SIMULATION OF SLOPE STABILITY WITH *EUGENIA OLEINA* AGAINST SOIL EROSION

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ABSTRAK

Teknik kejuruteraan-bio telah diguna diseluruh dunia sebagai suatu kaedah untuk mengawal kestabilan cerun bergantung kepada kedalaman cerun itu sendiri. Kaedah yang paling biasa digunakan adalah dengan penggunaan “live pole” pada bahagian cerun bagi mengelakkan kejadian hakisan tanah yang akan memberi masalah dalam bidang kejuruteraan geoteknikal. Hakisan tanah juga mungkin terhasil daripada fenomena hujan lebat dan juga tekanan matrik tanah. Kajian ini dijalankan bagi mengenalpasti faktor yang mempengaruhi hakisan tanah yang berlaku pada cerun berdekatan makmal FKASA di Universiti Malaysia Pahang dan menentukan tujuan penanaman pokok dikawasan cerun samada membantu mengelakkan hakisan tanah daripada berlaku. Bagi mengenal pasti potensi akar pokok tersebut untuk menahan tanah daripada terhakis, beberapa ujian makmal telah dijalankan oleh para pelajar terhadap akar pokok yang telah ditanam dikawasan cerun, bagi mengetahui kekuatan akar pokok tersebut. Hasil ujian makmal akan digunakan bagi menghasilkan simulasi kestabilan cerun dengan menggunakan perisian yang digunakan secara meluas di dalam bidang kejuruteraan geoteknikal. Perisian yang akan digunakan di dalam kajian ini dikenali sebagai Plaxis 2D, sebuah perisian geoteknikal yang digunakan secara menyeluruh di dalam industri. Hasil keputusan yang diharapkan melalui simulasi ini adalah untuk mencadangkan rujukan dari segi pengukuhan untuk panduan masa hadapan bagi mengurangkan masalah kestabilan cerun.

ABSTRACT

Soil bioengineering techniques has been used worldwide as to control the slope stability. A commonly used idea is to apply live pole at the slope area in order to prevent the soil erosion which causing the problem in geotechnical engineering. Soil erosion may occur due to heavy rainfall or also from soil matrix pressure. This research is conducted with aim to find out the cause of soil erosion that occured at the slope near FKASA surveying lab in University Malaysia Pahang and the purpose of having *Eugenia Oleina* species planted on the slope whether it is helpful in preventing soil erosion. In this research, the results from the previous lab test was used in simulating the slope stability with *Eugenia Oleina* using the finite element software that is widely used in geotechnical engineering, which is known as Plaxis 2D. The factor of safety obtained from the simulation shows that the rooted soil with *Eugenia Oleina* are low compared to the unrooted soil.

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β	slope angle (º)
c’	soil cohesion (kPa)
Δs	root cohesion (kPa)
$\emptyset'$	soil friction angle (º)
γ_{sat}	saturated bulk unit weight (kN/m^3)
γ_w	Unit weight of water (kN/m^3)
γ'	“submerged’’ bulk unit weight
z	vertical depth of the failure plane (m)
W_v	Overload due to vegetation (kPa)

LIST OF ABBREVIATIONS

FOS	Factor of Safety
KSU	Kompleks Sukan Universiti
FEM	Finite Element Method
FEA	Finite Element Analysis
SCD	Sand, Clay, Deep Clay
CSD	Clay, Sandy layer, Deep Sandy layer

CHAPTER 1

INTRODUCTION

1.1 Introduction

Slope stability problems always occur regardless of its location whether it happens in Malaysia or even worldwide. Slope is stable only when there is no movement happen or when it is stable to resist any soil movement at the slope. Slope also can be categorized into natural ground slope and man-made slope which exist along some highways and roads. Instability of slope often caused by the soil erosion that occurs after some heavy rainfall and also seepage pressure, despite of the gravitational forces which attracts the soils to fall down the slope.

The instability of slope may be reduced by using soil bioengineering techniques which has already been introduced in many countries in the world as a practical alternative using vegetation or live pole. It is stated that the vegetation technique is a combination of mechanical and hydrological effect to the slope (Ali N. et al, 2012). Shallow landslides with less than 2m deep are usually triggered by heavy rainfall and generally involve a thin layer of soil only but sometimes can affect large area.

Vegetation has both a silent effect on soil improvement to predict the landslide and a mechanical role to increase shear and pulling-out stress on the soil (Khalilnejad A et al, 2011). There are many researches has been done in centuries to prove that vegetation on the slope can prevent soil erosion to occur (Ali N. et al, 2012). It is stated that the roots from vegetation or live pole can give reinforcement and increase the shear strength of the slope itself. Hence, throughout this study, the focus will be on proving the roles of the live pole's roots in reducing the soil erosion at the slope in the research area.

The objective of this study is to measure the potential of the plant's roots in controlling the slope stability and the suction mechanism induce by the roots. The influence of the live pole will be derived and computed into Plaxis 2D (Jacob A. et al,

2018) to simulate the slope stability analysis. Another software which is Adonis also will be used in order to compare the results obtained from Plaxis 2D.

1.2 Problem Statement

Slope stability is an important aspect to make sure not only the safety of the area but also the civilians around the vicinity. Nevertheless, slope failure or soil erosion still can occur even though the design has already focused on the safety factor. It may occur to a shallow slope or even steep slope, no matter how the condition or the angle of the slope itself. In Malaysia, slope failure or soil erosion often happens even though Malaysia does not have a very steep slope, where the terrain of the mountains and hills is less than 25% (Hazlina and Jabil, 2017). Hence, a thorough study need to be establish in order to reduce the case of soil erosion where the slope design need to be observed.

Generally uncontrolled soil erosion may lead to slope failure. There are many factors that contribute to soil erosion and some of them already been mentioned in the introduction part. However, what is the main concern is if there are more to it especially with the live pole technique. Live pole is the bioengineering way of stabilizing and reinforcing slope from failure. Even though literature review shows the effectiveness of this method to anchorage slope and the soil, there is a subtle gap in this practice in Malaysia. There is no proper guideline or a well-documented research conducted using the local species or plants that works well for this purpose. Studies conducted in the past using live pole technique were only limited to check the stability of the slope and rather include the contribution of these plants in slope soil erosion. There should be a standard or a manual that suggests the type of species or plants that is suitable not only as to stabilize the slope but also to mitigate soil erosion at the same time. The choice of plants or species as live pole depends on the vulnerability of the slope soil to erosion.

1.3 Aim and Objectives

Aim

The main purpose of this research is to identify the cause of soil erosion which occurred at the shallow slope which is located near the surveying lab in University Malaysia Pahang.

Specific Objectives

1. To measure the potential of the plant roots in improving the soil properties.

2. To simulate the slope stability by using live pole.

1.4 Scope of Research

The focus for this research will be limited to the shallow slope which is available near the FKASA surveying lab and outside of KSU in University Malaysia Pahang, Gambang campus. The slope has been planted with a few of Eugenia Oleina's species, as a live pole, in order to study the role of its roots for reinforcement tools to prevent the soil erosion at the slope during rainfall. The research will be done by measuring the potential of the roots by using the data obtain from lab test.

The research will also focus on simulating the slope stability using the live pole with a 2D software which is Plaxis in comparison with another software called Adonis software. It will be taken about 3 months to complete this research on determining the cause of soil erosion and then simulate the stability of the slope by computing the data obtain from the previous investigation and lab tests. This research is also conducted to analyze the current shallow slope condition and previous investigations to propose a method in order to stabilize slope from future erosion.

1.5 Significance of Research

Slope instability is an inconvenient problem happens worldwide which occur without any warning. Some of the slope instability problems causing death and also infrastructural damage. Hence, by conducting this research, a guideline of how to retain the slope can be introduce for future references. This research is focusing on the importance of Eugenia Oleina species in inducing the slope stability. Thus, a guideline on species of live pole which is more suitable for slope stability also can be proposed in comparison to the current species used.

In addition, this research of simulating the slope stability using live pole also may contribute to a green technology, which adding to a very environmental-friendly and cost effective way in dealing with engineering design involving slope study. It is also can reduce the carbon print in comparison of using a traditional way of study apart from creating awareness on how technology can be useful to predict and prevent the problems arise.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Slope stability analysis became a very important aspect that need to be evaluated thoroughly in geotechnical engineering as it involves the safety of the area and the civilians. In a book with a title of "Slope stability analysis and stabilization: new methods and insight", it is stated that previously engineers preferred to use a stability charts which was established by Taylor (1937). Nowadays, as the time goes by and the era of technology blooms, the analysis of slope stability can be done by using computer software to evaluate the stability in design.

Slope stability, in terms of geology, can be defined as the resistance of an inclined surface to failure by sliding or collapsing. Slope only can be called stable when there is no movement happen or when it is stable to resist any soil movement at the slope. Gravitational forces are always acting on a mass of soil or rock beneath a slope. But, the movement does not occur when the strength of the mass is equal or greater than the gravitational forces. Slope failure can be classified in many types based on the kind of material involved and type of movement it applies. It can be divided into six categories of slope movements such as falls, topples, slides, lateral spreads, flows and also composites (Rahman, H and Mapjabil, J., (2017). It is further explained in the research that soil experiencing slides movement, will either have rotational (shallow) or translational (depth) while complex is the combination of two or more movements that happen to the soil.

Soil erosion can be classified as a slope failure which triggered by variety of factors or process. Erosion can be caused by wind or water, deterioration in physical, chemical and biological or economic properties of the soil and long-term loss of natural vegetation (Singh, 2016). Instability of slope often caused by the soil erosion that occurs after some heavy rainfall despite of the gravitational forces which attracts the soils to fall down the slope.

In Malaysia, soil erosion is often caused by the high intensity rainfall with average rainfall about 250 centimetre a year. It is stated that even though Malaysia does not have a very steep slope, where the terrain of the mountains and hills is less than 25%, slope failures are also frequently happened here (Rahman, H and Mapjabil, J., 2017).

2.2 Slope Classification

Slope can be classified based on its gradient and type, where the slope gradient may be obtained by measuring from its horizontal plane, while the type of slope can be categorized into natural and man-made slopes.

Based on Penang's Safety Guideline for Hill-site Development 2012, the slope classification can be divided into 4 class which is Class 1, 2, 3 (3A & 3B), 4 (4A & 4B). Table 2.1 shows the class of slope and its associated risk with types of slope as a reference on design purposes. This can be the benchmark of the design of slope by preventing the slope failure to occur.

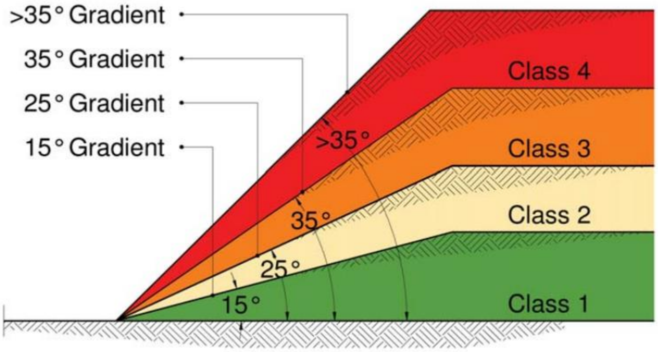


Figure 2.1 Classification of slope

Source: Penang Guideline for Hillsite Development (2012)

Table 2.1 Slope Classification for design purpose

Class	Slope Gradient	Associated Risk: Natural Slope	Associated Risk: Man-made slope – cut	Associated Risk: Man-made slope – fill	Maximum allowable hard surface footprint
1	0° - 15°	low	low	low	Refer to current policy
2	>15° - 25°	low	low	low	
3A	>25° - 35°	medium	medium	-	35%
3B	>25° -35°	-	-	high	35%
4A	> 35°	high	high	-	30%
4B	> 35°	-	-	Very high	30%

Source: Penang Guideline for Hillsite Development (2012)

Based on Table 2.1 above, it shows that with the increment of the slope gradient, the higher the risk of the slope to have any construction progress on the slope. It is stated in the book that the maximum allowable hard surface footprint has been reduced 5% intentionally for Class 3A & 3B and about 20% for Class 4A & 4B slopes. This will improve safety and enhance the preservation of the green environment.

2.2.1 Types of Slope

Slope also can be categorized into natural ground slope and man-made slope which exist along some highways and roads

2.2.2.1 Natural Slope

This type of slope exists in hilly area and formed in a natural process. Based on research conducted previously, analysis of the results shows that the slides of natural slope were influenced by the geotechnical properties of the soil, the weathering, the hydrogeological situation, and the erosion by waves (R. Azzam et al., 2006). This shows that this slope still can undergo failure even though it has been stable for so many years.

Creep–fatigue phenomena could be a possible explanation for failures of the natural slopes and cuts (S. Leroueil, 2001). In fact, fatigue is a well-accepted phenomenon in mechanical engineering, and even in rock mechanics. He also stated that if most natural soils are micro-structured hence that natural slopes and cuts can be affected by creep–fatigue phenomena, where creep and fatigue are the phenomenon that lead to deformation and eventually failure of components, and possibly ‘fail when they are ripe for failure’.

2.2.2.2 Man-made slope

Man-made slope or technically known as engineered slope can be categorized into cut-back slope and embankment. This type of slopes would have to be formed to facilitate such developments as terraces and corridors to make room for buildings and infrastructures like canals, railways and roads

A. Cut Slope

These include cut slopes in residual soils and in completely decomposed rock. Based on JKR's Guidelines for Slope Design, stabilisation measures can be considered when the design is inadequate and it may include the following:

ii. soil nailing with slope surface protection

iii. permanent ground anchors

iv. retaining walls, etc.

B. Embankment

Geosynthetic reinforcement is used in constructing the embankment over soft soil. the stability of the embankment and a factor of safety can be analysed and estimated when soil profile, soil strengths, and depth of ground water table have been determined by field explorations and/or field and laboratory testing.

2.3 Factors Affecting Slope Stability

1. Strength of soil and rock.

   As a result of weathering, rocks and indurated soils are subject to loss of strength, which involves various physical, chemical and biological process (Mitchell, 1993). The physical process will break the strong soil or rock into smaller pieces while the chemical and biological processes change them in to material with different properties (Duncan, 2014).

2. Type of soil and stratification.

3. Discontinuities and planes of weakness.

4. Groundwater table and seepage through the slope.

A research stated that the faster the reservoir water level dropped down, the more the safety factor of slope reduced (Liu et al., 2015). It means the drawdown velocity of water level is a key factor of affecting the stability of slope. The greater drawdown velocity of water level would reduce the stability of slopes.

5. External loading.

Based on previous research, it can be concluded that the stability of slopes depends upon the slope angle, the cohesion in the material and the applied surcharge load (Manna et al., 2014). It is observed that the failure of the slope occurs due to the bulging of the slopes and settlement of the crest. This bulging and the settlement however depend largely on the material used to model the slope and also on the surcharge load applied on the crest of the slope.

6. Geometry of the slope.

2.4 Soil Stabilization method

Based on JKR's Guideline for slope design, there are a few typical soil slope stabilisation method that is already being implemented at the slopes on Malaysia's highway.

2.4.1 Gabion Wall

Gabion wall is built from stack of one or more rows of gabion basket, which is in a cage shape and closed on all side. The materials used for the basket is the galvanized hexagonal meshes and will be filled with broken rock. It can also act as a cover wall despites its purpose on stabilizing the soil. Geotextile is placed at the surface of the slope in order to separate fine particles from stone material of the gabion wall. The purpose of geotextile is to secure the water permeability and filtration mechanism that limits the washout of the particles.

This retaining structure are applicable mostly on road construction, embankment, water barriers and slope protection. It is also permeable as it has pores or spaces between the rocks and will not affected by heavy rainfall.

2.4.2 Drainage

One of the most effective ways on decreasing the soil erosion during rainfall is by creating a diversion which channels excess water during rainfall down the slope to the drainage. Pipes and gutter also can be very useful and effective apart from simply create ditches or drain by digging along the regular interval.

2.4.3 Reinforced Concrete Wall

Concrete cantilever retaining wall is the most common type of retaining wall which consists of a wall connected to foundation. It must be well engineered as the wall holds back a significant amount of soil. The slab foundation is loaded by backfill where the weight of the backfill and surcharge will stabilize the walls against sliding and overturning.

2.4.4 Soil Nailing

This type of slope protection usually used to stabilize existing slopes or excavations where it is advantageous of having the top-to-bottom construction compared to other retaining wall systems. Moreover, soil nailing gives alternative from viewpoint of technical feasibility, construction cost, and construction duration when compared to ground anchor walls. When a soil nail wall is constructed, shotcrete or concrete is applied on the excavation face with the purpose of providing continuity.

The walls consist of passive reinforcement where there is no post-tensioning, in existing ground by installing closely spaced steel bars or sections (nails) and placing a front face support. If the soil nails are installed in the drilled holes, it will be grouted while ungrouted nail will be driven into the ground.

2.4.5 Vegetation

The idea of plant roots held the soil together is said to be effective in preventing soil erosion. Planting grass covers or shrubs on the slope is an environment-friendly method and also economically.

This research basically focusing more on vegetation method which is adapted as soil bioengineering techniques and has been used worldwide. In another research of vegetation conducted, it is highlighted about the rooting characteristic of seven tropical plants in order to determine its roots architectural and mechanical properties (Saifuddin et al., 2016). Throughout the research paper, they also recommended the location for planting the trees and shrubs on the slope based on their root system. Based on the conducted research, they classified that the species having root system of VH-type together with R- and H-types root systems respectively were recommended for planting in the middle of the slope while species with root system of M-type at the top or toe of the slope.

2.5 Bioengineering Techniques

Bioengineering techniques has been implemented throughout the world with various types of plants that are available. This techniques use plants and part of plants as a method of protecting and integrating within the infrastructure despite of functioned as landscape protection and restoration (Tardio et al., 2018).

It is further explained in the journal that by using plants, there are some limitations that need to be figured out. First and foremost is the availability of the habitat or species that have the necessary technical characteristics that is aimed for the technical solutions. Furthermore, as a living organisms, plants does not have the ability to precisely calculate the effectiveness of the techniques once installed. Next, the important part of the plants, which are roots, are said to have a limited growth thus hindering the capacity to stabilize soil for depths more than 1.5m, regarding the species used.

In another research, it is stated that by using this techniques it is more beneficial and provide better stability to use combination of different species rather than the presence of single species only (Cebada, 2017). Hence, it is advisable to have a combination of species instead of monocultures as they can act as fodder for the community. Furthermore, in her research also include the formula used to find the factor of safety for the slope stability which related according to variables that each researchers analyzed.

Factor of Safety (FOS) is one of the important aspect that need to be consider when doing the research on slope stability. The FOS of slope with influence of vegetation may be calculated by a formula which has been specified for vegetation on slope purposes:

$$FOS = \frac{(c\prime + \Delta s)}{(\gamma sat.z.cos\beta + Wv).sin\beta} + \frac{(\gamma\prime z.cos\beta + Wv)}{(\gamma sat.z.cos\beta + Wv)} \times \frac{tan\emptyset}{tan\beta} \tag{2.1}$$

Where:

FOS = Factor of safety

c' = soil cohesion (kPa)

Δs = root cohesion (kPa)

β = slope angle (º)

$\emptyset'$ = soil friction angle (º)

$\gamma'=\gamma_{sat}-\gamma_w$ "submerged'' bulk unit weight

γ_{sat} = saturated bulk unit weight (kN/m^3)

z = vertical depth of the failure plane (m)

W_v = Overload due to vegetation (kPa)

It is further explained by Cebada (2017) that Equation 2.1 is the simplification of an equation from infinite slope stability model which analyze the effect of vegetation on slope that was introduced by Morgan and Rickson (1995) as Equation 2.2 :

$$FOS = \frac{(c'+c'R)+\{[(\gamma z-\gamma whv)+W]cos2\beta+Tsin\theta\}tan\phi+Tcos\theta}{[(\gamma z+W)sin\beta+D]cos\beta} \qquad 2.2$$

Where (T) stands for tensile root force acting at the base of slip plane : angle between roots and slip plane (θ): and wind loading force parallel to the slope (D). Thus, by finding the improvement of the soil properties of slope, Equation 2.1 was used in this research.

This species of plant is selected as it is accessible throughout the vicinity of University Malaysia Pahang. *Eugenia Oleina (EO)* is planted on the slope in the research area. Theoretically, by having vegetation on the slope, it will be helpful in preventing the slope against soil erosion. Hence, the previous research has been done to prove this theory and by using the collected data, simulation of the slope stability can be done in this research.

Basically, the effectiveness of *Eugenia Oleina*'s root system is taken into account where it is represented by the tensile strength through pull out test that was done in the laboratory test. A research stated that different plant species have different functional roles acting on the slope (Saifuddin et al., 2016). Hence, the research by using *Eugenia Oleina* species that assessed root architectural and mechanical traits of plants growing along a degraded slope in University Malaysia Pahang.

2.6 Finite Equilibrium Method

The simulation of slope stability in this research will be conducted by using finite equilibrium method which is a method for numerical solution of field problems. It is said that by using this method, it cuts a structure into several elements which is the structure is cut into pieces. The elements then will be reconnected at nodes that will hold the elements together. Thus, resulting in a set of simultaneous algebraic equations.

The term finite element was first introduced by Clough in 1960. In the early 1960s, engineers used this method for find solutions of problems such as in stress analysis, fluid flow, heat transfer, and other areas. It is later in 1970s that this method is widely used for other engineering problems.

There are various types of software that include this method and can perform geotechnical simulation such as DIANA FEA, Plaxis, Adonis etc.

2.7 Simulation from previous research

Simulation of slope stability can be seen all around the internet with various methods and softwares for geotechnical engineering problems. Most of the simulations highlighted the behaviour of the slope with different soil layers, soil conditions and different angle of slope.

2.7.1 Simulation using Plaxis on Slope stability

For this research, the simulation will be based on Plaxis 2D which is more user friendly as it is also used to model a simple geometry problem and comes with student version. Based on the previous research, it shows that the predictions from closely followed observed output data, the predicted surface settlements of soil slope from FEM analysis agreed well with the observed data (Chakrabarti et al., 2017). The computed slope surface the beginning is higher value of factor of safety and it simultaneously decreased with increase of slope angle and slope height.

For example, a research done by Abbas J. (2015) stated that there are three cases of slopes that he already investigated and simulated using Plaxis 2D software. Hence, based on these research, it can be used to estimate the expected performance of slope cases in different conditions of soil. In his research, Abbas J. (2015) did not use any loading of plant species on the slope as the purpose of his research is to study the slope behavior when the soil condition is differ. Figure 2.2 shows the result of total displacement based on each cases that Abbas J. (2015) has simulated in his research.

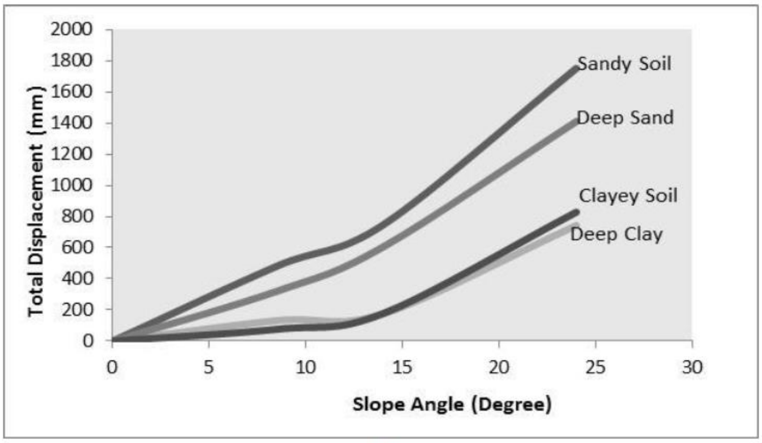


Figure 2. 2 Total displacement vs. slope angle for case 1

Source: Abbas J. (2015)

Figure 2.2 shows the graph of total displacement versus the slope angle which is the constant variables for each cases. Case 1 is the assessment of slope stability with one layer and different soil conditions. Based on this graph, it was concluded that the sandy soil has high displacement compared to clayey soil possibly due to high soil resistance for clayey soil.

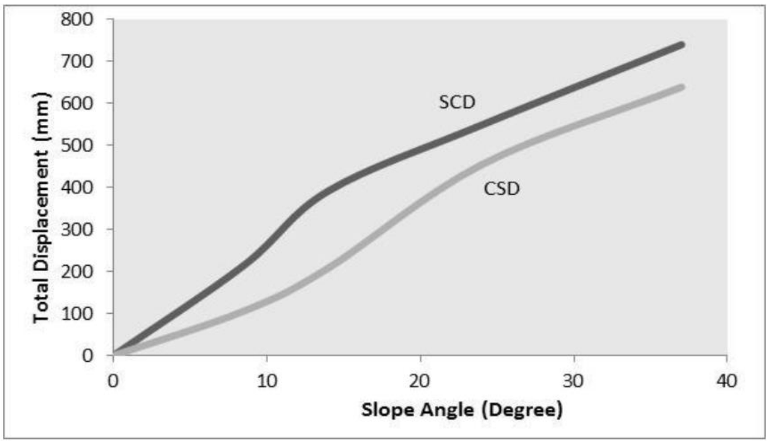


Figure 2. 3 Total displacement vs. slope angle for case 2

Source: Abbas J. (2015)

Case 2 is where the assessment of slope stability with three horizontal layers and different soil conditions. The three layers then categorized into two, which are known as

SCD and CSD, where SCD represent sand layer while CSD represent the clayey layer. Based on the result, it shown that SCD has high displacement compared to CSD due to the influence of layer interaction between soil layers.

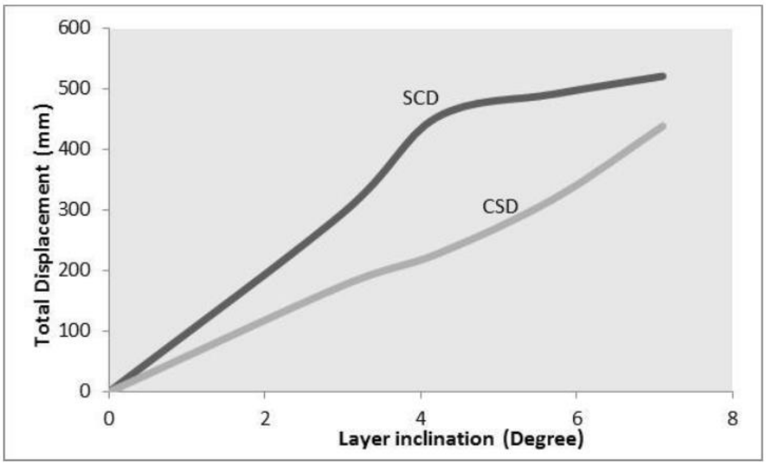


Figure 2. 4 Total displacement vs. slope angle for case 3

Source: Abbas J. (2015)

Case 3 is where the assessment is for slope stability with three inclined layers and different soil conditions. In this case study, it is also categorized into two which are SCD and CSD with different H2 values of 14m and 20m. The inclination also varies for each soil layers and the graph shows the influence of layer inclination for H2=14m where SCD is high in displacement compared to CSD due to little resistance proposed by SCD.

Another simulation done in a research wass on slope stability analysis with varying slope height and slope angle (Chakrabarti et al., 2017). With a constant value of cohesion and internal friction, the research done in order to determine the factor of safety for allowable displacement by stability analysis using finite element method of Plaxis 2D. The results of displacements based on cases are shown in Figure 2.5.

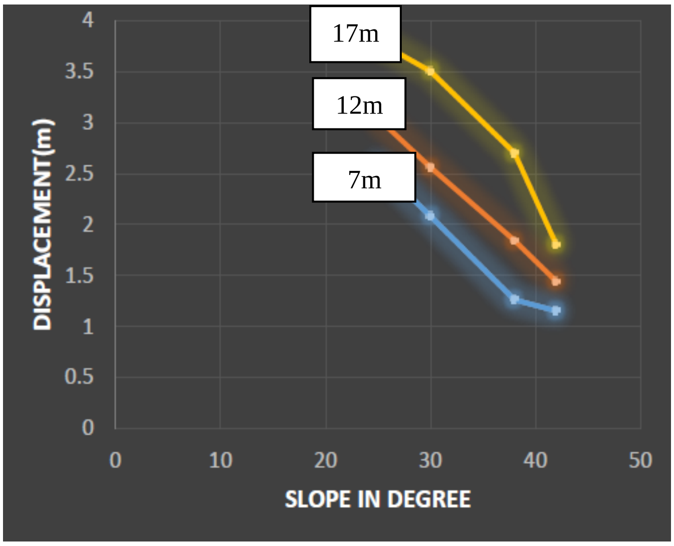


Figure 2. 5 Displacement of soil slope with varying height and slope

Source: Chakrabarti et al. (2017)

In this research, the slope angle used are 25º, 30º, 38º and 42º respectively. Based on the graph in Figure 2.5, the researchers concluded that in the beginning, the factor of safety for the computed slope has a higher value and simultaneously decreased with the increase of slope height and slope angle. It is also concluded that when the value of displacement is higher, the value of height also generally high.

2.7.2 Simulation of slope stability with vegetation using Plaxis 2D

The idea of conducting this research is to simulating slope stability with certain species of vegetation that can be found in the study area. Hence, the previous results of simulation that are related to vegetation on slope need to be identify and understand its relationship between factor of safety and also the displacement that occur to the slope when implemented the soil bioengineering techniques.

Selvaraj et al. (2015) in their research about finite element modelling of light weight slope biostabilization stated that they consider four different configurations on the slope which are Head-Face-Toe, Face-Toe, Face-Toe (partial) and Face as shown in Figure 2.6.

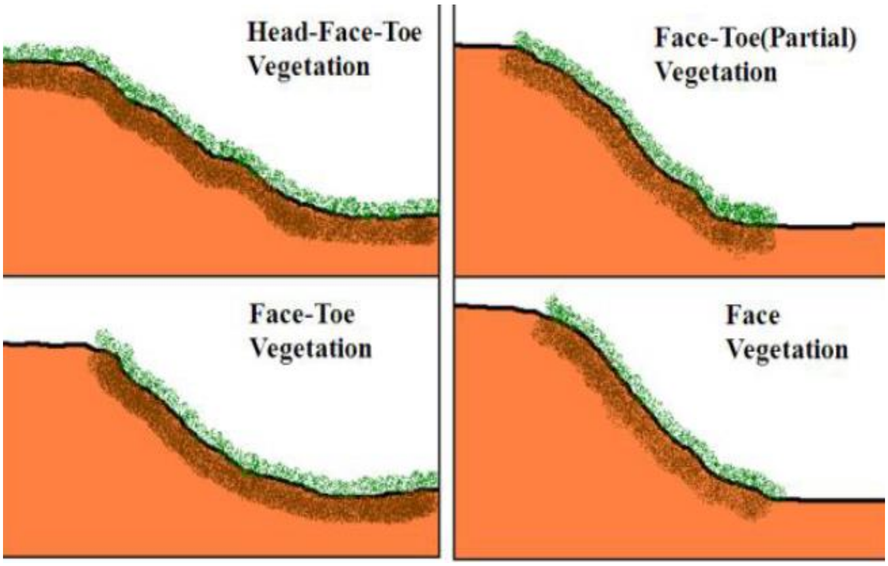


Figure 2. 6 Light weight vegetation configurations for slope bio-stabilization of hill slopes

Source: Selvaraj et al. (2015)

They stated further in the research that the weight of the vegetation has direct influence on the stability of the slopes because of increasing shear stress. Therefore, stability of slope is analyzed with vegetations whose weights vary from 0 to 50 kN/m. The simulation is done by placing the vegetation at head, face and toe of the slope, with a varying slope angle. Another slope was simulated without vegetation to compared the FOS with another three simulation. The results of the effect of vegetation surcharge at all three positions were shown in Figures 2.7.

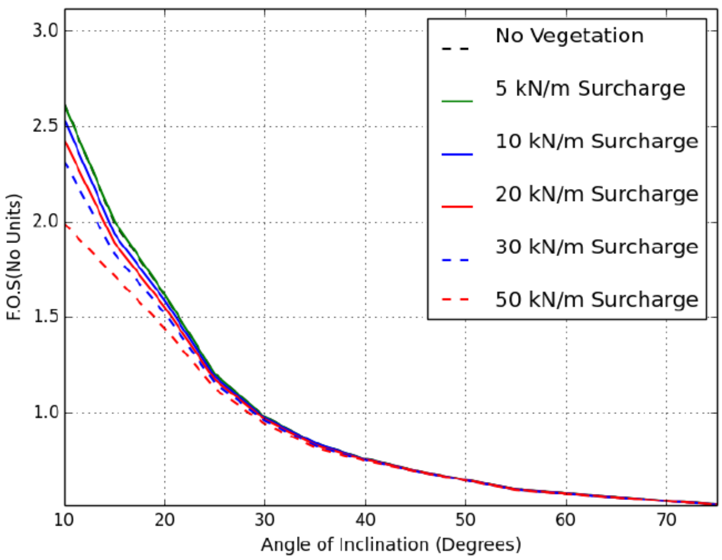


Figure 2. 7 Effect of surcharge (at head) on stability of the slope

Source: Selvaraj et al. (2015)

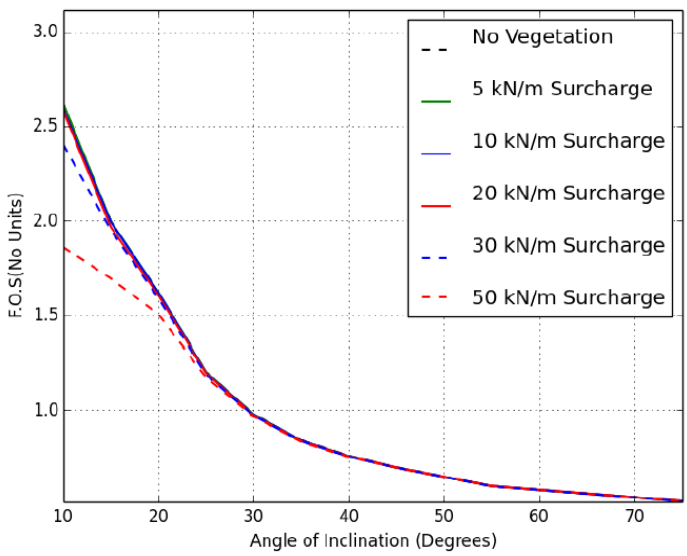


Figure 2. 8 Effect of surcharge (at face) on stability of the slope

Source: Selvaraj et al. (2015)

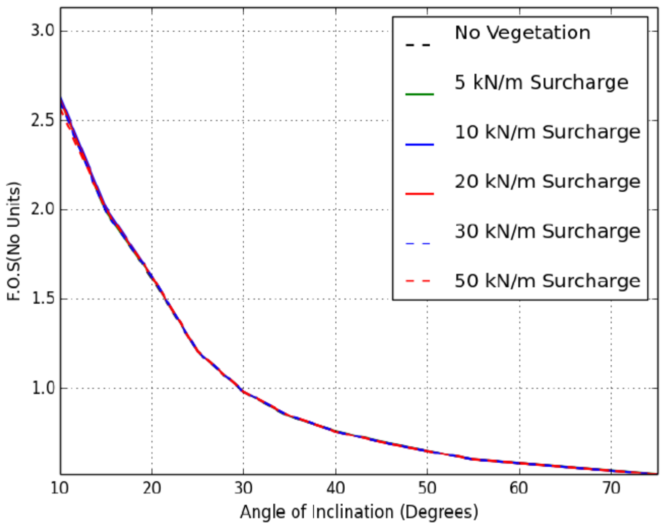


Figure 2. 9 Effect of surcharge (at toe) on stability of the slope

Source: Selvaraj et al. (2015)

Based on Figure 2.7 and Figure 2.8, due to an increment of shear stress by the surcharge near the head and face of the slope, the results show there are significant reduction in the FOS of the very gentle to moderately steep slope. However, the result in Figure 2.9 where the surcharge placed at the toe of the slope shows that there is no reduction of the FOS. This is because the surcharge is directly dissipated on to the base of the slope. Hence, making the slope unaffected to the surcharge.

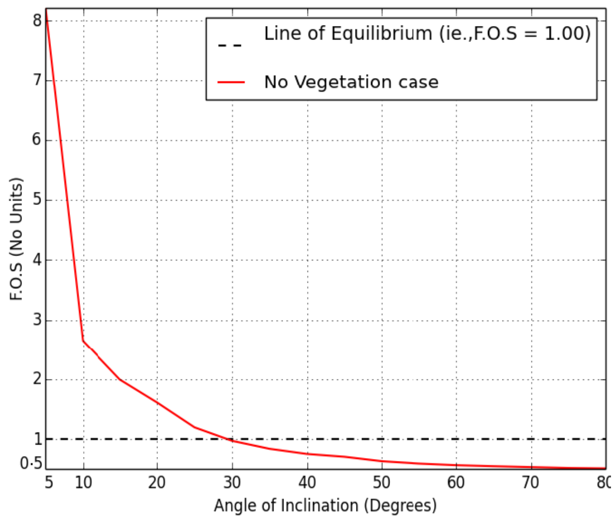


Figure 2.10 The stability of slope without vegetation

Source: Selvaraj et al. (2015)

In Figure 2.10 where the slope is unprotected with vegetation, the result shows that the slope up to 30º angle of inclination are stable while when the slopes angles are beyond 30º, the slopes are said to be unstable with FOS less than 1. It can be concluded that the stability of the slope decrease with an increment in the angle of inclination. They further explained that soil cohesion has influence on the stability of the slope, where due to the presence of soil cohesion, there is a significant increase in the inherent frictional resistance, which varies from 20º to 30º. It is shown in Figure 2.11 that with the change of soil cohesion, the stability of slope also affected as shown.

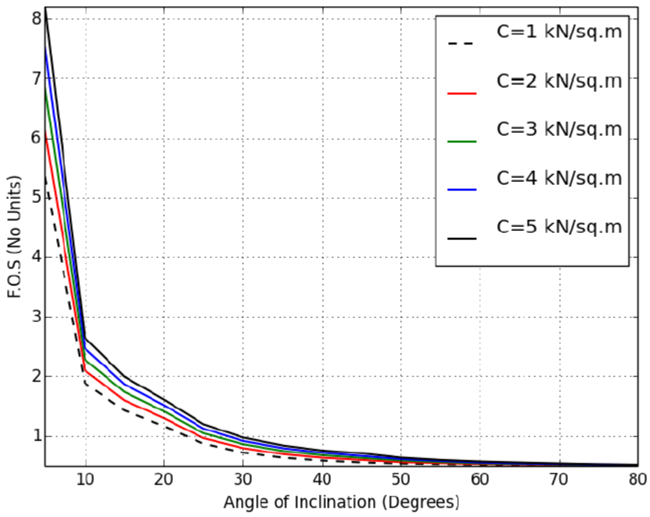


Figure 2.11 The effect of soil cohesion on slope stability

Source: Selvaraj et al. (2015)

In another research of slope stability and vegetation by Kokutse et al. (2016), the combined effects of different rectilinear slope geometries, soil types and vegetation mechanical parameters on the slope's factor of safety was investigated. It was stated that this research analyze the influence of geometrical parameters, height and angle of the slope on the stability of different slope configurations by computing the factor of safety.

Based on the results of the analysis done it was stated that the stability of a non-reinforced slope is significantly improved when plant's root additional cohesion was taken into account. This is because the root system was characterised by two major parameters which are additional root cohesion (c_R) and the depth of root zone (z_R). Moreover, the increment of FOS are more significant with a deeper root zone and higher additional root cohesion.

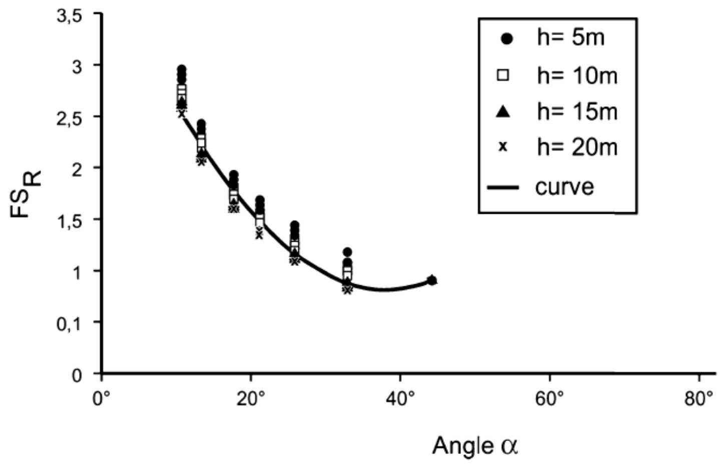


Figure 2.12 Mean values of FSR as function of slope angle for various slope heights H

Source: Kokutse et al. (2016)

Based on Figure 2.12, it shows the increment of FOS due to presence of roots. The graph shows that where all vegetation types and all types of soil are presented in the same graph and for each value of the angle, the results are corresponding to different value of the slope height. Figure 2.13 shows the mean value of FOS with slope angle for various soil type. The results for FOS is as same as in Figure 2.12 where the mean value of FOS decrease with the increase of slope angle.

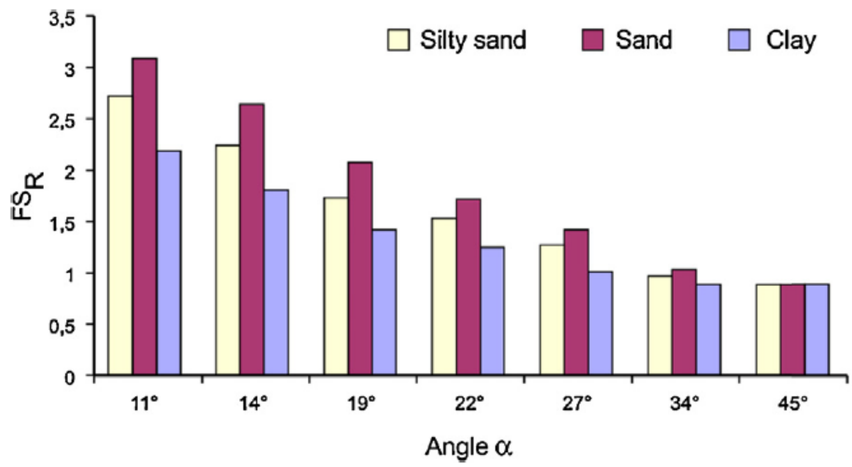


Figure 2.13 Mean values of FSR as function of slope angle for various types of soil

Source: Kokutse et al. (2016)

CHAPTER 3

METHODOLOGY

3.1 Introduction

Overview

This research was conducted by using a finite element method in a software namely Plaxis 2D which was introduced in 1993 by Plaxis Bv Inc. The purpose of choosing this software is because it is used by engineers worldwide in the industry in analyzing and solving problems regarding geotechnical by adapting the usage of calculation and simulation. This chapter will portray the version of Plaxis used and also the method that was adapted throughout this research in order to achieve the objectives. Preliminary test was done previously including the determination of soil properties and the tensile strength from pull out test. The data used in this research is a secondary data that was extracted from the previous research.

3.2 Study location

This research is focused on the shallow slope located near the FKASA surveying lab in University Malaysia Pahang. There are three sites which are known as Site A, Site B and Site C was selected as a controlled site. All these sites were chosen based on the soil erosion problem that occurred alongside the slope in that area.

3.3 Data Collection

The data of both the lab test and field test was collected from the previous investigation done and will be the input for the Plaxis 2D software analysis. Parameters that were used in the software is the cohesion of the soil, angle of the internal friction, Young modulus' value and field density of the soil.

3.4 Software

In this research, in order to validate the FOS obtained by Plaxis 2D, another geotechnical software which is ADONIS software was used to counter analyse the results obtained from Plaxis 2D. The simulation of the slope by using ADONIS software was done until the value of FOS is generated. Hence,this chapter covers about these two softwares based on its steps and procedures involved.

3.4.1 Plaxis 2D

This research was done by using the Plaxis 2D educational version. Upon receiving the secondary data from previously conducted research in the same area, the parameters serve t as an input in the Plaxis 2D software. Figure 3.1 shows the work flowchart by using the software.

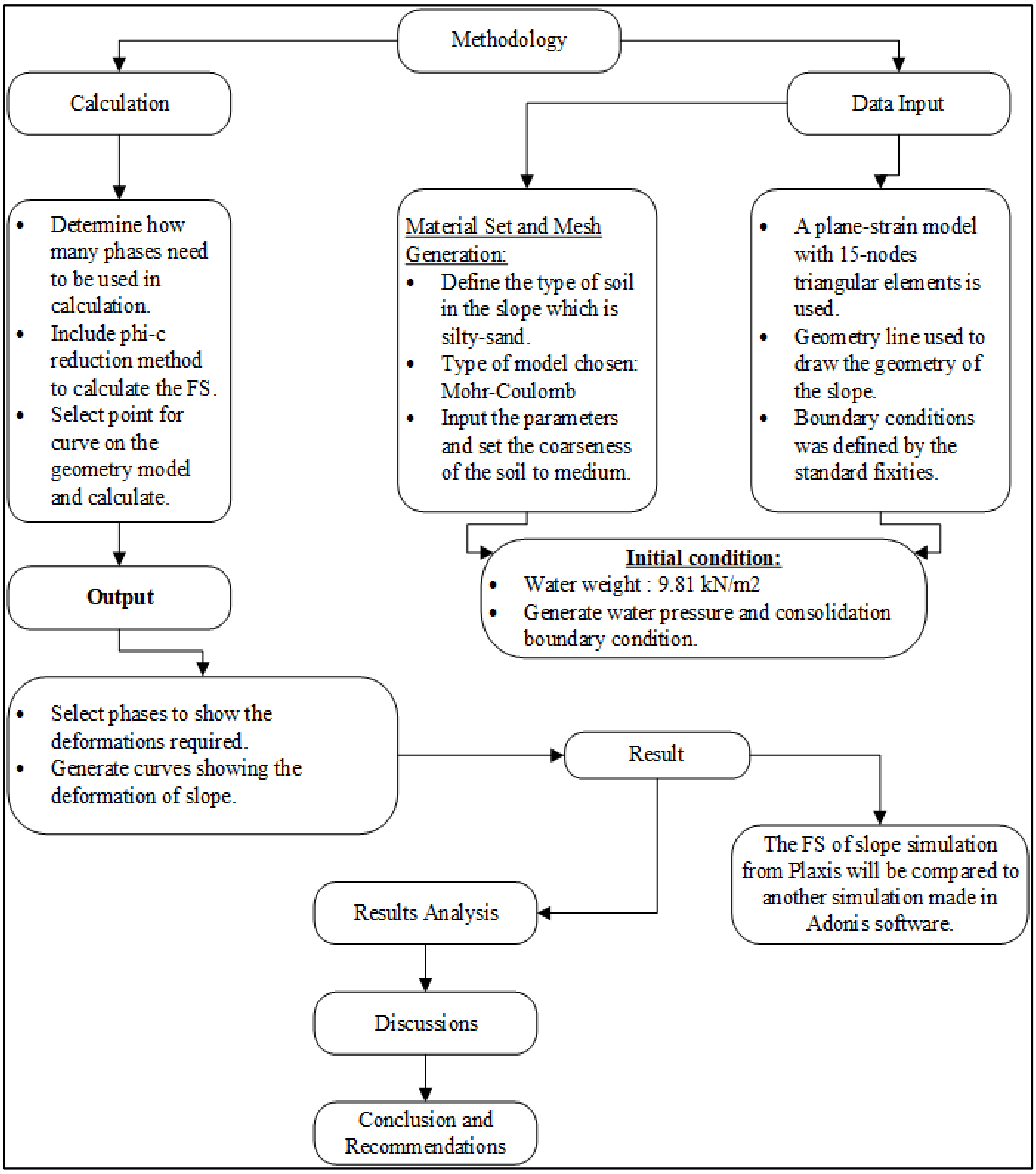


Figure 3.1 Work Flowchart in Plaxis 2D software

3.4.1.1 Data Input, Configuration and Simulation

After obtaining the data, a plane strain model with 15-nodes triangular elements is used and a geometry model of the slope was drawn by using the geometry line in the input window. Then, the boundary conditions of the slope was defined by the standard fixities.

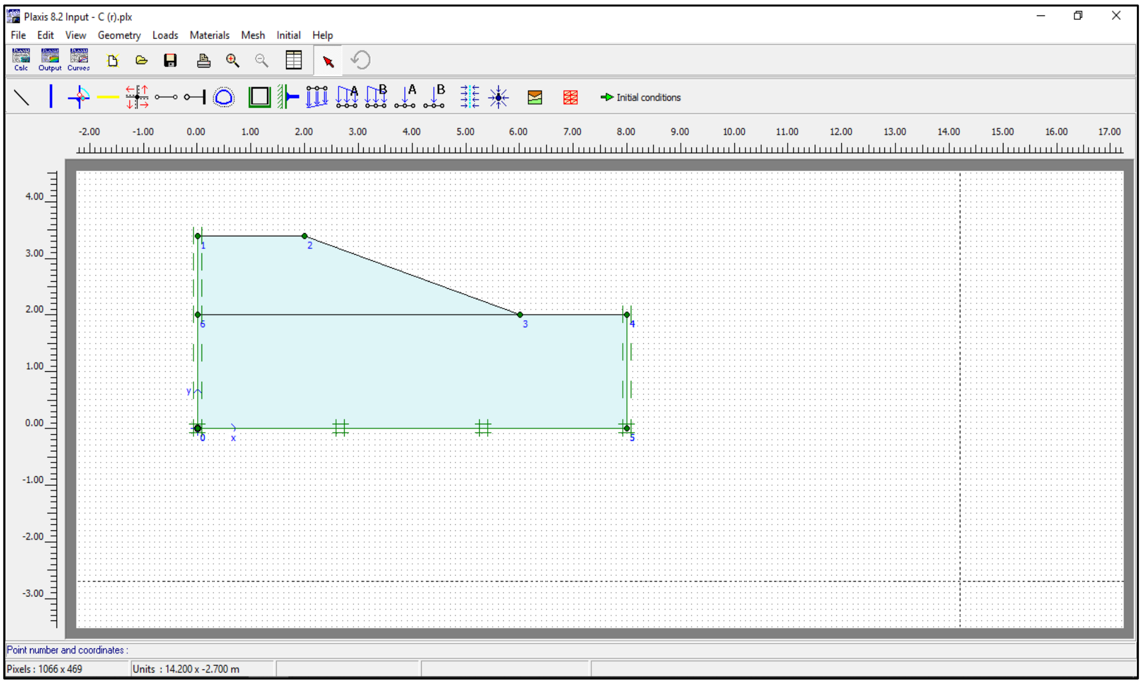


Figure 3. 2 Geometry model of slope with fixities.

3.4.1.2 Materials sets and Mesh Generation

The material of soil which is silty sand is created based on the given table below. The data is then assigned to the corresponding cluster in the geometry model. A simple finite element mesh was generated by setting the coarseness of the material. In this case, the medium coarseness for the material was used. The mesh is generated by clicking the generate mesh button.

Table 3.1 Material properties of the slope

Slope	**A**		**B**		**C (control slope)**
Type of slope	**rooted**	**unrooted**	**rooted**	**unrooted**	**unrooted**
Soil unit weight above phreatic level, γ_{unsat} (kN/m^3)	6.53		8.92		6.56
Soil unit weight below phreatic level, γ_{sat} (kN/m^3)	16.34		18.73		16.37
Horizontal permeability, k_x (m/day)	1.0				
Vertical permeability, k_y (m/day)	1.0				
Cohesion, c_{ref} (kN/m^2)	22.91	32.38	21.86	42.99	22.91
Friction angle, φ (˚)	30.17	35.23	29.48	28.53	30.17
Dilatancy angle, ψ (˚)	0.0	0.0	0.0	0.0	0.0

3.4.1.2 Initial condition

After generating the mesh, the initial condition is set where the unit weight of water is set to 9.81 (kN/m^3), which is standard value used in simulation, and the water pressures is fully hydrostatic on a phreatic level through point (0.0,2.0) to (8.0,2.0). The left and right vertical boundary must be closed because there is no free outflow at that boundary as shown in the Figure 3.3. The active pore pressure and the initial soil stress is then generated and shown in the Figure 3.4 and Figure 3.5 and then the next step was calculated.

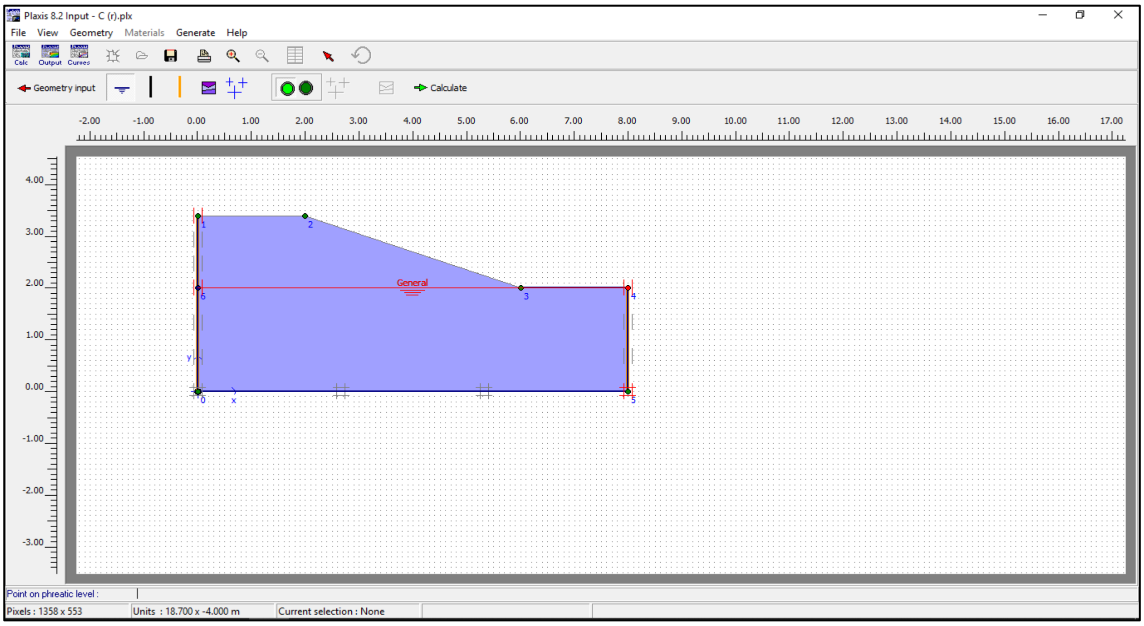


Figure 3. 3 Input of initial condition

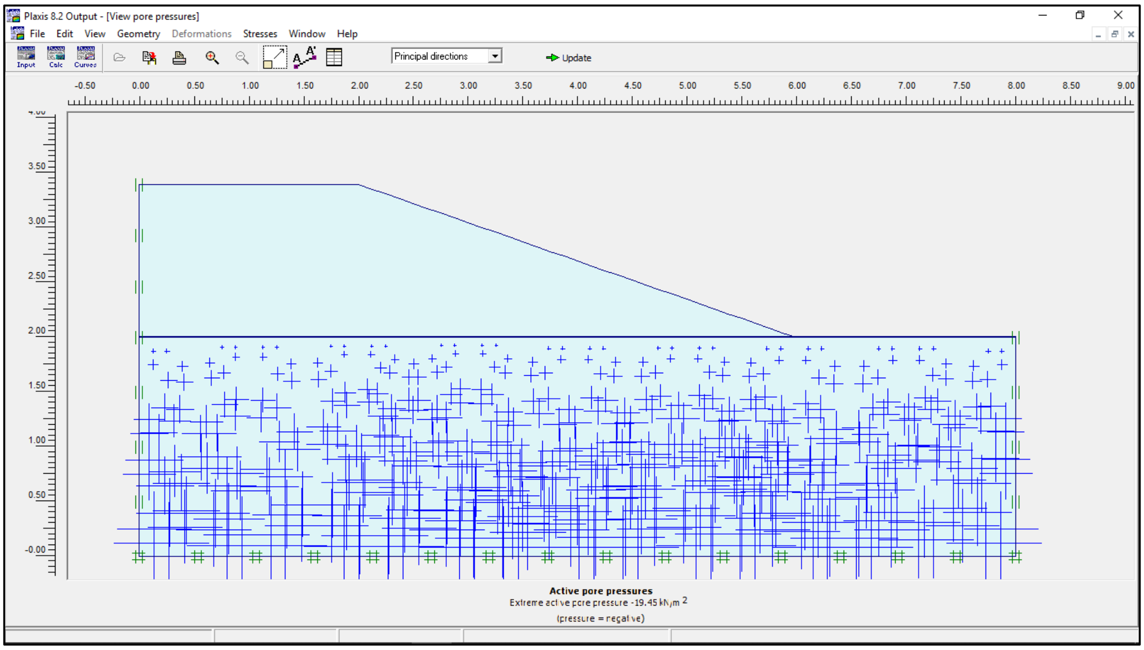


Figure 3. 4 The pore pressure generated

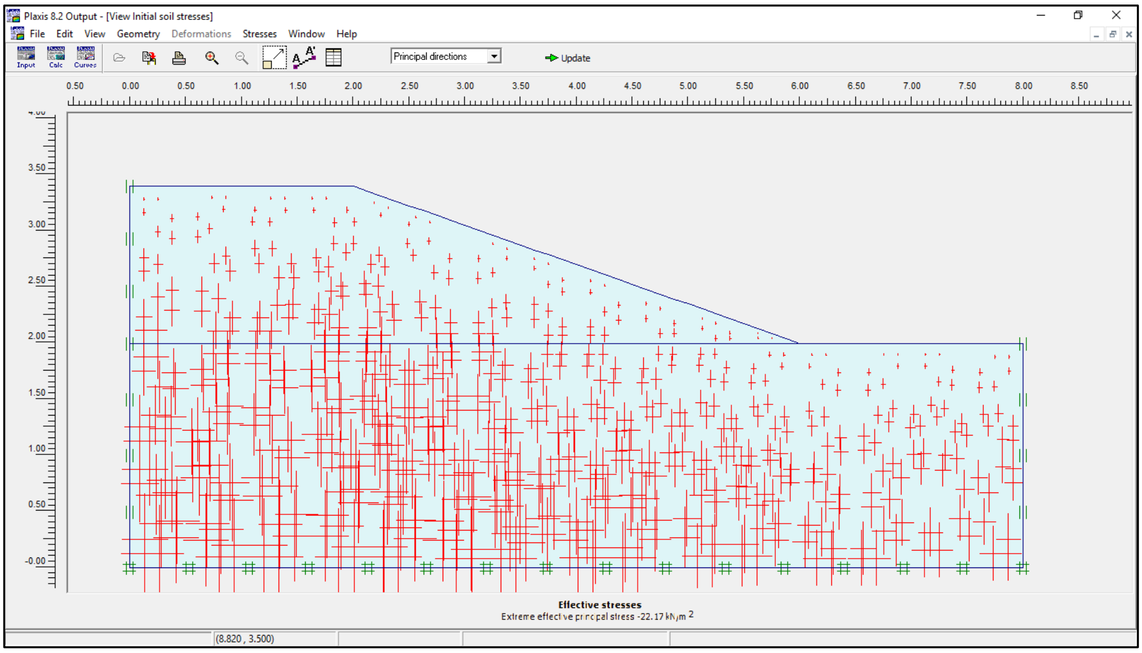


Figure 3. 5 The initial soil stress of slope

3.4.1.3 Calculations

In the calculation stage, there are six calculation phases where it includes the construction stage of the slope and also the consolidation period, where the first consolidation period is to allow the excess pore pressure to dissipate after the construction stage of slope. The second consolidation period is introduced after the second construction stage, where in this period, the final settlement may be determined. Plaxis allow the consolidation option to have fully automatic time stepping procedure to take account into the critical time step. Thus, there are three possibilities of the procedure which are staged construction, minimum pore pressure and incremental multiplier.

In staged construction, the consolidation is done in a predefined period and includes the changes in the active geometry while in minimum pore pressure where the consolidation takes place until all of the excess pore pressure is reduced to a predefined minimum value. After choosing on the procedure that need to be used, the point for curve need to be select in the geometry model where the first point will start from the toe of the slope while the second point will be used to plot the development of excess pore pressure. In the middle of the model, there will be more point needed.

The final phases includes the calculation of phi/c reduction, which is used by Plaxis software to compute the factor of safety in the simulation. By using this method, the cohesion and the tangent of the friction angle are reduced in the same proportion:

$$\frac{c}{cr} = \frac{tan\ \varphi}{tan\ \varphi r} = \Sigma Msf \qquad 3.1$$

Then, the calculation can be started.

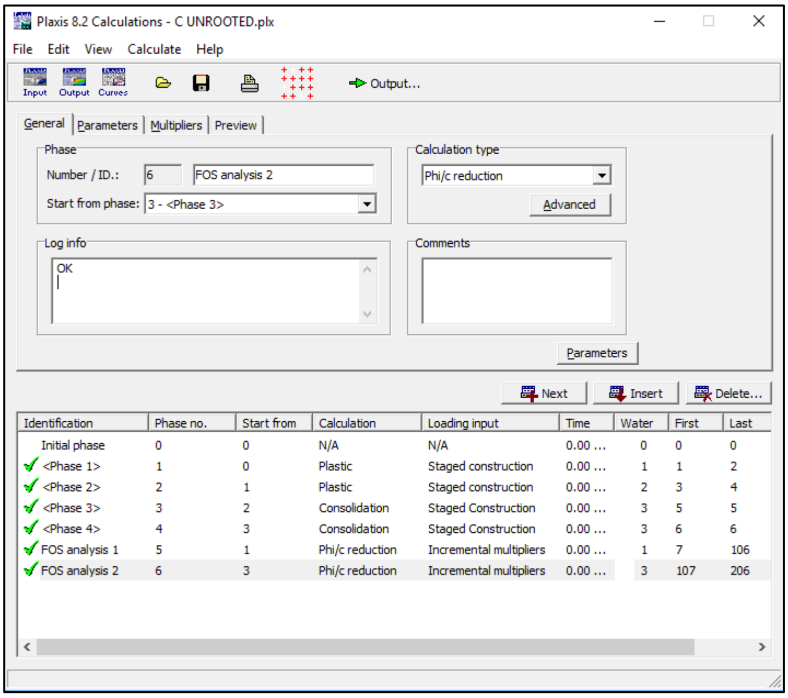


Figure 3.6 Phases in calculation window

3.4.1.4 Output

The output window will show the deformed meshes when two phases were selected from the previous calculation window. In this window, the deformed meshes can be accessed according to what we are looking for such as the total displacement, the excess pore pressure contours and even the effective stresses that occured in the soil layer. From the output window, curve also can be accessed based on the excess pore pressure under the slope and how it affect the slope stability.

3.4.1.5 Factor of Safety

In this research, the factor of safety for a slope without the presence of *Eugenia Oleina* species was compared to the model of slope with the species acting as live pole. This is done in order to show whether there is an improvement when using the *Eugenia Oleina* as the live pole on the slope.

3.4.2 ADONIS Software

ADONIS software is a software for geo-engineers which is developed by Roozbeh Geraili Mikola 2016. This software is a free finite element software for simulating geotechnical engineering problems. It is also a user-friendly software as an alternative to existing software for computing and simulation.This software also is scriptable where the users can create their own solutions and customize it based on the core functionality of ADONIS. By referring to the command line underneath the window, user can easily detect the input used in the simulation.

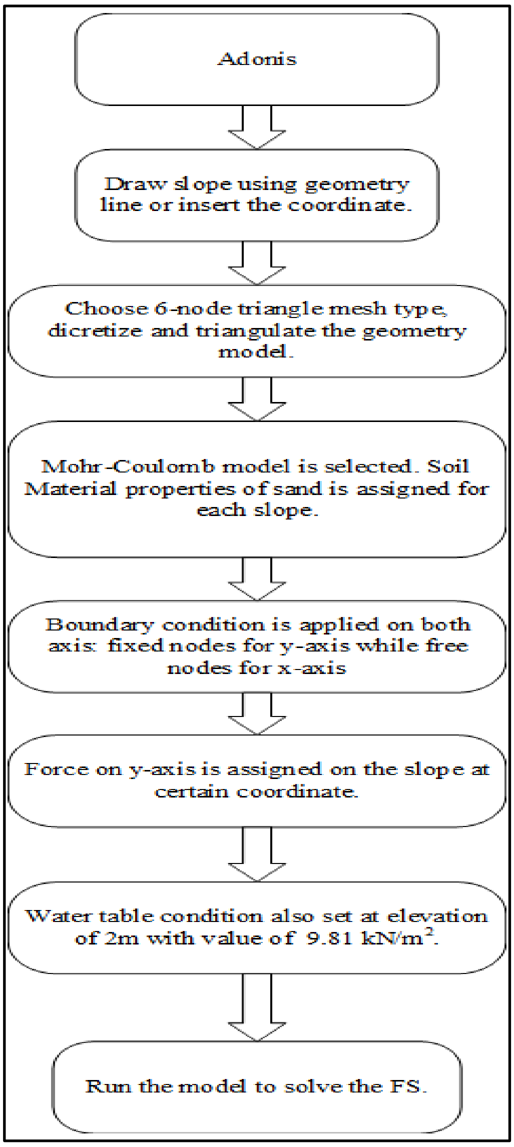


Figure 3.7 Flowchart of ADONIS software

Similar to any geotechnical software, the first step is to draw the geometrical model of the slope. Next is to draw it manually or by inserting the coordinates of the models based on the height of slope and its slope angle into the command panel at the left side of the window .

Next step is to create the meshing into the geometry model after discretizing the model boundary line. The meshing type can be chosen either using three-node or six-node triangular element. For this research, the six-node triangular element and the generated finite element mesh are shown as in Figure 3.8.

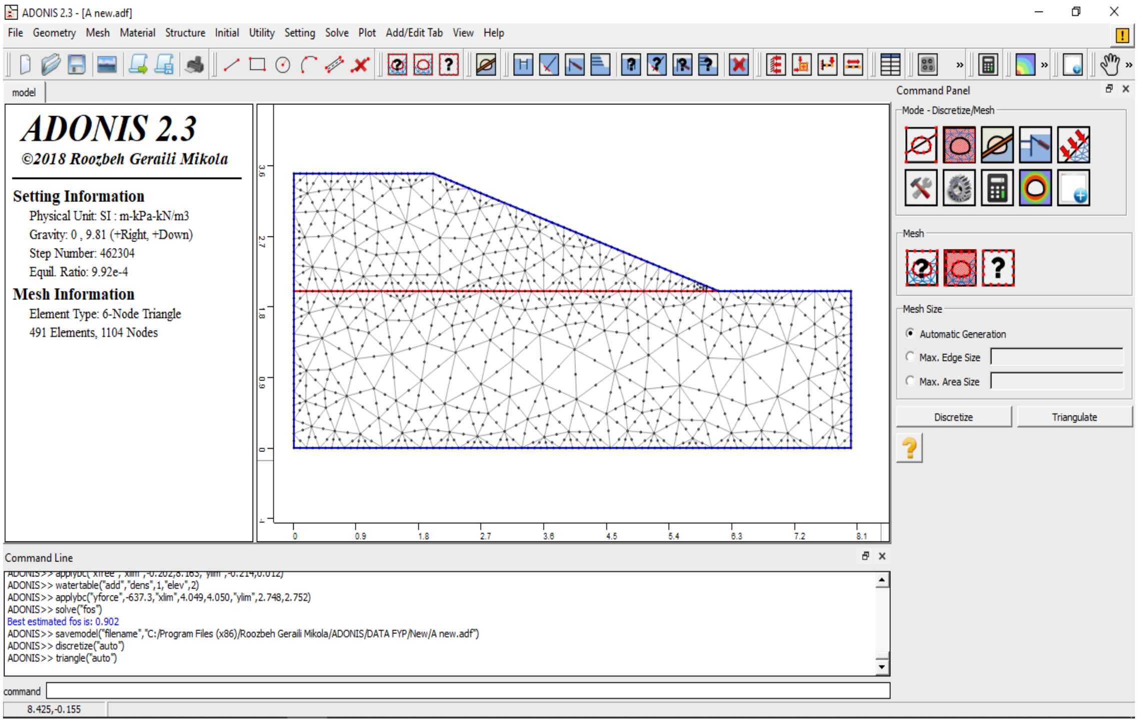


Figure 3.8 The geometry model used in the simulation

After setting out the meshing part, the Mohr-Coulomb model was chosen for this simulation, similar model used in Plaxis 2D. The material and soil properties of this geometry model is assigned based on Table 3.1 and the material name is set to sand. Alongside the step, the boundary condition for the slope is applied on both axis, x and y. On the y-axis, the nodes will be set to a fixed boundary while it will be free nodes for x-axis. This is done because the water will seep through the soil beneath it and to hinder the soil from moving horizontally.

For both slope A and B, there will be a load acting on the slope, representing the Eugenia Oleina species. Hence, by using the initial condition mode, the force will be applied by choosing “force” in the keyword list and click on the “yforce” as the load is in y-direction. Then, the value of the force used is keyed in at the space provided. Furthermore, the water table condition is set at an elevation of 2m while the water density is set to 9.81 kN/m^3.

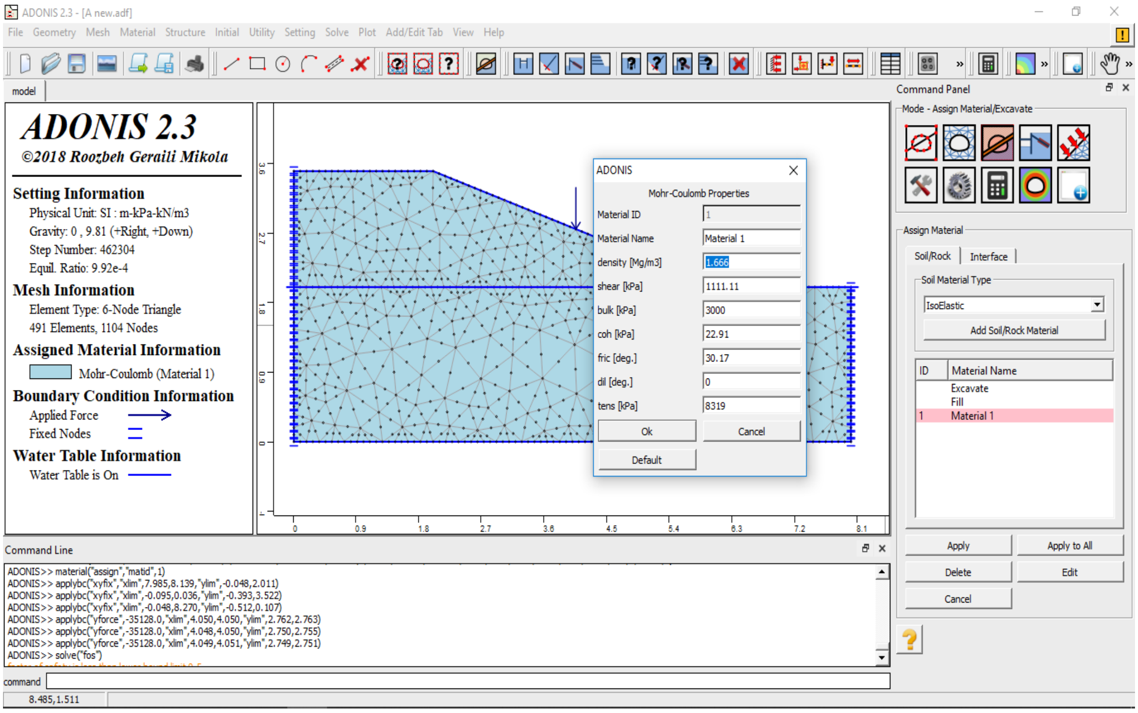


Figure 3.9 The geometry model setup for simulation

Lastly, to run the simulation, the command panel is set to calculation mode where we can choose which static mode to run. For this research, "solve fos" button is chosen and a few setup such as the lower boundary and upper boundary of FOS is needed so that the simulation can be initialized.

3.5 Results

The FOS from the simulated models that are obtained from Plaxis was compared with another geotechnical engineering software which is the ADONIS. This step is done to rectify the models that have been simulated through Plaxis 2D. The results then were presented using graph and charts as in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Simulation of slope stability with Eugenia Oleina (EO) trees against soil erosion is conducted by using a software known as Plaxis 2D, which was developed by Plaxis Bv Inc. This simulation is done in order to measure the potential of the E.O plant roots in improving the soil properties of the slope. There are several parameters, which have been gathered throughout the soil investigation in the previous research, that are required to be the input in this software such as unit weight (γ), cohesion of soil (c), and the angle of friction (ϕ).

There are three slopes that were simulated by using this software which are Slope A, Slope B and Slope C. Both slope A and B has E.O species planted on the slope while Slope C is acting as the control slope. The results of slope stability analysis using the software are presented and discussed in this chapter. The parameters used in this research are stated in Table 4.1.

Table 4.1 Material Properties of the slope

Slope	**A**		**B**		**C (control slope)**
Type of slope	**rooted**	**unrooted**	**rooted**	**unrooted**	**unrooted**
Soil unit weight above phreatic level, γ_{unsat} (kN/m^3)	6.53		8.92		6.56
Soil unit weight below phreatic level, γ_{sat} (kN/m^3)	16.34		18.73		16.37
Horizontal permeability, k_x (m/day)	1.0				
Vertical permeability, k_y (m/day)	1.0				
Cohesion, c_{ref} (kN/m^2)	22.91	32.38	21.86	42.99	22.91
Friction angle, φ (˚)	30.17	35.23	29.48	28.53	30.17
Dilatancy angle, ψ (˚)	0.0	0.0	0.0	0.0	0.0

Based on the observation, the slope underwent soil erosion and the soil that washed away during heavy rainfall can be seen in the drain near the slope. Hence, this research is done to simulate the purpose of the plant roots whether it helps on maintaining the slope or enhance the soil erosion to continuously occur.

Firstly, the parameters were set in to the Plaxis 2D software and by using Mohr-Coulomb model. After the model run the calculation phase, the factor of safety for the slope was generated through the output window. Next, the FOS from Plaxis 2D was compared to the FOS from Adonis software and also through manual calculations. The data was included in Appendix.

Table 4.2 show the factor of safety obtained from Plaxis 2D software, Adonis software and also by manual calculation for slope A, B and C.

Table 4.2 Factor of Safety based on calculation

Slope	**A**		**B**		**C**
	Rooted	**Unrooted**	**Rooted**	**Unrooted**	**Unrooted**
Plaxis	0.368	23.912	0.393	21.937	18.554
Adonis	0.945	15.035	1.878	16.570	8.379
Manual	1.500	4.9731	1.870	6.3338	3.6901

Based on Table 4.2, the FOS differs based on the calculation used in the software and manual calculation. Adonis software also been used in this research in order to validate the FOS obtained from Plaxis 2D software whether the FOS for the slope is acceptable or not. Throughout the calculation of FOS, it shows that the slope with EO species planted on it has smallest FOS compared to the slope without EO, which is not safe.

By using Plaxis software, it shows that the FOS for both rooted slope A and B have a value of 0.368 and 0.393 while for unrooted slope A and B, both shows value of 23.912 and 21.937 approximately, which are more higher compared to the rooted slopes. Slope C which is the controlled slope also have a big value which is 18.554.

As stated previously, Adonis software is used to validate the FOS data from Plaxis software. Hence the differences of the value obtained from Adonis software is acceptable as each software has their own ways of calculating the FOS. For both rooted slope A and B, the FOS obtained are 0.945 and 1.878 approximately while for the unrooted slope are 15.035 and 16.570. FOS for slope C for this software also have a high value of 8.379.

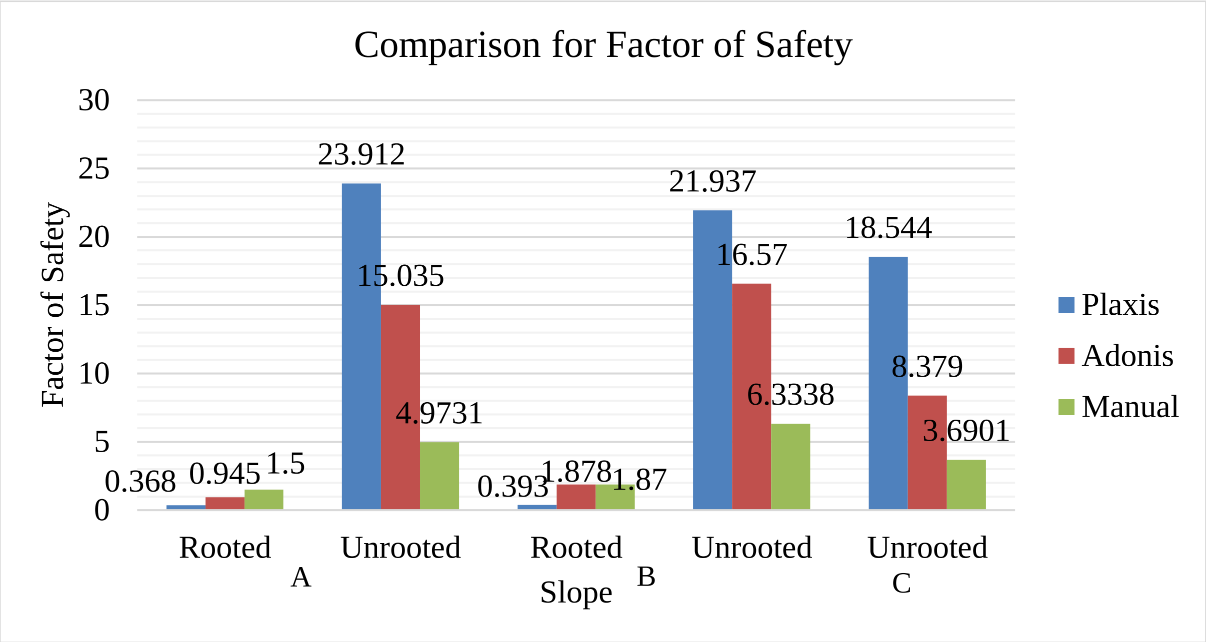


Figure 4.1 Graph of comparison between factor of safety

4.2 Results

4.2.1 Soil Properties Improvement

The effect of vegetation on slope stability can be defined by Equation 2.1 that has been stated in the previous Chapter 2. Based on the FOS obtained from Plaxis 2D software and the soil properties tabulated in Table 4.1, the cohesion of the soil is back calculated by using the equation above in order to identify the improvement of the soil properties in term of cohesion. The angle of friction (ϕ) for the slope is considered constant in this calculation as the angle of friction gives almost zero effect on the slope hence can be neglected. Further calculation on the changes of cohesion for rooted soil can be referred in Appendix section. Hence, the results are simplified in the Table 4.3. Slope C is not included in the calculation above as it acts as controlled slope.

Table 4.3 Comparison of soil properties (cohesion)

Slope	FOS (Rooted)	c' (input)	Effect on c'
A	0.368	22.91	- 3572.50
B	0.393	21.86	- 4036.84
C	-	-	-

The results is then best represented in form of bar graph in Figure 4.2 to show the differences that occur to the soil cohesion for the rooted slope. It shows that both cohesion of the slopes are decrease, where from 22.91 kN/m^2 and 21.86 kN/m^2 respectively to -3572.50 kN/m^2 and -4036.84 kN/m^2 respectively. The changes in cohesion can be said to be cohesionless because the cohesion value is less than zero. This shows that the FOS obtained from Plaxis 2D has an effect to the changes of soil cohesion. From the equation 2.1, it is clearly shows that the FOS is directly proportional to the soil cohesion. Hence, when the FOS is decrease, the soil cohesion also decrease. Thus, the slope is not safe and susceptible to failure even with root plants on the slope, where theoretically it should be safe.

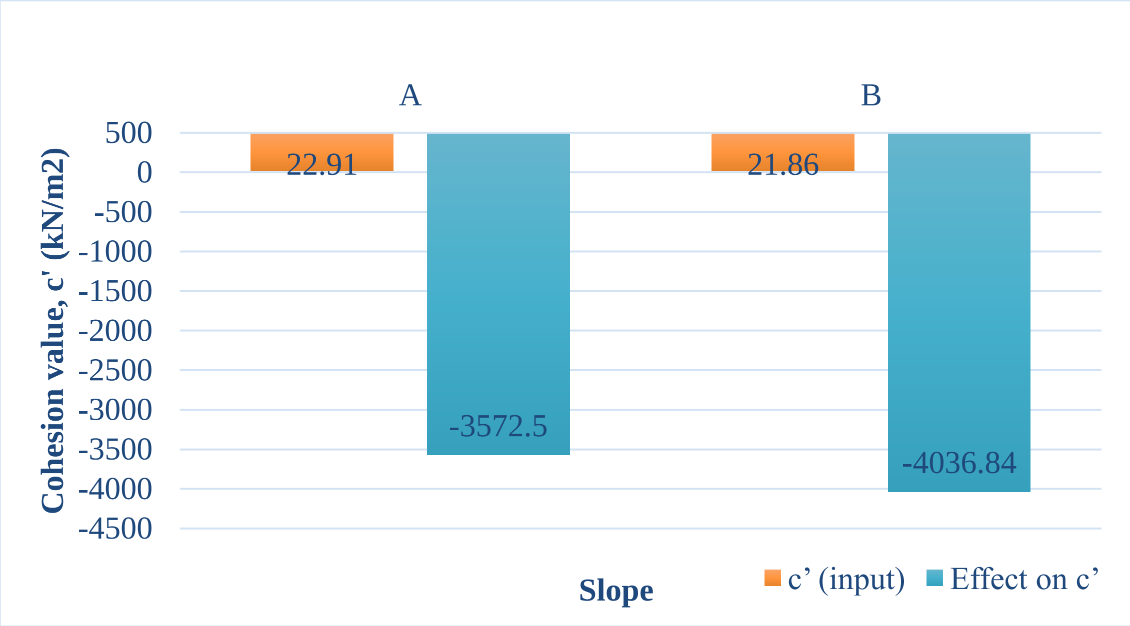


Figure 4. 2 Comparison of soil cohesion

4.2.2 Simulation of Slope Stability

Based on the simulation done in Plaxis 2D software, the deformation of the slope can be simplified in the Figure 4.3.

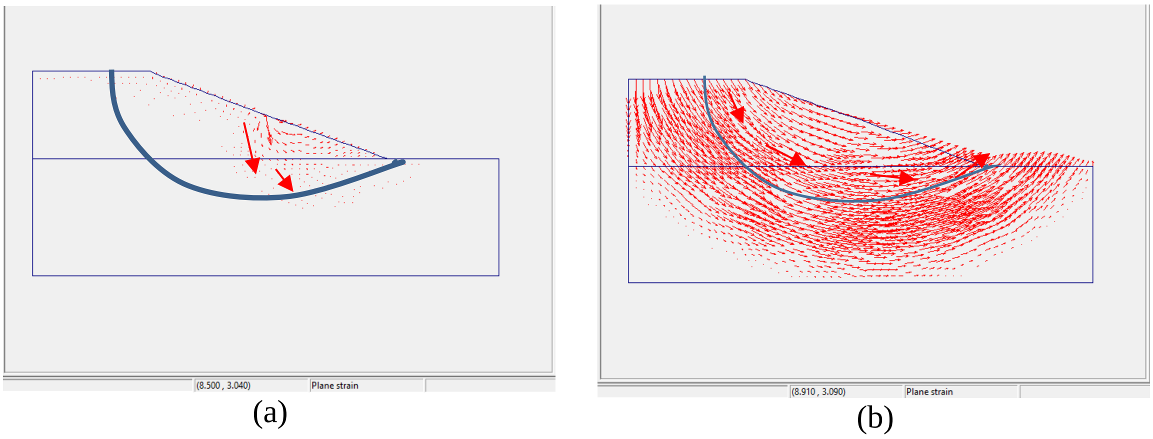


Figure 4.3 The comparison of displacement on slope A: (a) Rooted slope A (b) Unrooted slope A

Displacement can be seen by both rooted and unrooted slopes. As for the rooted slope A, the displacement of 0.937 mm only occur at the area of *Eugenia Oleina*'s root while for the unrooted slope A, the displacement of 1.434 mm clearly can be seen by the arrows representing the movement of the soil over time. Hence, by time, the displacement still can occur even though the slope is categorised as stable from the FOS obtained.

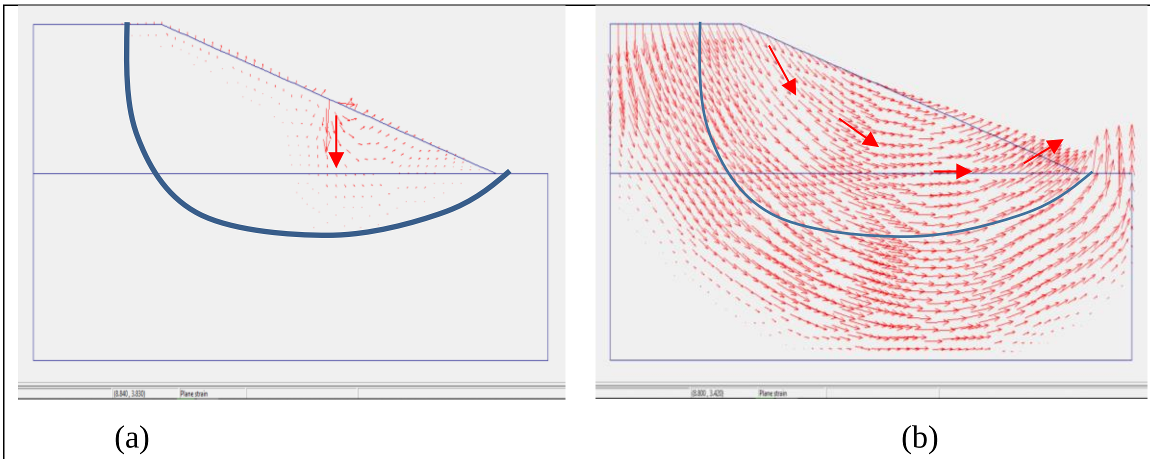
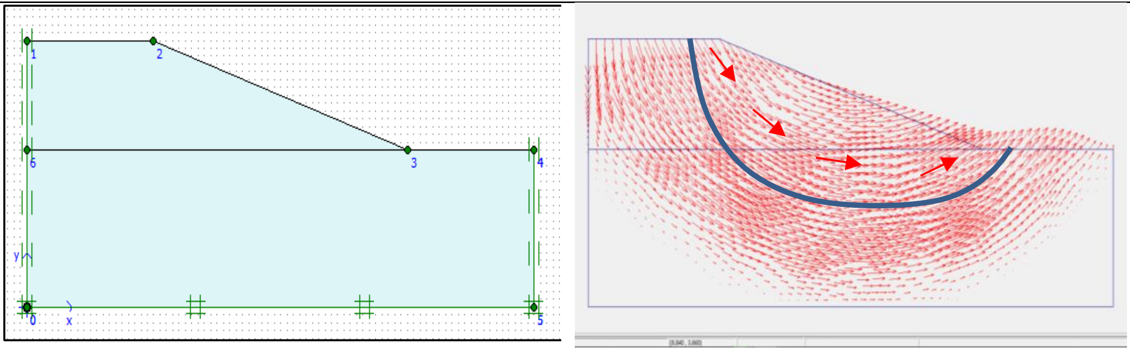


Figure 4.4 The comparison of displacement on slope B: (a) Rooted slope B (b) Unrooted slope B

The rooted slope B also having the same direction of displacement with a maximum value of 0.982 mm while the maximum value of displacement for unrooted slope B is 1.228 mm. It is shown in the Figure 4.4 that the displacement of unrooted slope is higher based on the direction shown by the arrow itself.



(a) (b)

Figure 4.5 The displacement on slope C: (a) before the simulation (b) result after the simulation

The displacement that happens on slope C with the maximum value of 0.96 mm shows that without the plant roots, displacement also take action on the control slope over time.

4.3 Analysis

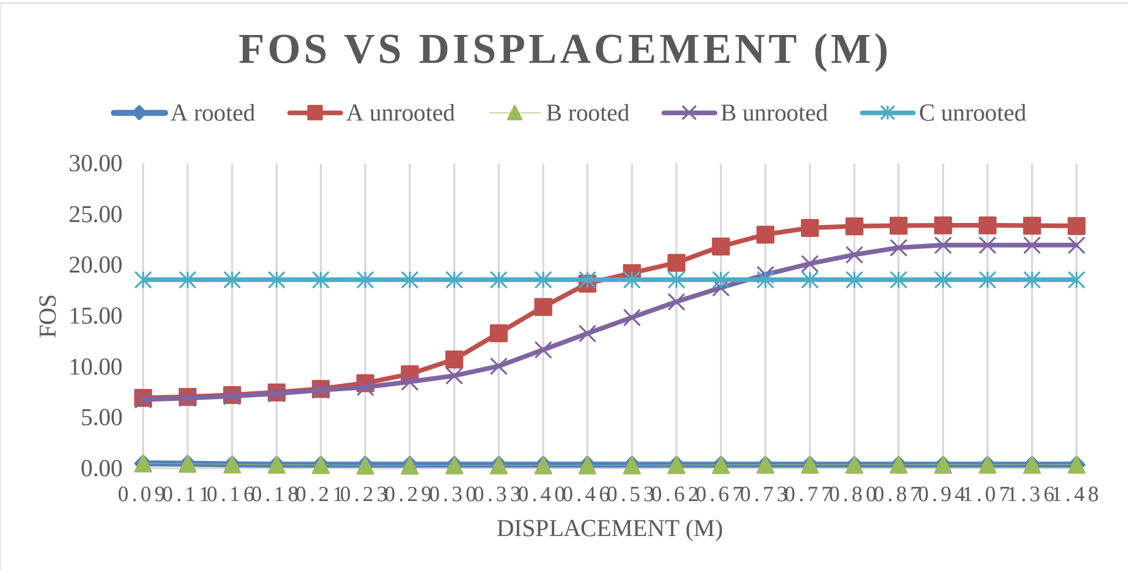


Figure 4. 6 Factor of safety vs Displacement of slope (mm)

Figure 4.6 portrayed the factor of safety against the displacements of each slope that are considered in this research. As been shown above, both rooted slope of A and B have lower factor of safety throughout the displacement curves. For the unrooted slopes, factor of safety are increased perpendicularly with the increment of the displacements. Hence, it shows even with high displacement, the factor of safety at the end of the calculation are still higher compared to the rooted slope.

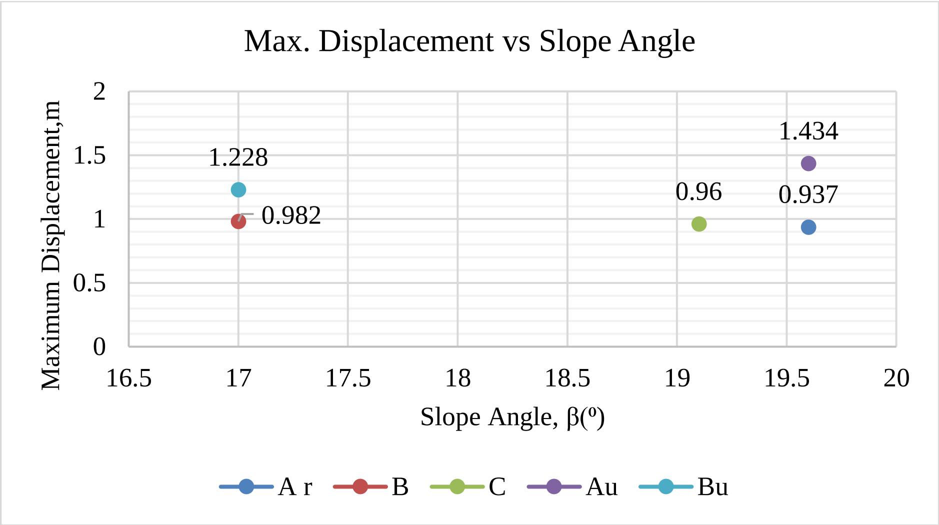


Figure 4. 7 Maximum displacement against Slope Angle

Figure 4.7 shows the graph of maximum displacements of the slope against their slope angle. Both rooted and unrooted slope of A and B have a slope angle of 19.6º and 17º respectively while slope C possessed a slope angle of 19.1º. Based on the graph, it clearly shows that the unrooted slope of A and B both having high values of maximum displacements which are 1.434 mm and 1.228 mm respectively while the unrooted slope C is slightly higher than the value of rooted slope A, with a value of 0.96 mm. Hence, by having a higher slope angle, the displacement also increase for the unrooted slope as they does not have any protection on the slope that can reduce the deformation happens.

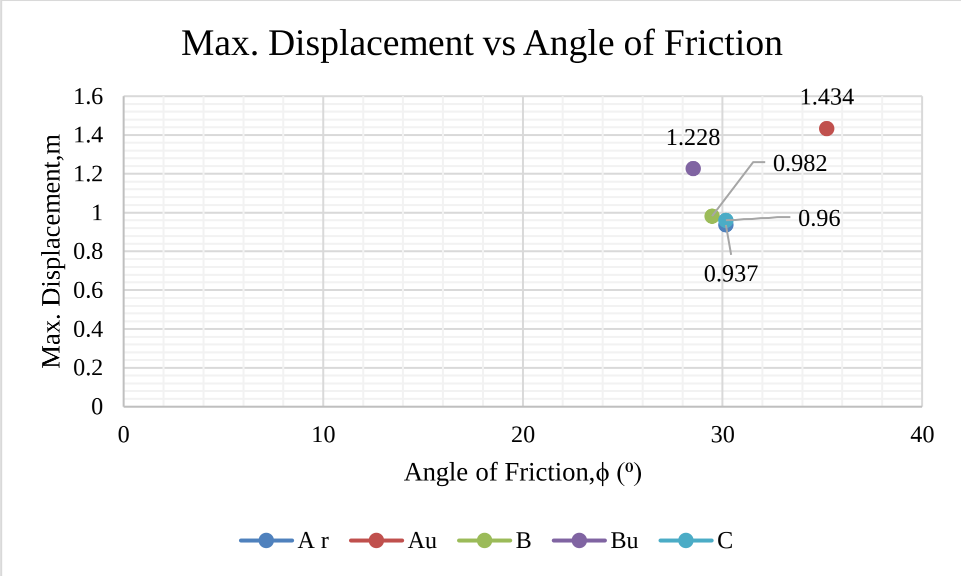


Figure 4. 8 Maximum displacement against angle of friction

Figure 4.8 shows the maximum displacement against the angle of friction of the slope. Angle of friction is the angle of inclination with respect to the horizontal axis of Mohr-Coulomb shear resistance line. Based on the simulation and the interpretation of the data in form of the above graph, it shows that the unrooted slope A which has higher angle of friction obtain higher value of maximum displacement while the rooted slope A has the lowest maximum displacement with a value of 0.937 mm. Unrooted slope B also obtain a value of maximum displacement which is higher compared to the rooted slope B.

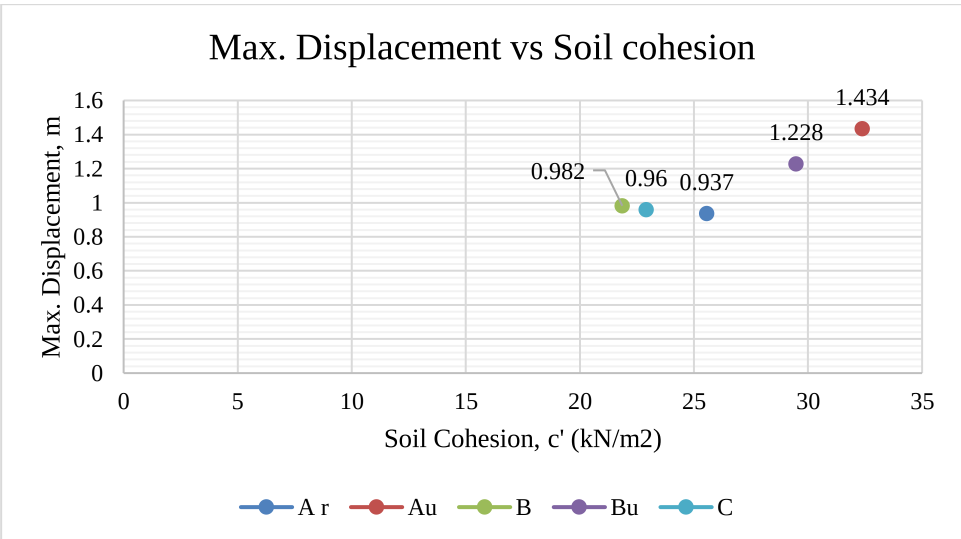


Figure 4. 9 Maximum displacement against soil cohesion

Each of the slope that have been simulated has different value of soil cohesion as shown in the graph of Figure 4.9. Soil cohesion used in this research are obtained from the literature review from previous research. Based on the figure above, it shows that the rooted slope B with the lowest soil cohesion obtained a maximum displacement of 0.982 mm while the unrooted slope A with highest value of soil cohesion obtained a high maximum displacement with a value of 1.434 mm. The graph also shows that the unrooted slope for both A and B obtain higher value of maximum displacement compared to their rooted slope. Hence, when the soil cohesion is decrease, the maximum displacement shall be increase as there is no shear strength from the soil which prevent it from collapse. The graph shows the opposite way as the rooted slope has a loading of *Eugenia Oleina'*s root plants acting on the slope.

4.4 Discussions

Based on the results obtained and portrayed above, it is clearly that the *Eugenia Oleina* species is not suitable to be used in order to implement the bioengineering techniques to prevent the soil erosion. By simulating the slope stability in Plaxis 2D, the factor of safety obtained shows that with presence of *Eugenia Oleina* species, the slope is unstable as the FOS is lower compared to the bare slope without the presence of the species. Furthermore, from the back calculation of equation 2.1 by using the factor of safety obtained in the simulation, it shows by planting the *Eugenia Oleina* species, the soil cohesion obtained will decrease abruptly and thus can behave like cohesionless materials because the cohesion value is less than zero.

Furthermore, the analysis in Figure 4.7 shows the agreement with a research in Chapter 2 with a Figure 2.3 where with the increase of slope angle, the total displacement also increase. However, in Figure 2.5 based on research by Chakrabarti et al (2017), it shows that for a slope stability analysis with varying slope height and slope angle, the displacements for each height are decrease when the slope angle increase. Selvaraj et al (2015) conclude that when the soil cohesion increase, the value of FOS also increase. Hence, the same pattern can be identified in this research where the soil cohesion for unrooted soils are clearly high compared to the slope with Eugenia Oleina roots. Thus, the FOS of the unrooted soil is higher when the soil cohesion increase.

In addition, the displacement graphs against the slope angle, angle of friction and the soil cohesion shows that the rooted slope of both A and B possessed a lower maximum displacement compared to the unrooted slope. Hence, it shows that based on this term that the *Eugenia Oleina*'s roots also help to retain the slope from eroded.

Both software used in this research to find the factor of safety for the slope generated different values from one another despites of their similarities. Plaxis 2D is easier to use but sometimes it is hard to figure out the functions of each and every one of the buttons available. ADONIS in the other hand is a very handy tools but one of the disadvantages is it does not have any "undo" button. Hence, with a single mistake, the simulation and data input need to be restarted from the square one. Apart from the limits, it is also user-friendly as it also provides a forum to discuss between the users and have interaction with the developers themselves.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the simulation and analysis done in this research, it can be concluded that one of the cause for shallow soil erosion to happen at the slope is the inability of the roots of Eugenia Oleina to retain the soil from eroded.

Furthermore, based on the simulation of slope stability with live pole by using Plaxis 2D, it shows the FOS for each slopes are different when compared to other calculation method. Even though having different values from one another, it still shows that the FOS for rooted slope is lower when compared to the FOS obtained for unrooted slope. This shows that *Eugenia Oleina* is unsuitable for acting as slope reinforcement tool except for landscaping purpose.

The factor of safety for the rooted slope with *Eugenia Oleina* species shows that the slope is unstable with FOS below than 1 compared to the slope without the presence of the species. Even though the displacement shows that the rooted slope is safe, but the factor of safety which was calculated from the strain of the soil stated the opposite. Based on the manual calculation done to obtain the new soil cohesion based on FOS from the simulation, it shows that the *Eugenia Oleina*'s root does not help in improving the soil properties as the calculated value of cohesion is lower compared to the cohesion value used in the simulation. Hence, the *Eugenia Oleina* is proven not suitable in maintaining the slope from undergo erosion.

Moreover, soil cohesion and root cohesion plays a very important role in retaining the slope from undergoing erosion. Softwares used in this research are great in its own respective way, which means it has its own specialty. Hence, it is a good way on enhancing technical skills by having to operate both Plaxis 2D and ADONIS software throughout this research.

5.2 Recommendation

As a recommendation from this research, every bio-engineered slope with plant shall be covered with grass in order to give extra protection from excessive erosion. Based on this research, it is clearly shown that the existence of *Eugenia Oleina* on the slope by itself is not enough. Hence, by adding more grass bed or applying the mulching techniques can avoid debris erosion. Next, the *Eugenia Oleina* plants are proven that it is not suitable species to act as reinforcement or for slope stabilization. Thus, it is best to reconsider in using the species for future planting with limiting it only in landscaping purposes.

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APPENDIX A
CALCULATION FOR SOIL PROPERTIES (COHESION)

Deteremination of soil cohesion by using formula:

$$FOS = \frac{(c' + \Delta s)}{(\gamma sat.z.cos\beta + Wv).sin\beta} + \frac{(\gamma' z.cos\beta + Wv)}{(\gamma sat.z.cos\beta + Wv)} \times \frac{tan\emptyset}{tan\beta} \qquad 1$$

Where:

FOS = Factor of safety

c' = soil cohesion (kPa)

Δs = root cohesion (kPa)

β = slope angle (º)

$\emptyset'$ = soil friction angle (º)

γ' = $\gamma_{sat} - \gamma_w$ "submerged'' bulk unit weight

γ_{sat} = saturated bulk unit weight (kN/m^3)

z = vertical depth of the failure plane (m)

W_v = Overload due to vegetation (kPa)

Rooted Slope A:

Soil Properties:

FOS = 0.368
β = 19.6°
$\emptyset'$ = 30.17°
γ_{sat} = 16.34 kN/m^3
γ' = $\gamma_{sat} - \gamma_w$
= 16.34 – 9.81 = 6.53 kN/m3
z = 1.5 m
Δs = 41.8024

Based on equation 1;

$$FOS = \frac{(c' + \Delta s)}{(\gamma sat.z.cos\beta + Wv).sin\beta} + \frac{(\gamma' z.cos\beta + Wv)}{(\gamma sat.z.cos\beta + Wv)} \times \frac{tan\emptyset}{tan\beta}$$

$$0.368 = \frac{(c' + 41.8024)}{[16.34(1.5)cos19.6 + 8319)(sin19.6)]} + \frac{(6.53cos19.6 + 8319)}{(16.34(1.5)cos19.6 + 8319)} \times \frac{tan30.17}{tan19.6}$$

c' = -3572.5022

Rooted Slope B:

Soil Properties:
FOS = 0.393
β = 17°
$\emptyset'$ = 29.48°
γ_{sat} = 18.73 kN/m^3
γ' = $\gamma_{sat} - \gamma_w$
= 18.73– 9.81 = 8.92 kN/m3
z = 1.5 m
Δs = 44.0771

Based on equation 1;

$$FOS = \frac{(c' + \Delta s)}{(\gamma sat. z. cos\beta + Wv). sin\beta} + \frac{(\gamma' z. cos\beta + Wv)}{(\gamma sat. z. cos\beta + Wv)} \times \frac{tan\emptyset}{tan\beta}$$

$$0.393 = \frac{(c\prime + 44.0771)}{[18.73(1.5)cos17 + 9370)(sin17)]} + \frac{(8.92cos17 + 9370)}{(18.73(1.5)cos17 + 9370)} \times \frac{tan29.48}{tan17}$$

c' = -4036.84

APPENDIX B
PLAXIS SIMULATION RESULTS

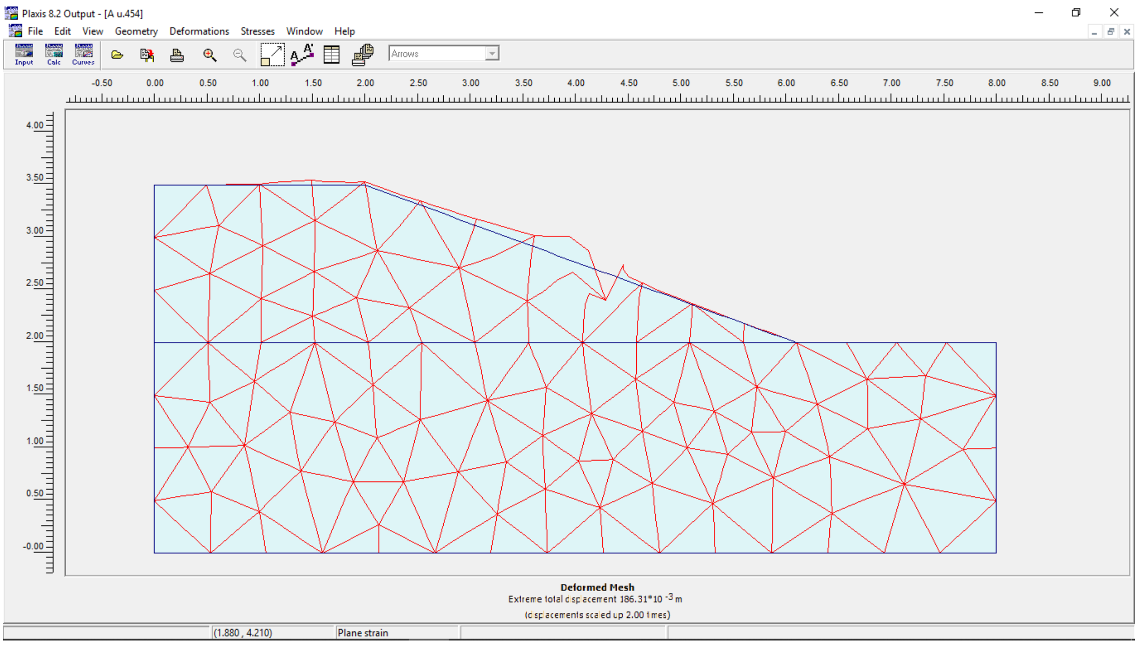

Figure a Deformation Mesh of Slope A rooted

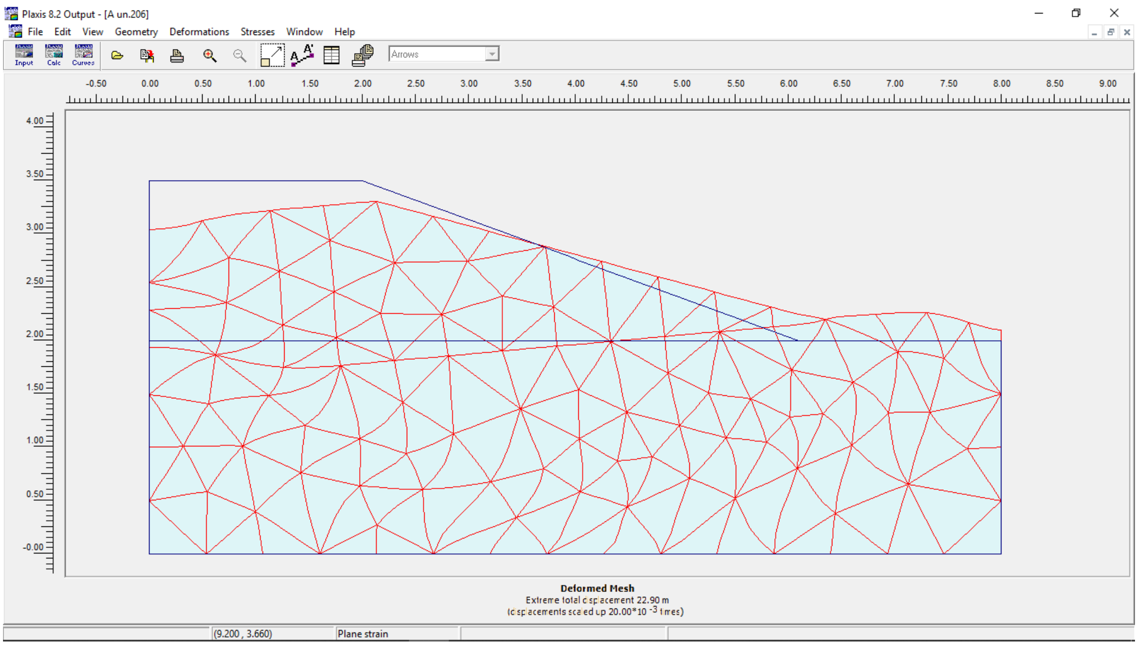

Figure b Deformation Mesh of Slope A unrooted

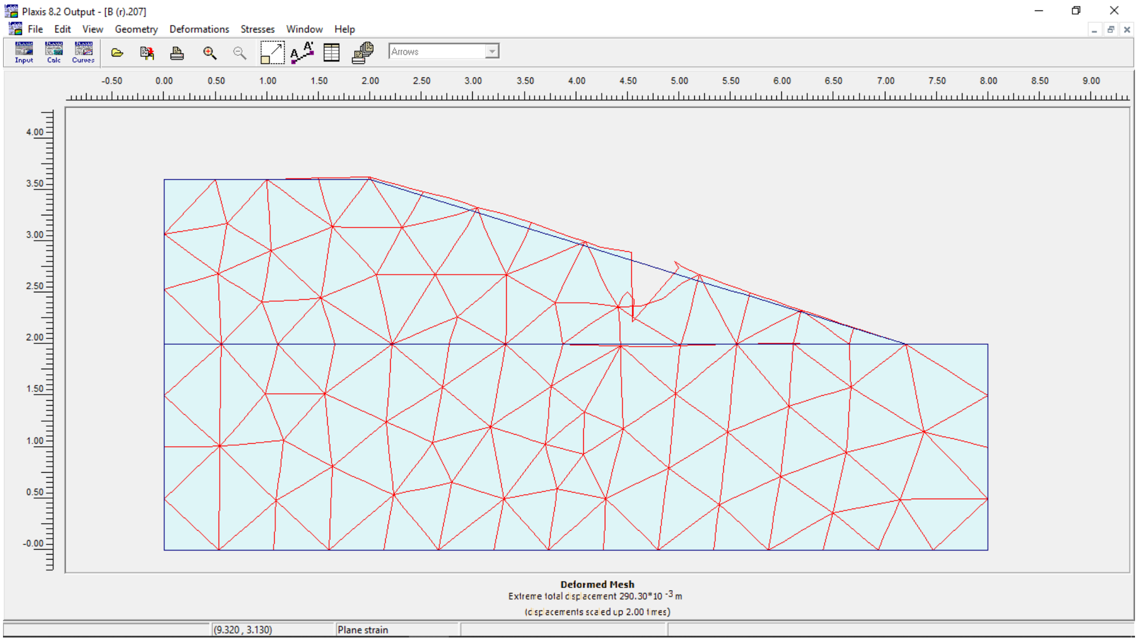

Figure c Deformation mesh of Slope B rooted

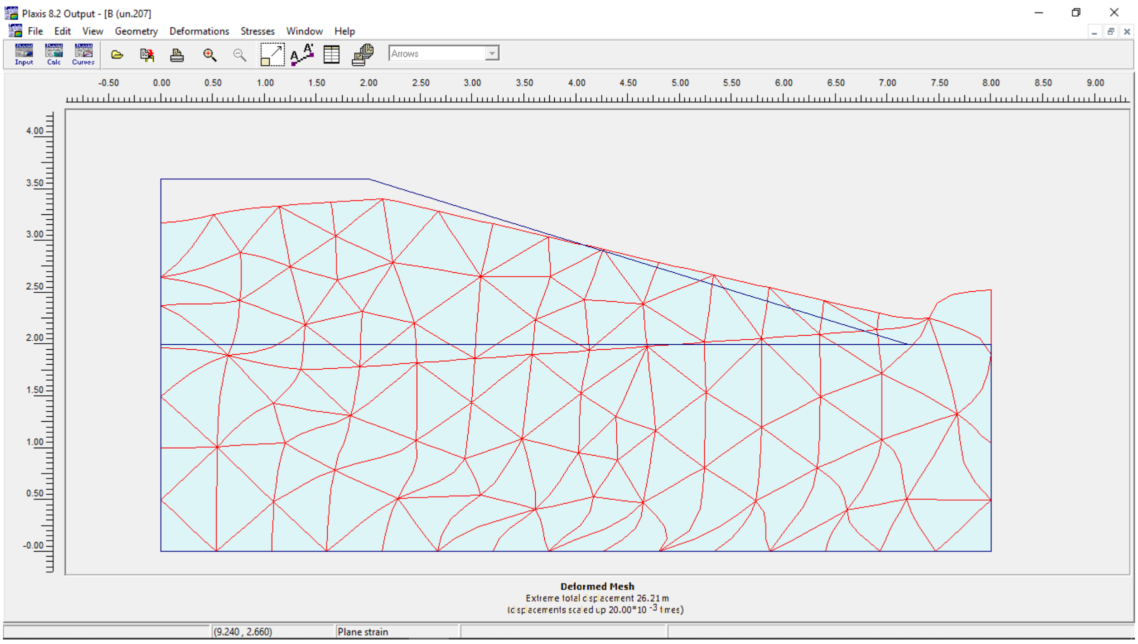

Figure d Deformation mesh of Slope B unrooted

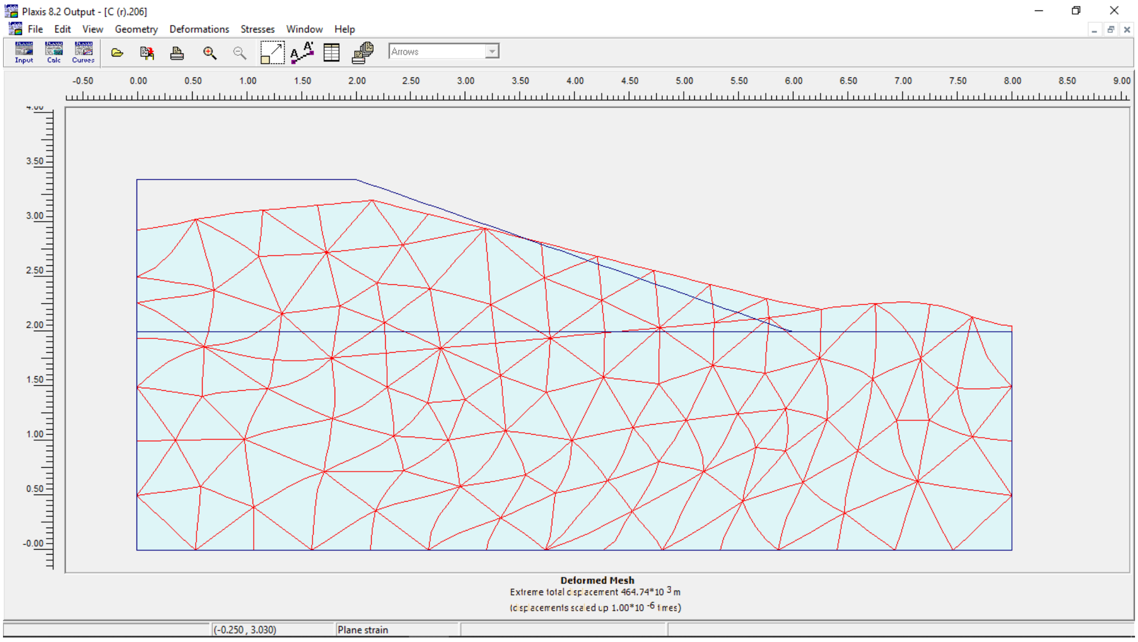

Figure e Deformation mesh of Slope C (Control Slope)