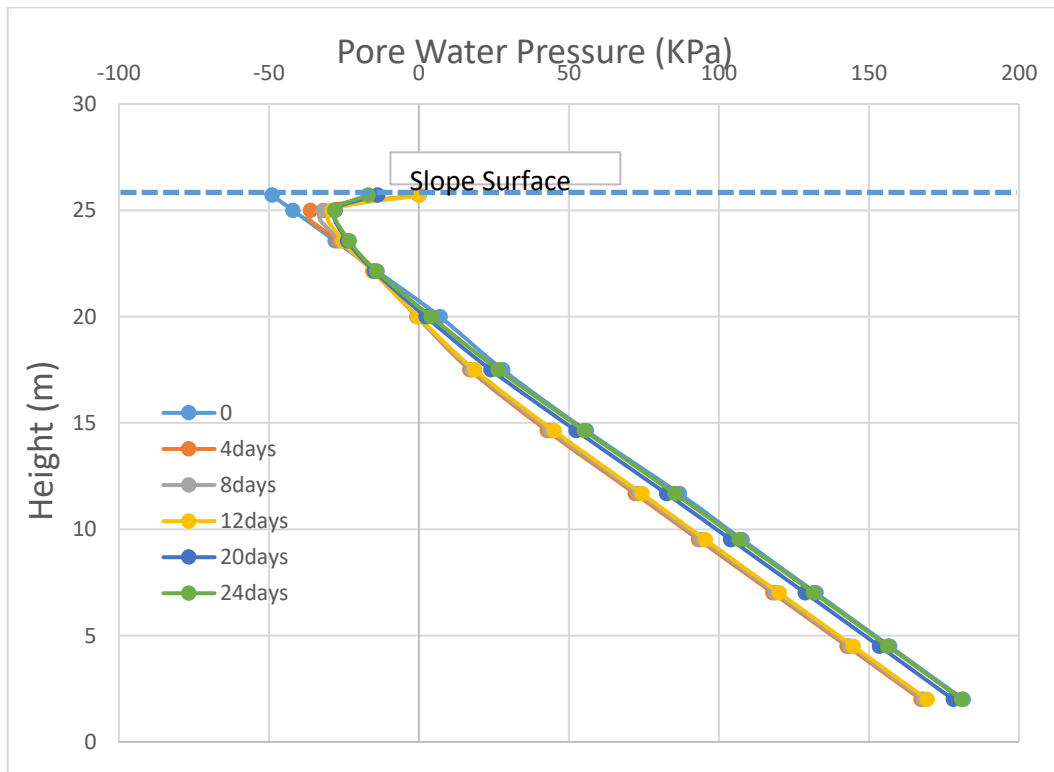


Figure A6. Pore water pressure for the CNT stabilized slope 10m 45 deg

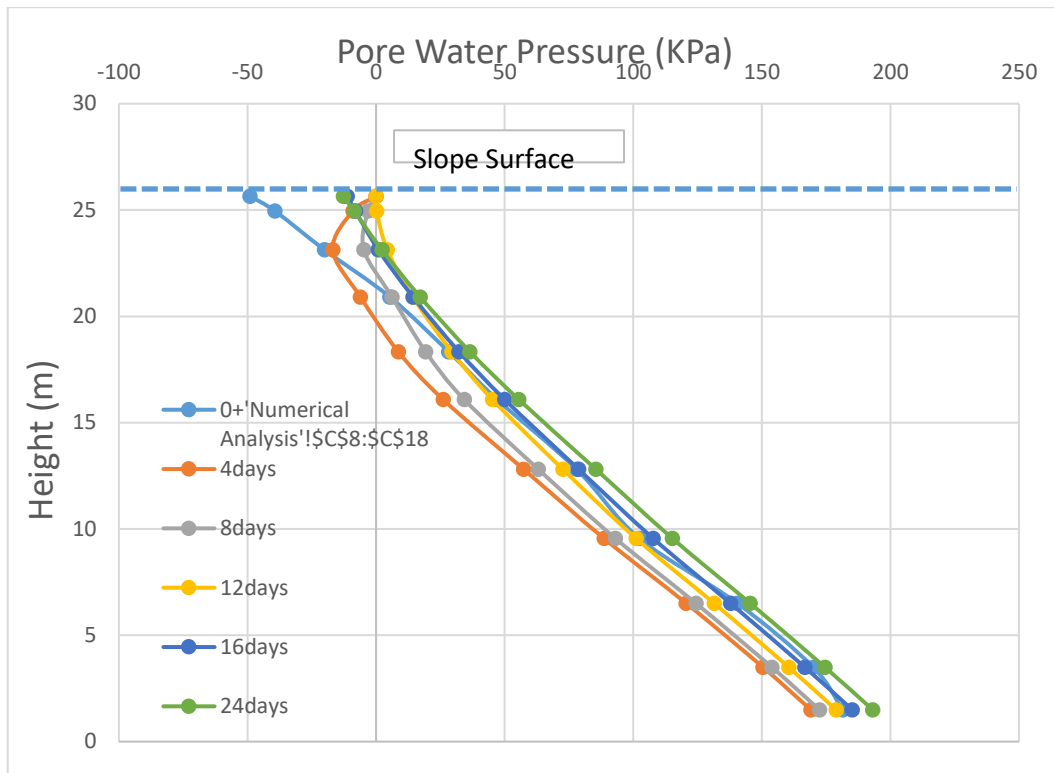


Figure A7. Pore water pressure for the normal slope 10m 60 deg

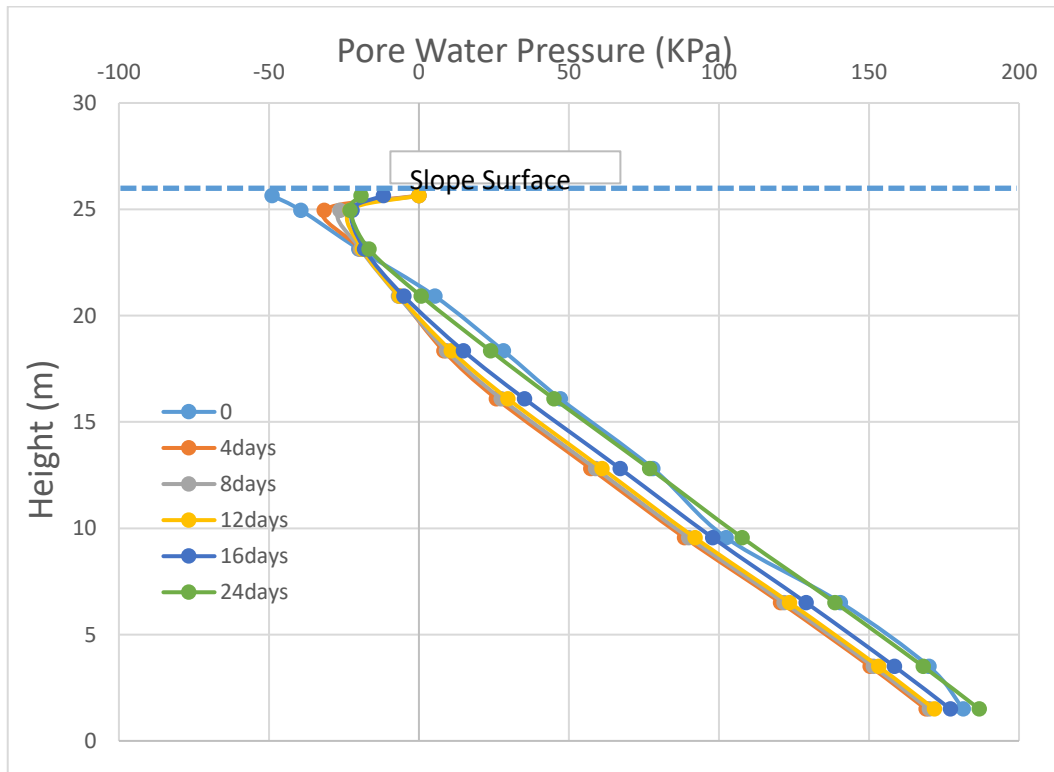


Figure A8. Pore water pressure for the CNT stabilized slope 10m 60 deg

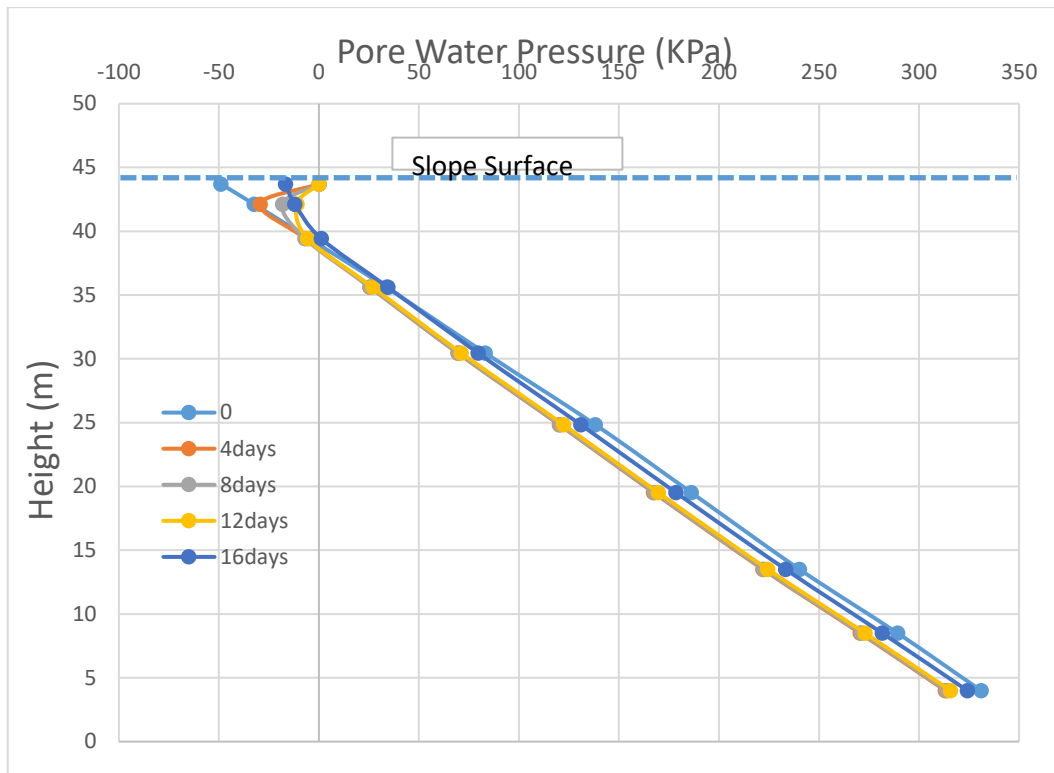


Figure A9. Pore water pressure for the normal slope 20m 27 deg

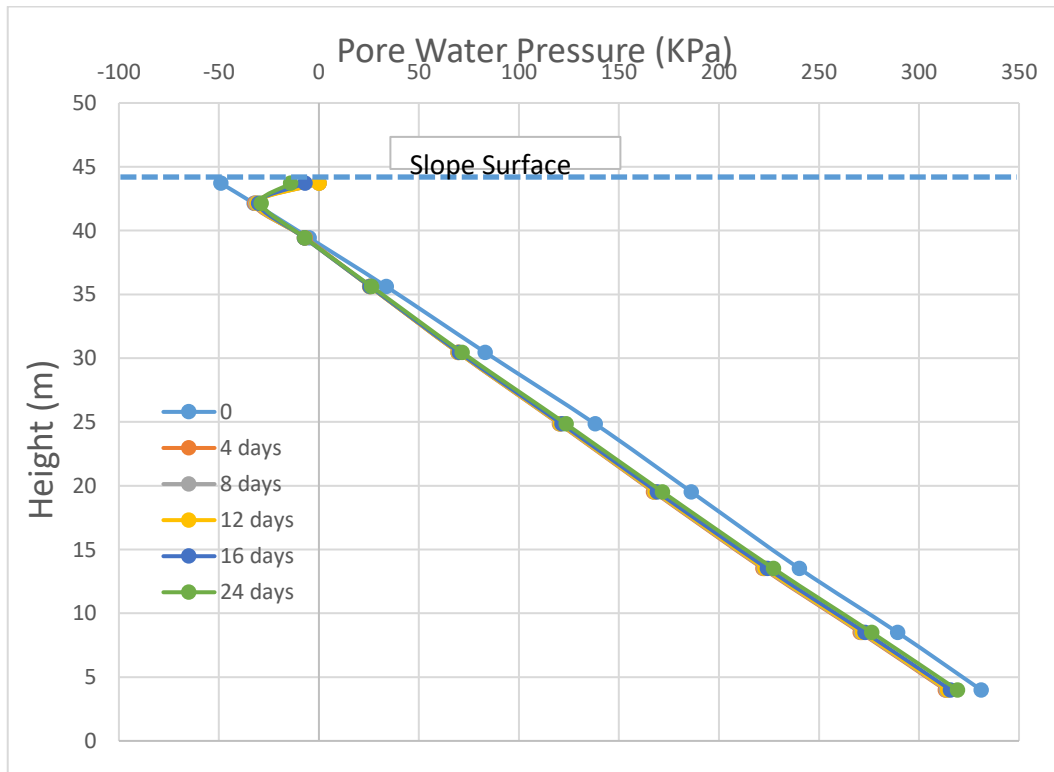


Figure A10. Pore water pressure for the CNT stabilized slope 20m 27 deg

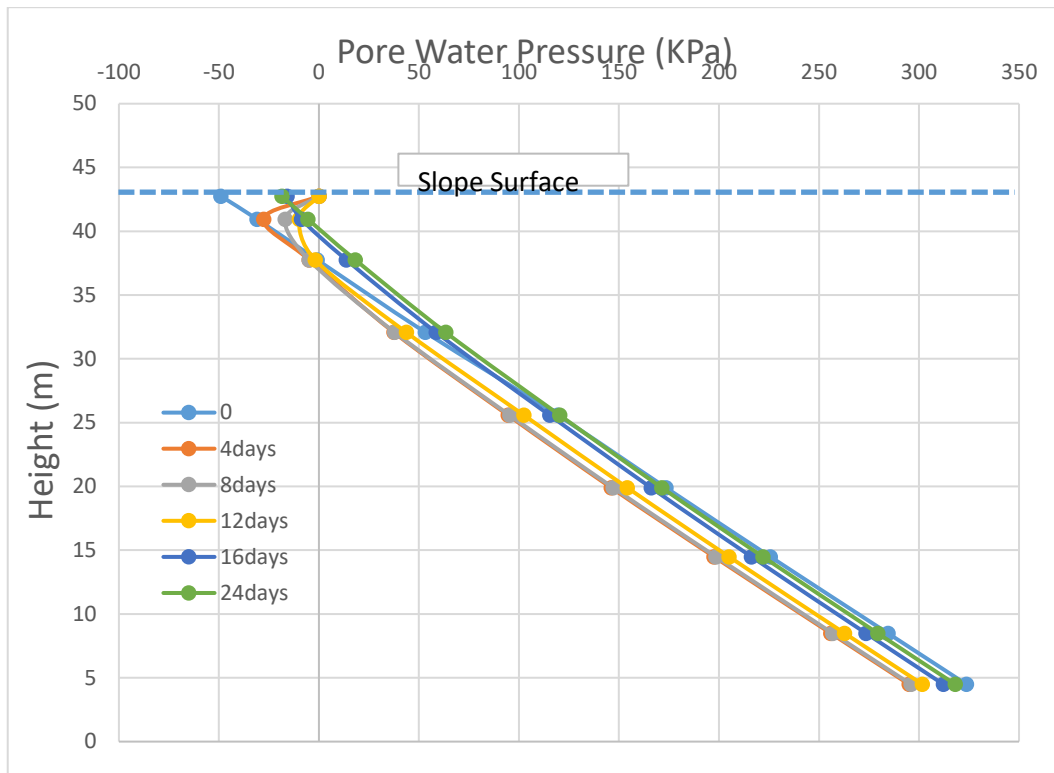


Figure A11. Pore water pressure for the normal slope 20m 35 deg

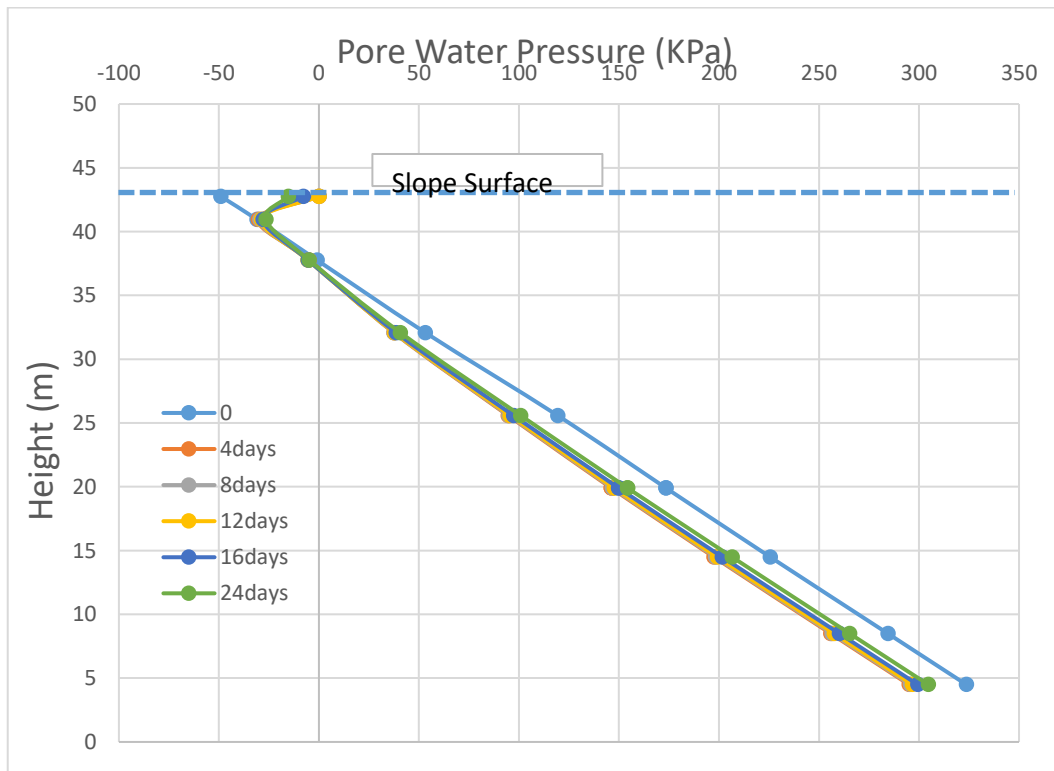


Figure A12. Pore water pressure for the CNT stabilized slope 20m 35 deg

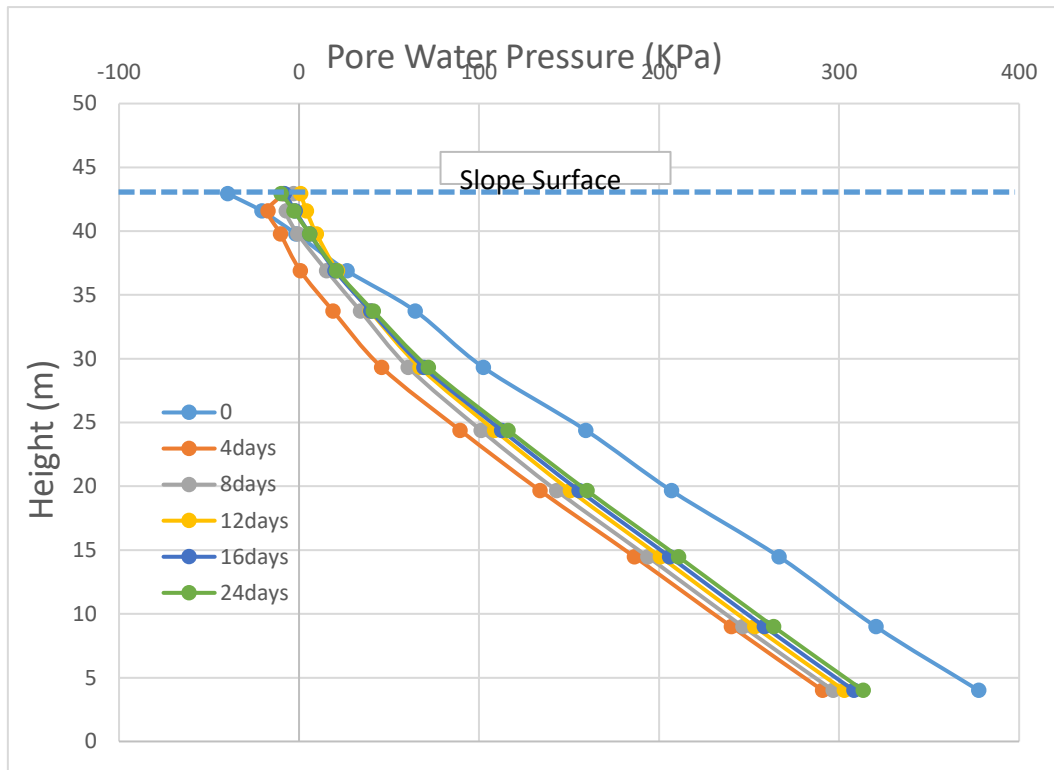


Figure A13. Pore water pressure for the normal slope 20m 45 deg

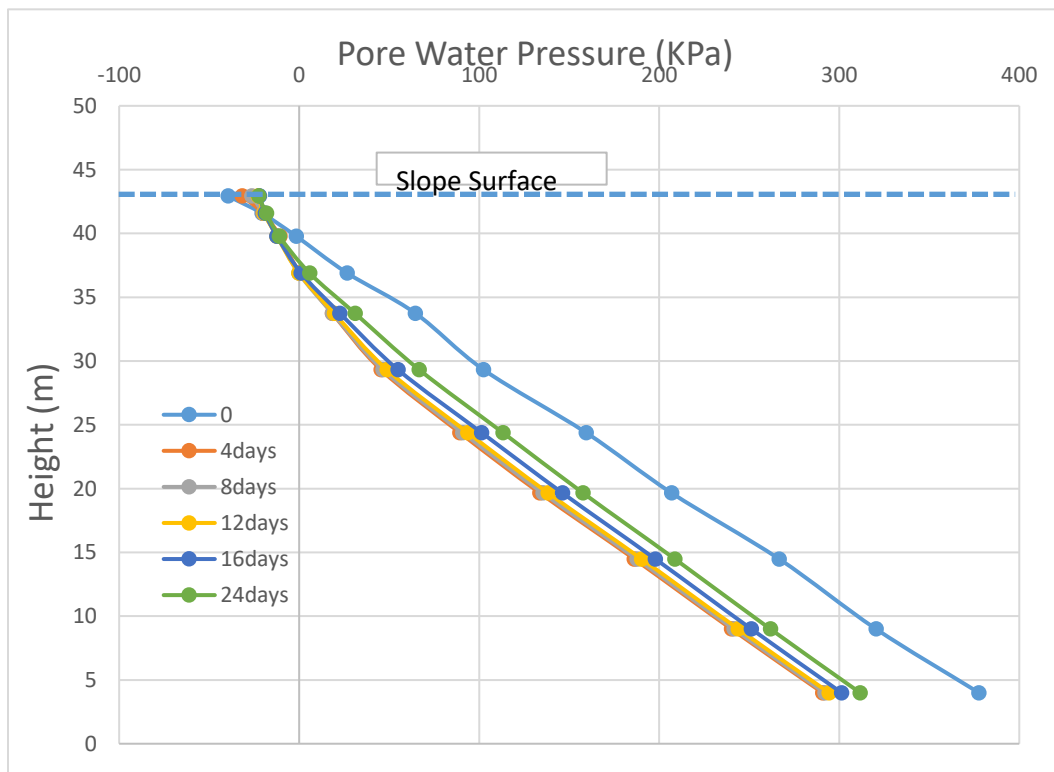


Figure A14. Pore water pressure for the CNT stabilised slope 20m 45 deg