Optimization of Soil Nailing under Some Uncertainties

by

Bong Yan Sheng

15135

Dissertation submitted in partial fulfillment of

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CERTIFICATE OF APPROVAL

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TRONOH, PERAK

September 2014

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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BONG YAN SHENG

ABSTRACT

Soil Nailing is generally practiced in Malaysian slopes for highway and hillside development projects as a stabilization method for very steep cut slopes. Due to its ease of construction and is relatively maintenance free as an effective slope stabilization method, soil nail slopes with a height greater than 20 m is gradually being used for slopes in Malaysia. In this study, "Slope A" which is an existing cut slope with reinforcement of soil nailing is being reanalyzed in order to minimize the cost. Therefore, parametric studies are conducted using this existing project model to study the effects of certain factors such as slope geometry, water table level, soil parameters and factor of safety on the slope stability. Also, a few areas such as the soil nailing configuration (arrangement and length) and other parameters are taken into account to determine the optimization in terms of project cost. A software, named SLOPE/W is used by applying soil nails to improve the slope stability and to propose the most economical slope condition. The results obtained from the study will determine the most economical slope which optimize in terms of reduction in total length of soil nailing.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION & NOMENCLATURE

FOS	Factor of Safety
JKR	Jabatan Kerja Raya (Malaysian Public Works Department, also known as PWD)
FHWA	US Department of Transportation, Federal Highway Administration
RL	Reduced Level
CH	Chainage

Chapter 1 INTRODUCTION

Moving into the 21st century, the advent of technology has brought vast development to the society. Civil Engineering discipline has been acknowledged as one of the fields which contribute to this development. Any constructions or mega projects built are meant to rest on the surface of earth. In order to live a better life, the demand of future accommodation is not only subjected to be comfortable, but also subjected to have beautiful scenery. This phenomenon eventually led to a lot of housing, condominiums and recreational park development to be carried out on the hill slope. Due to the vast development and limited land area, excavation of certain areas like mountains and slopes are also carried out for future development such as retaining walls and highways. The main concern here is on the structures which were built on the hill slopes. There might be slope instability in that particular area caused by infiltration, runoff and inadequate shear strength on the excavated hill slope. In order to prevent slope failure and landslides, reinforcement of soil must be applied on excavation slopes.

Soil nailing is used to ensure public safety from slope failure hazard due to its reputation as one of the fastest, cheapest and efficiency reinforcement techniques. Besides, it is used to enhance soil stability in areas where landslides might be a problem, by inserting steel reinforcement bars into the soil while excavation goes on phases by phases, and anchoring them to the soil strata.

Furthermore, due to its relatively maintenance free and somewhat straightforward construction method, soil nailing has gained popularity in Malaysia for highway and also hillside development projects (Chow & Tan, 2006). In addition, because of its technical and economic advantages, soil nailing technique had achieved a remarkable accomplishment over the past two decades for constructing in situ earth support systems such as retaining walls, bridge abutments, and steep slopes (Unterreniner et al., 1995).

In this study, SLOPE/W software is used for the determination of the soil behavior in order to optimize the cost. This is done through some control and parametric studies by monitoring the soil nailing arrangement and the length of the soil nailing.

1.1 Problem Statements

Few problem statements have been raised related to this study. First and foremost, analysis obtained from software does not necessarily produce the same results in the real world problem as there are a lot of uncertainties. Secondly, overly design of soil nailing might cause an increment in terms of cost for the entire project. Thirdly, there is a concern on how to optimize the design of soil nailing. Last but not least, how will the changes in geometry of slope, the water table level, the length and arrangement of soil nail affects the Factor of Safety (FOS) and cost optimization.

1.2 Objectives

This study aims to study the effect of soil nailing improvement method on the slope stability. Based on the background research presented above, few objectives have been listed out to outline the direction of this research project:

i. To study the effects of some slope stability parameters, such as (slope geometry, water table, control slope with and without soil nailing, the length of the soil nailing) on the type of failure mechanism and Factor of Safety (FOS).
ii. To propose the most economical slope condition in terms of cost optimization and lowest Factor of Safety (FOS) based on the existing project.

1.3 Significant of this project

As soil reinforcement is important in supporting constructions on hilly areas and is now a popular construction method for Malaysian highway and hillside development projects, this study is aimed to study the effect of soil nailing on the failure behavior of slope. The slope behavior will be predicted by various parametric studies, such as slope geometry, water table, control slope with soil nailing and control slope without soil nailing. Analysis are carried out to determine the most economical slope condition as well as to provide cost optimization for the installation of soil nailing.

1.4 Scope of Study

This paper emphases on the practice of soil nailing method in Malaysian slopes, in particular the slope stability analysis. The scope of the project is constricted as a result of time constraint so that the project is feasible and could be accomplished within the allocated time frame.

The SLOPE/W software, further discussed in Section 3.3 shall be used for the prediction of slope stability and failure, using the control of parameters as below:

i. Geometry of slopes
ii. Pore water pressure
iii. Soil parameters

Chapter 2 LITERATURE REVIEW

2.1. Background Study on Slope Stability

2.1.1 Introduction

Dated back into the human history, slope stability problems exist either naturally such as landslides or when the nature and balance of natural soil slopes are disrupted by humans. With the developments of soil and rock mechanics nowadays, slope stability analyses have achieved its advancement in geotechnical field. A better understanding of geology, soil properties and hydrology is essential to practice slope stability principles properly. Common methods analyses such as the simplified Janbu method, simplified Bishop Method, Spencer’s method, ordinary method of slices, other limit equilibrium methods and computer programs are used to solve problems in slope stability.

There are a lot of methods of improving the stabilization of slopes, such as the commonly known regrading of slope profile, rock berms (toe counterweight), reinforced soil wall and soil nailing. However, this study is carried out to look at the effect of soil nailing arrangement and length on the slope failure mode and cost optimization. The details are further discussed in Section 2.2 and Chapter 3.

2.1.2 Mode of Failure

Failure mechanisms is one of the concerns that should be considered when doing design assumptions. Terzaghi and Peck (1967) stated that slides may occur in almost every conceivable manner, slowly or suddenly, and with or without any apparent provocation. The aspect ratio used to differentiate between the translational and rotational surfaces is shown in Figure 2.1.

Two common failure mechanism, known as the global instability and local instability are explained in Table 2.1. A clearer example of global instability and local instability is shown in Figure 2.2. Slope fails on the planar failure is referred as local instability which is related to the surficial facing of a channel bank. This also relates to the connection strength between the facing and internal reinforcements in a constructed slope. Meanwhile, slope which fails on the rotational failure plane is referred as global stability which relates to deep seated rotational failures that are generally outside the limits of a constructed slope. In this case, cracks on earth could be identified before the occurrence of a slope failure.

Figure 2.3.shows the general slope collapse mechanism and they can be divided into three types, mainly the toe failure, face failure and base failure.

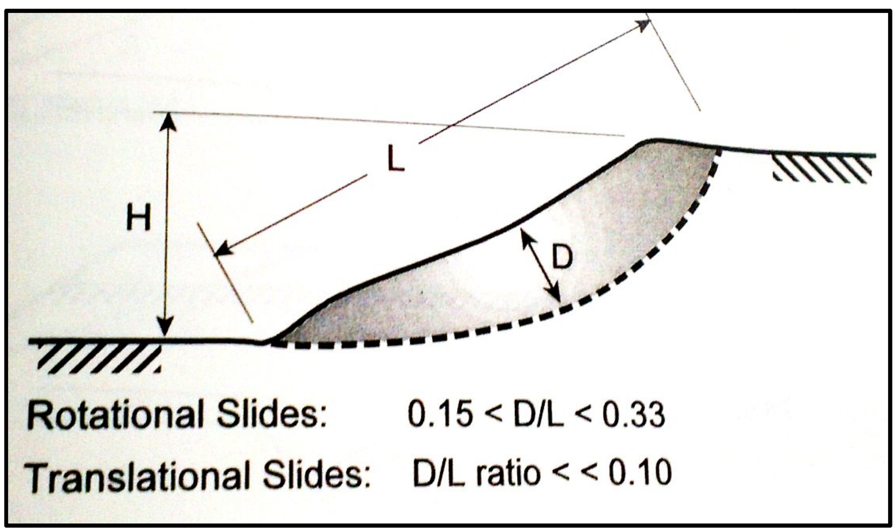

Figure 2.1: Aspect ratio of failure mass, the grey area, where 0.1 < D/L < 0.15 has been left account for the case of a combined rotational and translational failure (Lee.A.W et al., 2002)

Table 2.1: Failure mechanism of Slope: Global instability and local instability

Global (overall) instability	Local instability
Foundation failure: Slip surface failure or an excessive settlement.	Hydraulic instability of rubble foundation
Overturning	Hydraulic instability of fronting rubble protection
Lateral displacement or sliding on foundation	Breakage and displacement of structural elements

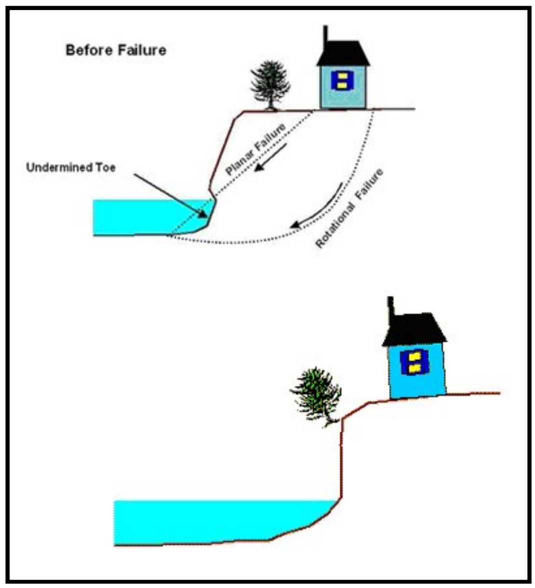

Figure 2.2.: Slope failure showing global and local instability

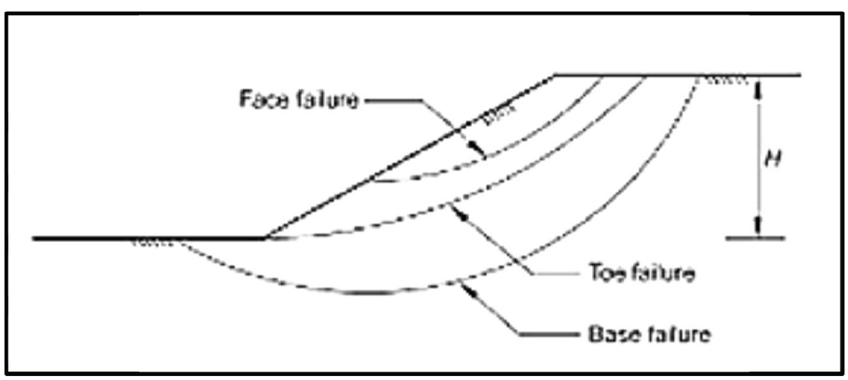

Figure 2.3: Three types of slope collapse mechanism, face failure, toe failure & base failure (Gao, Y.F. et al., 2013)

Geoguide 7 (2008) suggested that engineering judgment should be made to identify all potential modes of failure under the specific ground and groundwater conditions, and the type of soil-nailed system which are illustrated in Figures 2.4 and Figure 2.5.

External failure refers to the development of potential failure surfaces essentially outside the soil-nailed ground mass. The failure can be in the form of sliding, rotation, bearing, or other forms of loss of overall stability. Meanwhile, internal failure refers to failures within the soil-nailed ground mass. Internal failures can occur in the active zone, passive zone, or in both of the two zones of a soil-nailed system.

In the active zone, internal failure modes include:

i. failure of the ground mass, i.e., the ground disintegrates and 'flows' around the soil nails and soil-nail heads,
ii. bearing failure underneath soil-nail heads,
iii. structural failure of the soil nail under combined actions of tension, shear and bending,
iv. structural failure of the soil-nail head or facing, i.e., bending or punching shear failure, or failure at head-reinforcement or facing-reinforcement connection, and
v. surface failure between soil-nail heads, i.e., washout, erosion, or local sliding failure.

In the passive zone, pullout failure at ground-grout interface or grout-reinforcement interface should be considered.

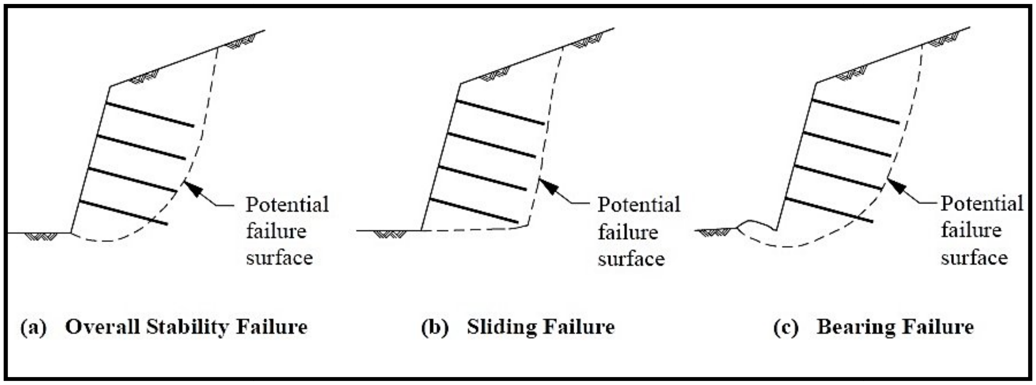

Figure 2.4: Potential External Failure Modes of a Soil Nail System

(Geoguide 7, 2008)

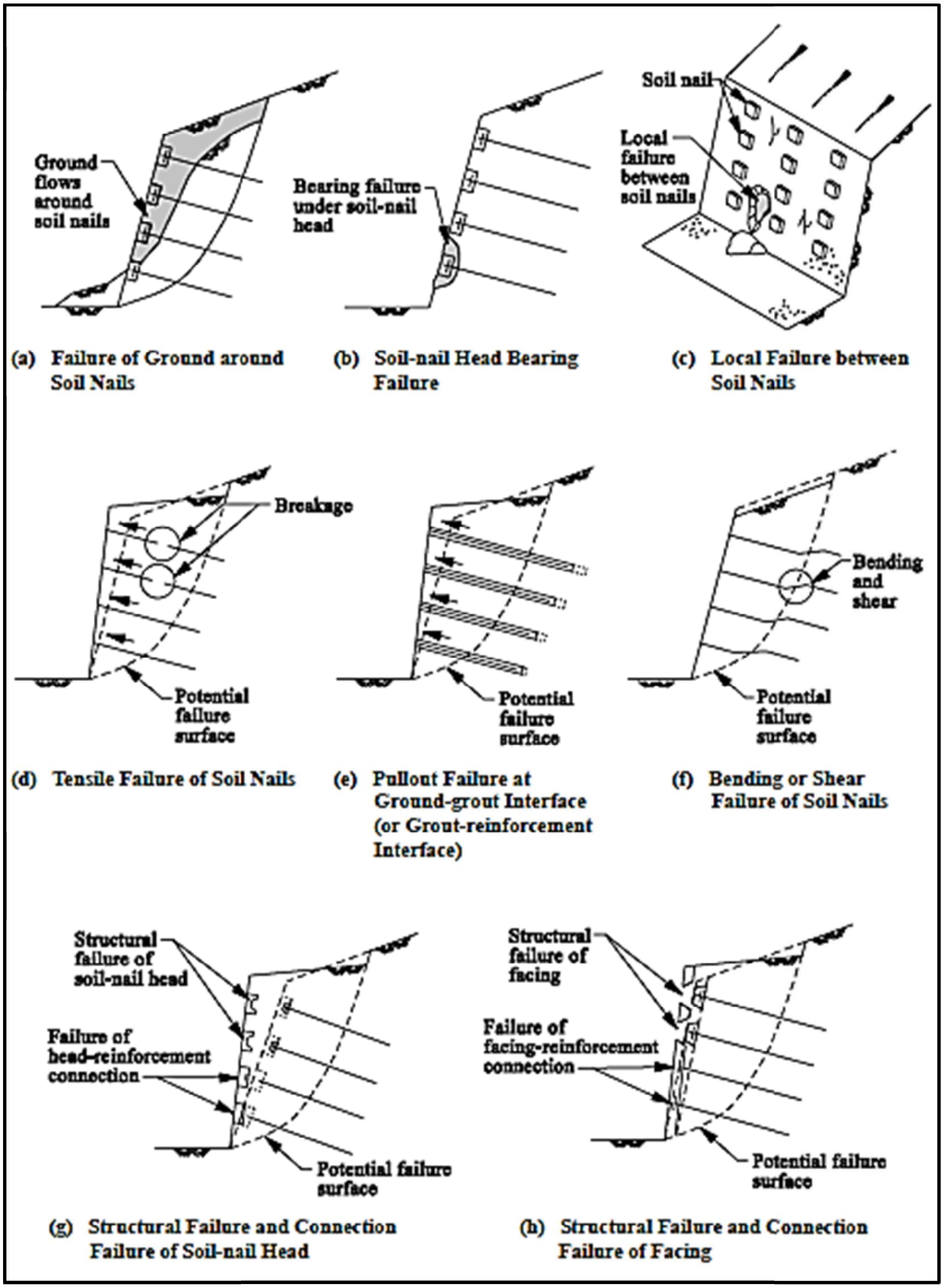

Figure 2.5: Potential Internal Failure Modes of a Soil Nail System

(Geoguide 7, 2008)

2.1.3 Factor of Safety (FOS)

Factor of safety for slope stability analysis is usually defined as the ratio of the ultimate shear strength divided by the mobilized shear stress at incipient failure (Cheng & Lau, 2008). Besides, factor of safety is also known as the strength reduction failure divided by the disturbing force. An understanding of the role of the factor of safety (FOS) is essential in rational design of slopes and to account for uncertainty. Meanwhile, determination of factor of safety is to ensure whether the condition of a particular application is either long or short term, in order to determine the reliability of soil parameters & analytical model as well as to know the consequences of each design on a particular slope project.

Lee et.al (2002) state that for typical slope designs, the required FOS (non-seismic) is usually in the range of 1.25 to 1.5. In general, if FOS is greater or equal to 1, it can be said that the slope is in a stable condition. However, if FOS is less than 1, it is usually regarded as unstable. Table 2.2 shows the comparison of FOS requirements based on different references. Figure 2.6 illustrates the various definition of FOS using limit equilibrium, forces, and moment. For this project, JKR Road Works standard is used in the reanalyze of “Slope A” where the FOS for reinforced slope is 1.5.

Table 2.2: Comparison between various references on the Factor of Safety (FOS) requirements

References	FOS Requirements
BS 6031	1.3-1.4 for first time slide 1.2 for slide with pre-existing slip surface
JKR Road Works	1.2 for unreinforced slope & embankment on soft ground 1.5 for reinforced slope
Hong Kong Geoguide	1.0-1.4 for new slopes depending on risk categories 1.0-1.2 for existing slope depending on risk categories
NAVFAC DM7.1	1.5 for permanent loading condition 1.15-1.2 for transient load
Britain National Coal Board 1970	1.5/1.35 (peak/residual strength used) for risky slope 1.25/1.15 (peak/residual strength used) for non-risky slope
Canada, Mines Branch 1972	1.5/1.3 (peak/residual strength used) for risky slope 1.3/1.2 (peak/residual strength used) for non-risky slope

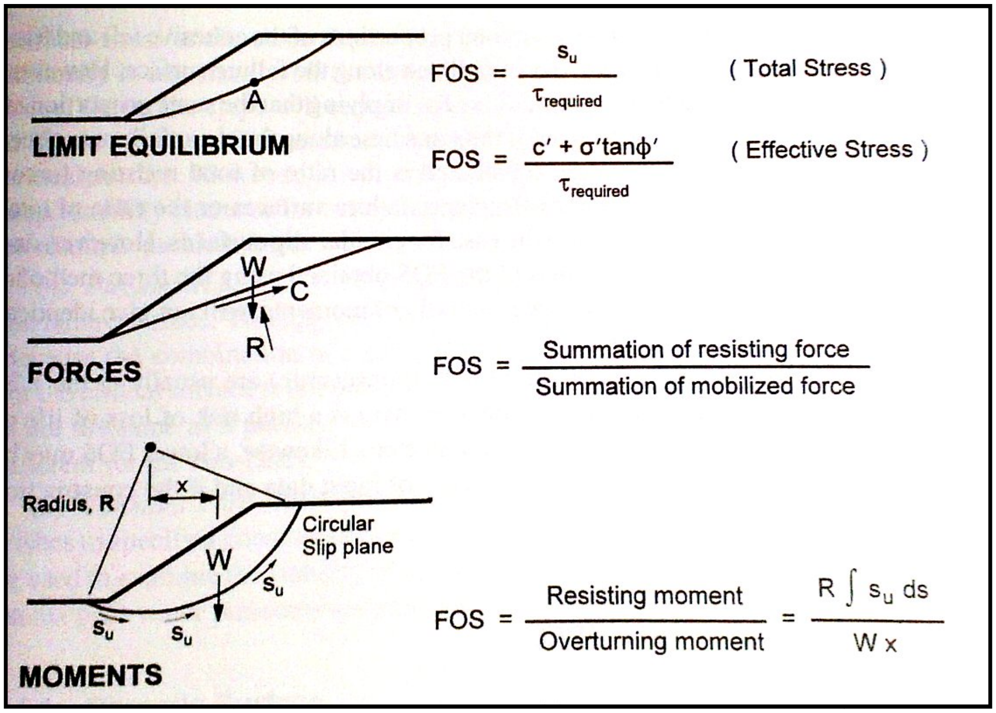

Figure 2.6: Various definition on the Factor of Safety (FOS) (Lee.A.W et al., 2002)

2.1.4 Important slope stability factor

There are tons of factors influencing the stability of slopes, such as: shear strength of the soils, slope geometry, pore pressures or seepage forces and loading and environmental conditions. However, only a few common ones are discussed in this section. Gravitational force, as a disturbing force is a necessary condition for slope instability. Other sufficient condition which leads to slope instability are the reduction of slope strength as in water resistance, additional disturbing forces such as surcharge and groundwater drawdown as well as a drastic change of slope geometry such as steepening.

2.1.4.1 Importance of groundwater and pore water pressure

Rainwater run offs at the slope may cause surface erosion if there is incomplete surface protection. Failure in residual soils cut slopes might be caused by 'wetting-up' process which causes a decrease in soil suction and hence, decreases the soil strength. There is also evidence suggesting that transient rises in groundwater table are responsible for some rain-induced landslides (Premchitt et al., 1985). Lambe and Silva (1998) also reported that over the 60 slope failures that they have investigated, about three-quarters of these failures were due to an increase in pore water pressure.

In view of the high soil permeability, much of the water will infiltrate into the subsoil. This causes the water level in the slope to rise or it may cause a perched water table to be formed at some less permeable boundary, usually dictated by the weathering profile. Above the water table, the degree of saturation of the soil increases and thus reduces the soil suction (i.e. negative pore pressure) (Tan & Chow, 2004).

The effect of ground water table profile is also viewed as a crucial factor in slope stability. For hill slopes, the ground water table is generally low and fluctuates with time, especially during rainy season as shown in Figure 2.7 & Figure 2.8. High ground water table increases the risk of failure as the shear resistance in the potential failure plan decreases due to increased water pressure between soil particles. Besides, ground water table on the upslope acts as additional driving forces. All those factors contributes to a declination of the FOS of a slope.

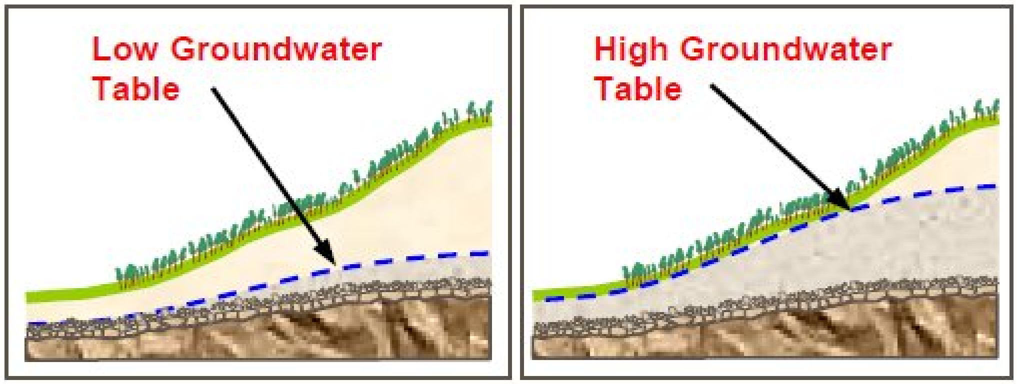

Figure 2.7: Two general types of ground water table profile which may be found in a slope (Gue & Fong, 2003)

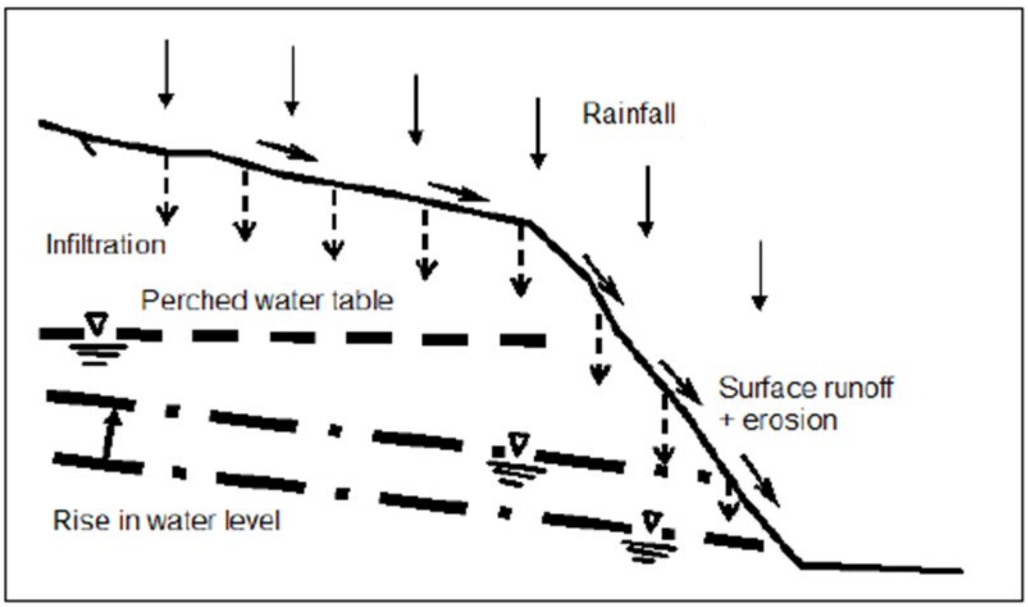

Figure 2.8: Effect of rainfall on permeable slope (Tan & Chow, 2004 – after Brand 1995)

2.1.4.2 Effect of slope geometry or ratio of steepness

Slope geometry is indeed one of the most important factor contributing to slope stability as shown in Figure 2.9. Gue and Fong (2002) stated that low and gentle slope is safer than high and steep slope for a similar soil as the latter has more mass on the upslope acting as a driving forces (F) compared to that of a gentle slope.

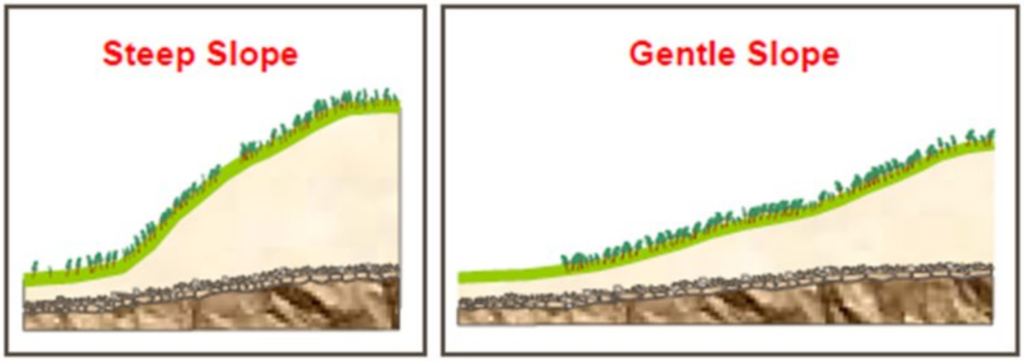

Figure 2.9: Steep & gentle slope (Gue & Fong, 2003)

2.2 Background Study on Soil Nailing

Soil nailing is a construction technique of providing temporary earth support and retention during excavation for new construction. It is also used for construction of slope stabilization, underpinning, permanent retaining walls, and protection of existing cuts (Tuozzolo, 1997). Apart from that, soil nailing can be used to treat unstable natural soil slopes or act as a construction technique which allows the safe over-steepening of new or existing soil slopes.

FHWA (2003) reported that soil nailing was first applied in 1972 for a railroad widening project near Versailles, France, where an 18m high cut slope in sand was stabilized using soil nails. It was the cost effective and fast construction which leads to success of this project that ensure encouragement and a source of reference to others. Eventually, soil nailing was adapted for use in the Paris underground extensions. FHWA (2003) also mentioned that the first usage of soil nail wall in Germany was in

1975, but the first major research program on soil nail walls was done by University of Karlsruhe and a construction company Bauer in Germany from 1975 to 1981. As compared to the early implication of soil nails method in the European countries, Chow and Tan (2006) discussed that the soil nail method has slowly gained popularity in Malaysia for highway and hillside development projects due to its rather straightforward and relatively maintenance free construction method.

Stabilization of slopes using soil nailing has the distinct advantage of strengthening the slope without causing further disturbance to the existing slope. Therefore, this method is very popular for strengthening work involving distressed slopes. The basic concept of soil nailing is to reinforce and strengthen the existing ground by installing closely-spaced steel bars called ‘nails’ into a slope as construction proceeds from ‘top-down’. This process creates a reinforced section that is in itself stable and able to retain the ground behind it. The reinforcements are passive and develop their reinforcing action through nail-ground interactions as the ground deforms during and following construction (Tan & Chow, 2004). In passive reinforcement, some movement of the nailed mass of earth is anticipated in order to create the tensile & shear stress needed for stability.

In order to resist ground movement, the reinforced soil mass later provides lateral or vertical support for slope stabilization or excavations. Reinforcing elements (or nails) typically are steel bars which can resist tensile, bending, and shear stress. Nails may be driven directly into the ground, or placed it in a drilled hole and grouted along the entire length. Solid bars are usually installed into pre-drilled holes and then grouted with mix cement into place using a separate grout line, whereas hollow bars may be drilled and grouted simultaneously by the use of a sacrificial drill bit and by pumping grout down the hollow bar as drilling progresses.

Kinetic methods of firing relatively short bars into soil slopes have also been developed. Bars installed using drilling techniques are usually fully grouted and installed at a slight downward inclination with bars installed at regularly spaced points across the slope face. A rigid facing (often pneumatically applied concrete, otherwise known as shotcrete/guniting) or isolated soil nail head plates may be used at the surface. Alternatively a flexible reinforcing mesh may be held against the soil face beneath the head plates. Wire mesh and environmental erosion control fabrics and may be used in conjunction with flexible mesh facing where environmental conditions dictate. Some soil nail wall requires bench drain and horizontal drain to draw and drain away water from the existing slopes to the existing drains nearby. Geotextiles are used at the inner hole of horizontal drains to prevent the soil from flowing out, but only water are being drain out. The basic design concept for soil nailing is that earth pressures and external loads are being transferred directly to the nails in the form of tensile forces (Turner et al., 1999). Soil nail forces are then transferred into the surrounding of soil through friction mobilized at the soil/nail interfaces.

In Malaysia, usually 25 mm or 32 mm diameter steel rods are used and are inserted into the soil either by simple driving or by grouting in predrilled borehole (Tan & Chow, 2004). The types of soil nails which is commonly used are flexible nails with diameter less than 25 mm which are installed in a drilled and grouted hole and oriented to mobilize tension, stiff nails that are directly inserted without the addition of grout and are oriented to generate both shear and bending in the nail as well as tension, grouted soil nails, driven nails, corrosion protected nails, jet grouted nails, launced nails and screwed anchor soil nails. Figure 2.10 illustrates a typical cross section of a soil nail wall design.

Various codes of practice and design manuals such as listed below are available for design of soil nailing:

i. British Standard BS8006: 1995, Code of Practice for Strengthened/Reinforced Soils and Other Fills.
ii. U.S. Department of Transportation, Federal Highway Administration (FHWA 1998), Manual for Design & Construction Monitoring of Soil Nail Walls.
iii. U.S. Department of Transportation, Federal Highway Administration (FHWA 2003), Geotechnical Engineering Circular No.7. Soil Nail Walls. (FHWA0-IF-03-017)
iv. HA 68/94, Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques.

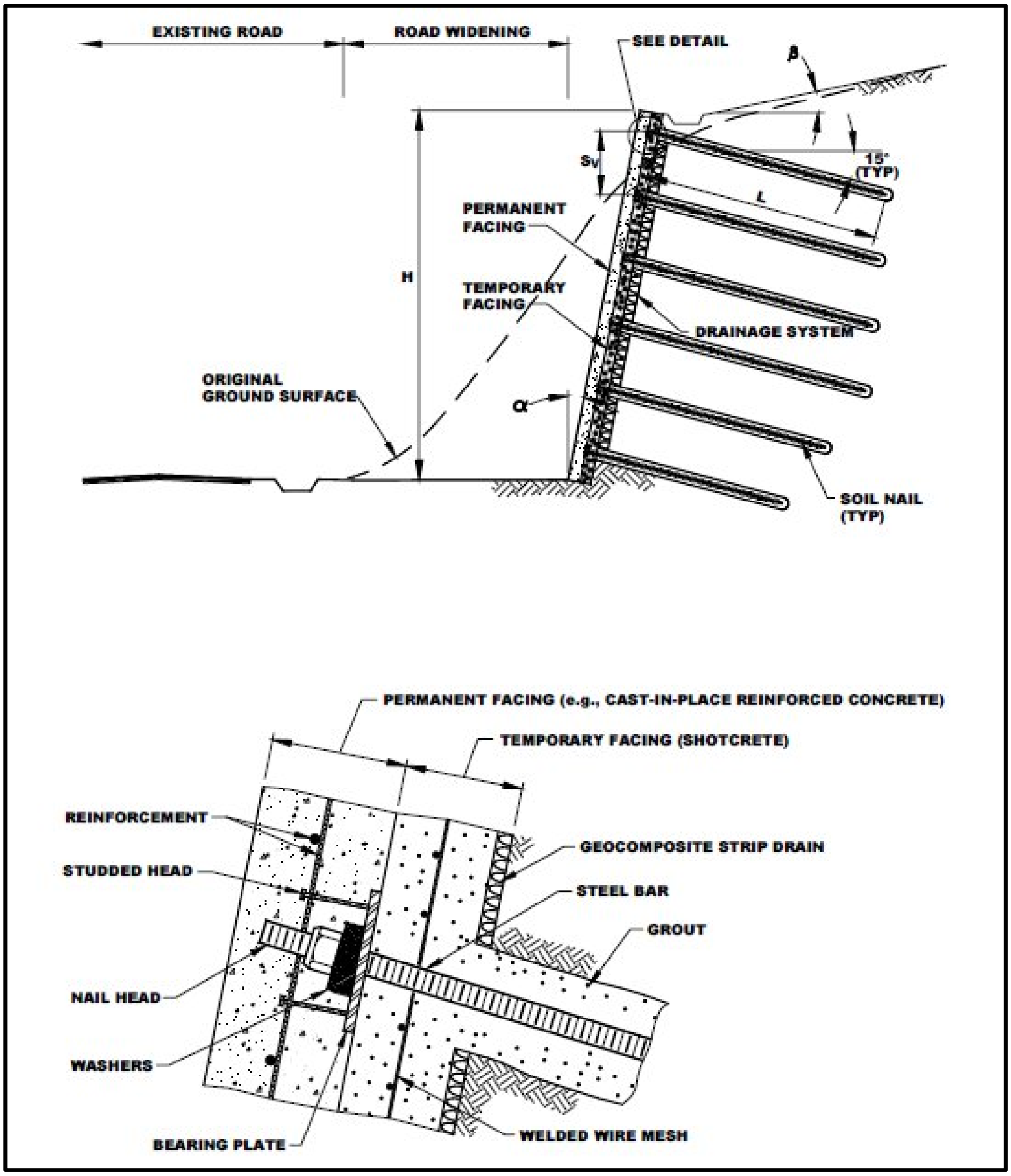

Figure 2.10: Typical cross section of a soil nail wall (FHWA0-IF-03-017, 2003)

2.2.1 FHWA, Manual for Design and Construction Monitoring of Soil Nail Walls

In this research, much focus is given to FHWA manual compared to the other codes as it is regarded as a reference guide in Malaysia practice for soil nail walls.

Malaysia Public Road Works Department (Jabatan Kerja Raya – JKR) has been referring to FHWA manual as a guideline in soil nail practices.

FHWA method with some modifications is adopted in Malaysian practice as it provides a rational approach towards soil nail design inclusive of the aspects for shortcrete, soil nail head, etc. (Chow & Tan, 2006) The major difference between FHWA's method with BS8006 and HA 68/94 is on the failure mechanism assumed. Both BS8006 and HA 68/94 recommends the use of two-part wedge and log spiral failure mechanism in soil nail design. However, FHWA recommends the "slip surface" method.

Some significant benefits of the slip surface limiting equilibrium approach to soil nail design are discussed in FHWA. One of the advantages is assumption of slip surface limiting equilibrium failure mechanism can be easily adopted in practical applications as various commercial slope stability analysis software (eg. SLOPE/W) are available to carry out such analysis. Besides, practicing engineers are more familiar with slip surface limiting equilibrium failure mechanism (as stated in FHWA) as compared to the two part wedge and log spiral failure mechanism (as stated in BS8006:1995 & HA 68194).

FHWA soil nail design method provides a complete and rational approach towards soil nail design, incorporating the following elements (FHWA, 1998):

i. Based on the slip surface limiting equilibrium concepts
ii. Consider the strength of the nail head connection to the facing, the strength of the nail tendon itself and the pullout resistance of the nail ground interface

Further understanding of the concept and explanation can be made reference to FHWA, Manual for Design and Construction Monitoring of Soil Nail Walls, 1998 or its later version FHWA0-IF-03-017, Geotechnical Engineering Circular No.7. Soil Nail Walls, 2003.

Chapter 3 METHODOLOGY

3.1 Flow Chart

As illustrated in Figure 3.1, SLOPE/W is chosen to analyze the existing slope and reanalyze it through parametric studies such as varying slope geometry, water table level, and length and arrangement of soil nailing based on local failure. This research aims to study the cost optimization of soil nailing by looking into the length and the arrangement of soil nailing. Great initiative is taken by the author to study and learn SLOPE/W software for a better understanding in future analyzing and performing slope stability analysis on “Slope A”. Control analysis and parametric studies are carried out to reanalyze “Slope A”. 102 analysis are conducted whereby detail analysis and further explanation are explained in Section 3.6.

In order to ensure smooth delivery of the research, a Gantt chart (please refer Appendix section) is proposed to monitor the progress and the key milestone and important dates throughout the research period. However, the author encountered some hardships in the middle of the research due to time constraint and other unexpected uncertainties which will further discussed in the recommendation & discussion section.

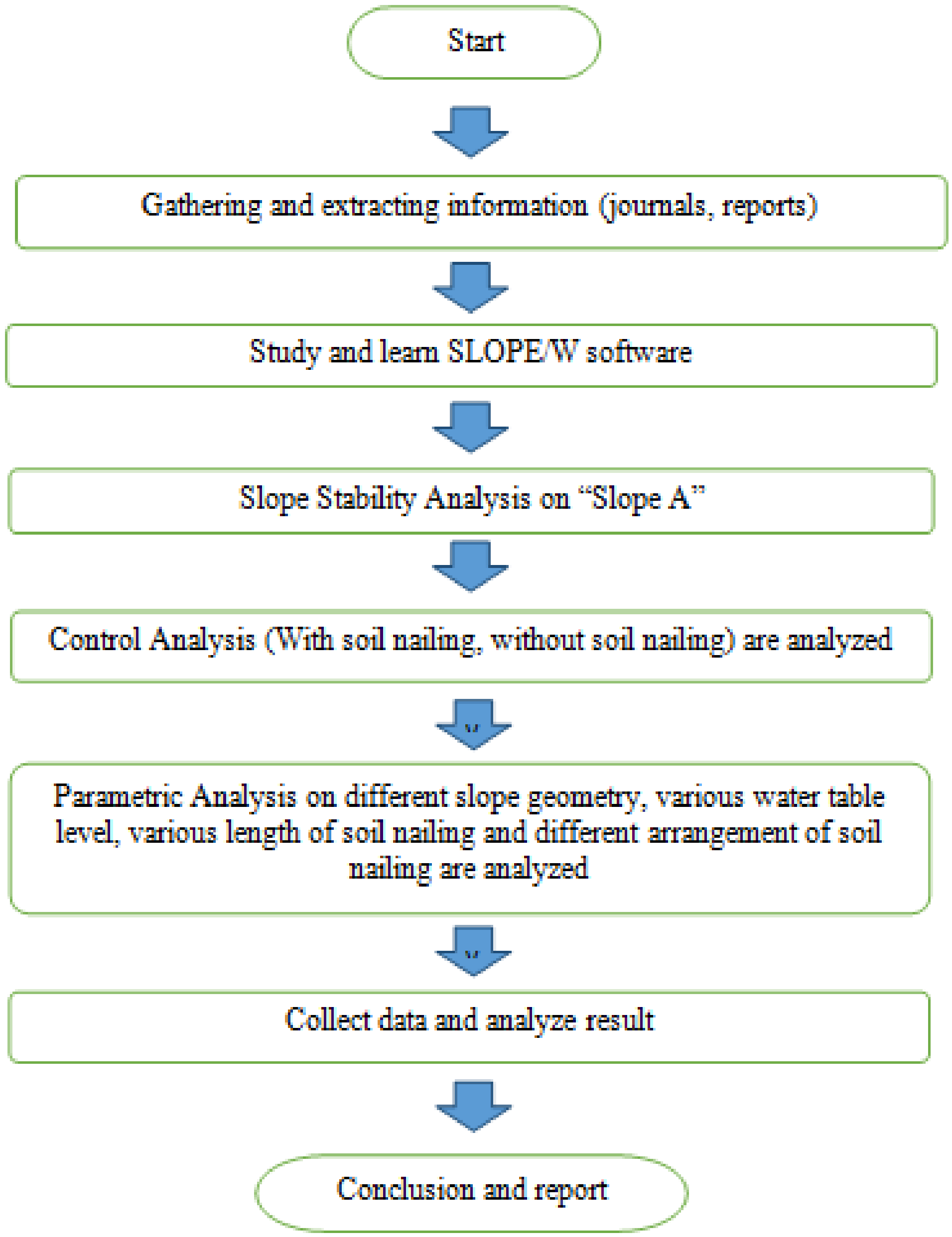

Figure 3.1: Project Flow Chart

3.2 GeoStudio

This project aims to study the optimization of soil nailing under some uncertainties, which focuses on the analysis study of the slope stability and the effect of different parametric studies on the soil behavior. Therefore, GeoStudio is chosen as the software to perform these parametric studies is useful for a wide variety of geotechnical problems:

i. Dams and levees
ii. Reinforced walls and slopes
iii. Excavations and open pit mines
iv. Roads, bridges & embankment
v. Environmental protection
vi. Construction ground freezing
vii. Climate change and arctic engineering
viii. Earthquake deformation

In GeoStudio, there are a lot of functions to aid in solving geotechnical problems, such as SLOPE/W, SEEP/W, SIGMA/W, QUAKE/W and VADOSE/W. However, in this study, because of the time constraint, only SLOPE/W is used to analyze the slope stability, failure behavior mode and also carry out some parametric study analysis.

3.3 SLOPE/W

As the foremost slope stability CAD software product, SLOPE/W can be used for computing the factor of safety of earth and rock slopes as shown in Figure 3.2. By applying limit equilibrium, SLOPE/W can model heterogeneous soil types, complex stratigraphic and slip surface geometry, and adjustable pore-water pressure conditions using a large selection of soil models. Slope stability analysis can be performed using deterministic or probabilistic input parameters. In addition to the limit equilibrium computations, stresses computed by a finite element stress analysis may be used for the most complete slope stability analysis available.

John Krahn (2004) stated that the myriad of options in SLOPE/W can be somewhat confusing, especially for beginners who are still new to this software. There are five components which are usually considered in addressing a problem:

i. Geometry – a description of the stratigraphy and shapes of potential slip surfaces
ii. Soil strength – parameters used to describe the soil strength
iii. Pore water pressure – Pore water pressure condition in a particular site location
iv. Reinforcement or soil structure interaction – nails, fabrics, anchors, piles, walls
v. Imposed loading – surcharges/ dynamic earthquake loads

These wide-ranging of features enable SLOPE/W to be able to analyze almost any slope stability problem which engineers will encounter in their profession, be it in geotechnical, civil or mining engineering projects. Hence, SLOPE/W can effectively analyze and model almost any stability complications which consist of:

i. Slip surface shapes
ii. Pore water pressure conditions
iii. Soil properties and behavior (saturated or unsaturated)
iv. Analysis methods
v. Loading conditions, which includes seismic and earthquake loading
vi. Line load at any point
vii. Natural earth and rock slopes
viii. Sloping excavations
ix. Earth embankments
x. Open pit high walls
xi. Anchored retaining structures
xii. Berms at the toe of a slope
xiii. Earth reinforcement, which includes soil nails and geofabrics

xiv. Tension cracks
xv. Partial and total submergence

SLOPE/W is formulated in terms of moment and force equilibrium factor of safety equations. For instance, the Morgenstern-Price method satisfies both force and moment equilibrium. The general formulation makes it easy to compute the factor of safety for a variety of methods and to readily understand the relationships and differences among all other methods.

Probabilistic analysis can be performed by using normal distribution functions to vary soil properties and loading conditions. Using a Monte Carlo approach, SLOPE/W calculates the probability of failure in addition to the conventional factor of safety.

John Krahn (2004) also mentioned that SLOPE/W is designed and developed to be a general software tool for the stability analysis of earth structure, but not designed for certain specific cases. For instance, SLOPE/W was not created to specifically to design either a soil nail wall or retaining wall, but it can be used to access sliding stability of a gravity wall, or to find the active earth forces on the wall, or to analyze the stability of wedge of soil that has been reinforced by a soil nail, pre stressed anchor or other reinforcement method. Hence, SLOPE/W enables the users to apply engineering judgment and creativity in analyzing a problem.

Below are some of the features from SLOPE/W:

i. Limit equilibrium methods include Morgensten Price, GLE, Spencer, Bishop, Ordinary, Janbu and more
ii. Soil strength models include Mohr-Coulomb, Spatial Mohr-Coulomb, Bilinear, Undrained (Phi=0), anisotropic strength, shear/normal function, and many types of strength functions
iii. Specify many types of interslice shear normal force functions

iv. Pore water pressure options include Ru coefficients, piezometric lines, pressure contours, a grid of values, spatial functions, or finite element computed heads or pressures

v. Define potential slip surfaces by a grid of centers and radius lines, blocks of slip surface points, entry and exit ranges, fully specified shapes, or automatic

vi. Use probabilistic soil properties, line loads and piezometric lines

vii. Transient stability analysis

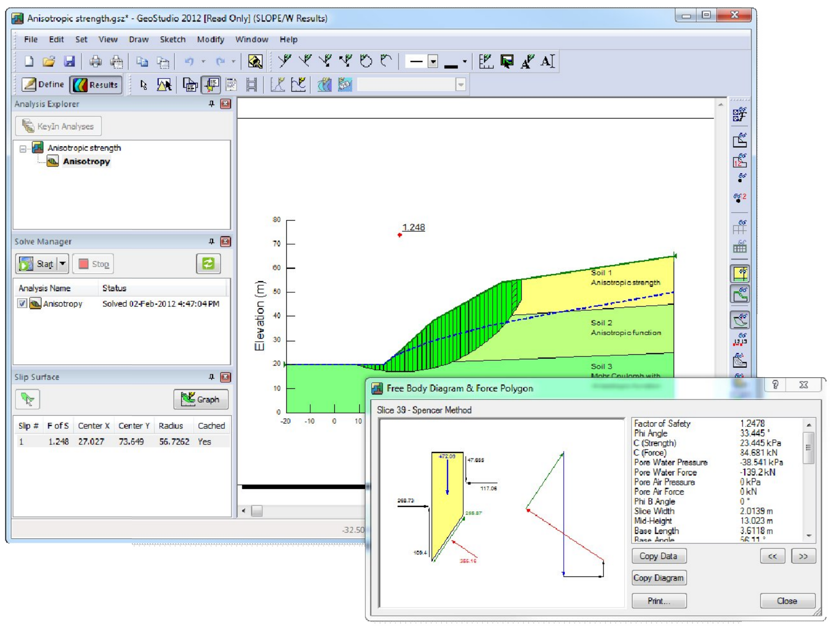

Figure 3.2: SLOPE/W can be used for computing the factor of safety of earth and rock slopes. (Stability Modelling with SLOPE/W)

3.4 Case Study on "Slope A"

A slope in Sarawak is chosen for this research to reanalyze the pre-existing design to study the effect of slope stability and the optimization of soil nailing length and cost for the entire project. For this research purpose, the slope is known as "Slope A" due to the confidential status of the project. Figure 3.3 shows "Slope A" as one of the existing slope in Sarawak with a length of 200 m and a highest height of 25 m. Chow and Tan (2006) argue that soil nail slope up to more than 25 m high is increasingly being used in Malaysian slopes due to its ease of construction, relatively maintenance free and its technical credibility as an effective slope stabilization method.

Figure 3.3: Overview of "Slope A"

A portion of the entire "Slope A" design is extracted for this research. Analysis at reduced level (RL 256.5) and chainage (CH) 4060 to chainage (CH) 4140 of "Slope A" is chosen for this study. Table 3.1 below shows the type of materials and the soil behavior properties of "Slope A". The borehole log for "Slope A" (RL256.5) is attached in Appendix section.

Table 3.1: Materials and soil behavior properties of "Slope A"

Material	Legend colour	Unit Weight, γ (kN/m^3)	Cohesion, C (kPa)	Phi, ø (°)
Weathered Sandstone	Yellow	25	20	0
Loose Sand	Blue	18	3	30
Firm Sandy Silt	Pink	20	8	33

Figure 3.4 and Figure 3.5 are the original slope stability design. The existing design consists of 16 arrangement of soil nailing reinforcement based on top of slope, reduced level RL 256.5 at CH 4060 to CH 4140. The factor of safety (FOS) obtained for global failure is 1.654 whereas the FOS obtained for local failure is 4.638. The slope is quite stable with mostly weathered sandstone, but the concern is more on the local failure of the slope.

The purpose of the slope is to prevent erosion of the slope and landslide which might affect the existing roadway. Besides, it serves the purpose to enhance slope stability of the permanent cut slope which will withstand the construction load such as building facilities on top of the slope.

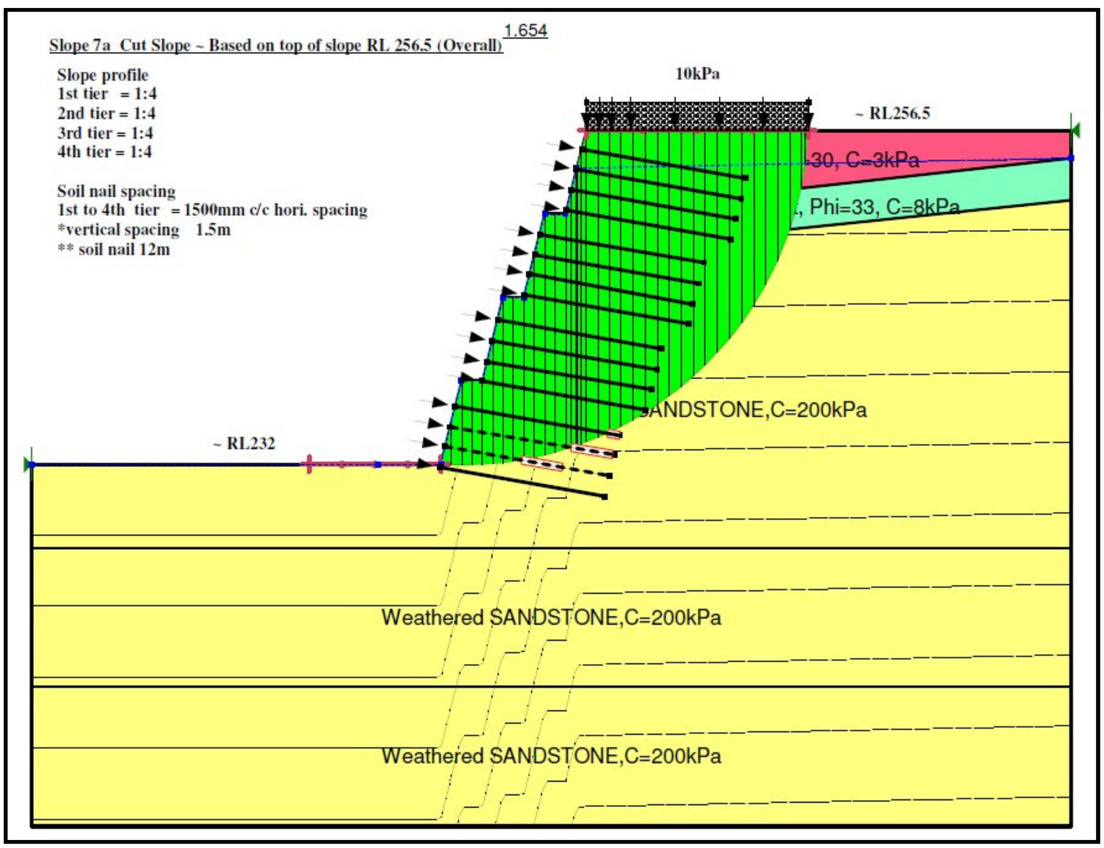

Figure 3.4: “Slope A” Overall Analysis using SLOPE/W software (RL 256.5 at CH 4060 to CH 4140)

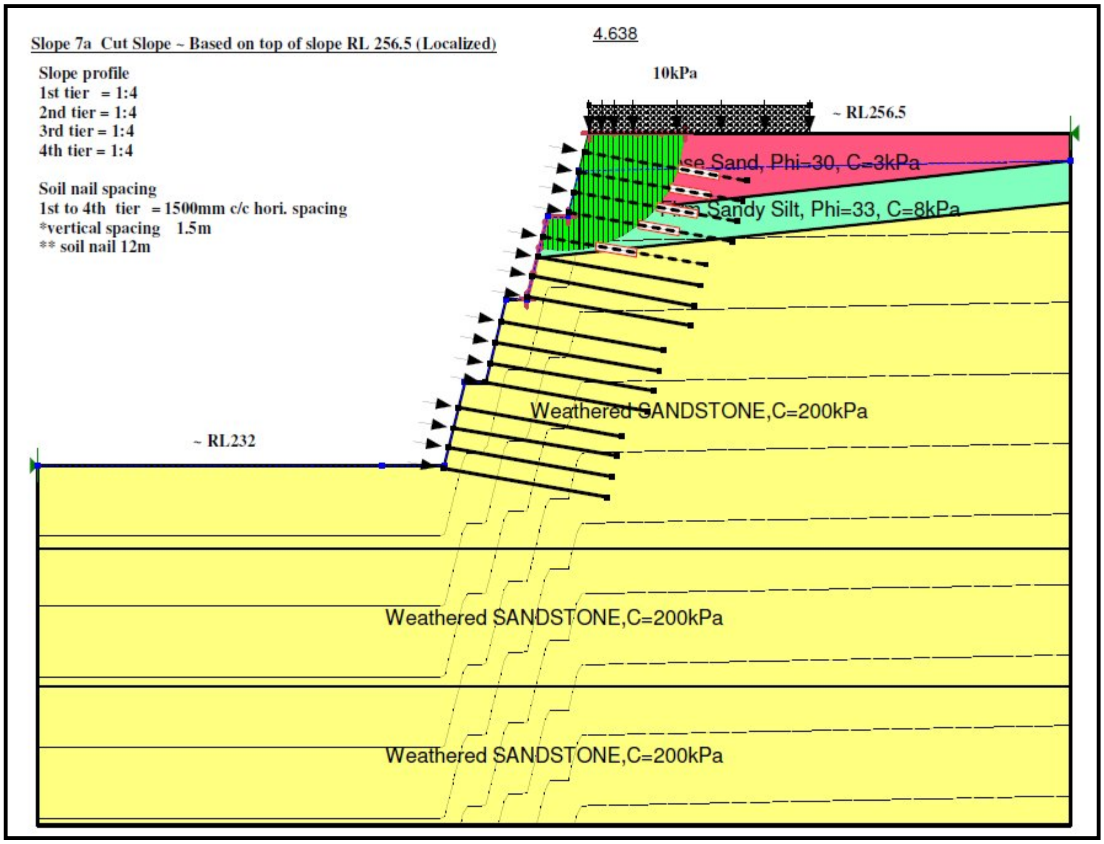

Figure 3.5: "Slope A" Localized Analysis using SLOPE/W software (RL 256.5 at CH 4060 to CH 4140)

3.5 SLOPE/W Analysis

The slope analysis is categorized into 2 analysis: control analysis & parametric analysis. Total 106 analysis (4 control analysis, 102 parametric analysis) are carried out to study the effect of various parameters on the slope failure behavior and the possibility to achieve cost optimization based on the new proposed design. A control analysis consists of the original slope been analyzed to determine its factor of safety in terms of global failure and local failure. Details are further explained in Section 3.6.

Parametric Analysis are carried out as well by changing some parameters, such as the water table level, arrangement of soil nailing and the reinforcement length of soil nailing. The results obtained from the parametric analysis are later compared with the results obtained from control analysis.

Chow and Tan (2006) suggest that the Factor of Safety (FOS) for soil nail wall shall be determined using the "slip surface" method (Simplified Bishop method, Morgenstern Price method, etc.). "Slope A" analysis is carried out using commercially available software (SLOPE/W) to perform the analysis based on Bishop Method. The required FOS for soil nail wall shall be based on recommended values for conventional retaining wall or slope stability analyses (FOS 1.4 for slopes in high risk to life and economic risk as recommended by Geoguide 7). Explanation of FOS can be made reference to Section 2.1.3.

3.6 Control Analysis

Figure 3.6 shows the 4 types of control analysis that are carried out in this research. The control analysis are carried out with reference to the existing parameters of "Slope A". The slope geometry has a ratio of 1:4, surcharge load of 10kN/m^3, existing water table level and 16 arrangement of 12 m length soil nailing.

Control analysis C1, C2, C3 and C4 consist of slope geometry of 1:4, surcharge load of 10kN/m^3, existing water table level and 16 arrangement of 12 m soil nailings (except C2 with no soil nailing reinforcement, C3 with flooded water table, C4 with flooded water table and no reinforcement of soil nailing.

Control Analysis	Slope geometry	Surcharge Load	Water Table	Soil Nailing		
				Length	Nos	Remark
C1	Slope 1:4	$10kN/m^3$	existing	12m	16 bars	/
C3				No		
C2			flood	12m	16 bars	
C4				No		

Figure 3.6: Control Analysis of "Slope A"

3.7 Parametric Analysis

As discussed earlier, the existing slope is considered as a stable slope due to almost two third of weathered sandstones. The permanent cut slope of "Slope A" has a highest peak of 25 m. Thus, it is favorable to use soil nail as reinforcement due to its ease of construction and rather straightforward "top to bottom" construction (FHWA, 1998). Reinforcement is applied in order to overcome and counter the possibility of global failure and local failure of the slope. Thus, in the beginning of this research, objectives have been made clear to look into the cost optimization by altering some parameters. The parameters that are made variable are the length of soil nailing, arrangement of soil nailing, water table level and slope geometry.

Figure 3.7 shows parametric analysis which focus on the changes in soil nailing configuration in terms of length and arrangement. The soil nail length is reduced from 12m to 10m, 8m and 6m. Besides, the number of bars is reduced from 16 bars to 12 bars based on random arrangement (T1, T2 and T3). T1 is the reduction of 16 bars to 12 bars from toe level. T2 is the arrangement whereby the bottom bar is reduced from each terrain, whereas T3 refers to the arrangement of bars whereby the upper bar from each terrain is reduced. The purpose of using random arrangement of T1, T2 and T3 is to study the effect of cost optimization. The actual arrangement should consists of close to close soil nail reinforcement whereby the vertical and horizontal spacing of successive bars should be 1.5 m to 2.0 m.

The water table is categorized as existing water table level and the worst case flooded water table. Parameters that are kept constant as original “Slope A” design is slope geometry 1:4 and surcharge load of 10kN/m^3.

				Existing water table				Flooded water table			
				12 m	10 m	8 m	6 m	12 m	10 m	8 m	6 m
Slope geometry	Surcharge Load	No of bars (Nos)	Types of Arrange-ment	Analysis Code name				Analysis Code name			
Slope 1:4	$10kN/m^3$	16	/	C1	P13	P26	P39	C2	P64	P77	P90
		15	T1	P1	P14	P27	P40	P52	P65	P78	P91
			T2	P2	P15	P28	P41	P53	P66	P79	P92
			T3	P3	P16	P29	P42	P54	P67	P80	P93
		14	T1	P4	P17	P30	P43	P55	P68	P81	P94
			T2	P5	P18	P31	P44	P56	P69	P82	P95
			T3	P6	P19	P32	P45	P57	P70	P83	P96
		13	T1	P7	P20	P33	P46	P58	P71	P84	P97
			T2	P8	P21	P34	P47	P59	P72	P85	P98
			T3	P9	P22	P35	P48	P60	P73	P86	P99
		12	T1	P10	P23	P36	P49	P61	P74	P87	P100
			T2	P11	P24	P37	P50	P62	P75	P88	P101
			T3	P12	P25	P38	P51	P63	P76	P89	P102

Control Analysis based on the original "Slope A"

Figure 3.7: Parametric Analysis with 12m, 10m, 8m and 6m soil nail length (existing and flooded water table level)

Types of arrangement	T1- reduce the bar from toe one by one
	T2- reduce the bottom bar form each terrain
	T3- reduce the upper bar from each terrain

Figure 3.8: Types of random arrangement bars used for analysis

3.7.1 12 m soil nail length

When the existing and flooded water table are used for analysis, 12 m soil nail bar is reduced from 16 bars to 12 bars. Starting from 15 bars to 12 bars, there are 3 types of arrangement, T1, T2 and T3 as discussed in Section 3.7 (Figure 3.8).

Parametric analysis P1, P4, P7, P10, P52, P55, P58 and P61 consist of existing water table level and T1 arrangement (except P52, P55, P58 and P61 with flooded water table level). Meanwhile, parametric analysis P2, P5, P8, P11, P53, P56, P59 and P62 consist of existing water table level and T2 arrangement (except P53, P56, P59 and P62 with flooded water table level). On the other hand, parametric analysis P3, P6, P9, P12, P54, P57, P60 and P63 consist of existing water table level and T3 arrangement (except P54, P57, P60 and P63 with flooded water table level).

3.7.2 10 m soil nail length

With reference to the 10 m design in Figure 3.7, parametric analysis P14, P17, P20, P23, P65, P68, P71 and P74 consist of existing water table level and T1 arrangement (except P65, P68, P71 and P74 with flooded water table level). Meanwhile, parametric analysis P15, P18, P21, P24, P66, P69, P72 and P75 consist of existing water table level and T2 arrangement (except P66, P69, P72 and P75 with flooded water table level). On the other hand, parametric analysis P16, P19, P22, P25, P67, P70, P73 and P76 consist of existing water table level and T3 arrangement (except P67, P70, P73 and P76 with flooded water table level).

3.7.3 8 m soil nail length

For the 8 m design in Figure 3.7, parametric analysis P27, P30, P33, P36, P78, P81, P84 and P87 consist of existing water table level and T1 arrangement (except P78, P81, P84 and P87 with flooded water table level). Meanwhile, parametric analysis P28, P31, P34, P37, P79, P82, P85 and P88 consist of existing water table level and T2 arrangement (except P79, P82, P85 and P88 with flooded water table level). On the other hand, parametric analysis P29, P32, P35, P38, P80, P83, P86 and P89 consist of existing water table level and T3 arrangement (except P80, P83, P86 and P89 with flooded water table level).

3.7.4 6 m soil nail length

For the 6 m design in Figure 3.7, parametric analysis P40, P43, P46, P49, P91, P94, P97 and P100 consist of existing water table level and T1 arrangement (except P91, P94, P97 and P100 with flooded water table level). Meanwhile parametric analysis P41, P44, P47, P50, P92, P95, P98 and P101 consist of existing water table level and T2 arrangement (except P92, P95, P98 and P101 with flooded water table level). On the other hand, parametric analysis P42, P45, P48, P51, P93, P96, P99 and P102 consist of existing water table level and T3 arrangement (except P93, P96, P99 and P102 with flooded water table level).

Chapter 4 RESULTS & DISCUSSION

As outlined in the methodology, “Slope A” design is being reanalyzed to study the effect of cost optimization on the installation of soil nailing alone. SLOPE/W from Geoslope is used in this research.

Figure 4.1 shows the parameters set for this research. Slope geometry is kept at 1:4 which is the original slope geometry of “Slope A”. The parametric studies focus on 4 categories, namely length (12m, 10m, 8m, 6m), water table level (existing, flooded), number of bars (16, 15, 14, 13, 12) and types of arrangement (T1, T2, T3). T1 is the reduction of bars from the toe level from 16 bars to 12 bars, T2 is the reduction of the bottom bars from each terrain, whereas T3 is the reduction of upper bars from each terrain.

Parameters	Values
Slope geometry	1:4
Soil Nail Length	12m, 10m, 8m, 6m
Water Table	Existing, flooded
Number of bars	16, 15, 14, 13, 12
Types of arrangement	T1- reduce the bar from toe one by one
	T2- reduce the bottom bar form each terrain
	T3- reduce the upper bar from each terrain

Figure 4.1: Set parameters for SLOPE/W parametric analysis

4.1 Existing Water Table

		Existing water table											
		Length = 12m			Length = 10m			Length = 8m			Length = 6m		
No of bars (Nos)	Types of Arrange-ment	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS
16	/	C1	1.654	4.638	P13	1.603	4.639	P26	1.557	3.031	P39	1.523	1.517
15	T1	P1	1.654	4.638	P14	1.603	4.639	P27	1.557	3.031	P40	1.523	1.517
	T2	P2	1.654	4.638	P15	1.603	4.639	P28	1.557	3.031	P41	1.523	1.517
	T3	P3	1.621	4.638	P16	1.583	4.639	P29	1.557	3.031	P42	1.523	1.517
14	T1	P4	1.604	4.638	P17	1.554	4.639	P30	1.51	3.031	P43	1.488	1.517
	T2	P5	1.635	4.638	P18	1.598	4.639	P31	1.557	3.031	P44	1.523	1.517
	T3	P6	1.621	4.638	P19	1.583	4.639	P32	1.557	3.031	P45	1.523	1.517
13	T1	P7	1.558	4.638	P20	1.51	4.639	P33	1.488	3.031	P46	1.485	1.517
	T2	P8	1.635	4.3	P21	1.598	4.295	P34	1.557	3.031	P47	1.523	1.517
	T3	P9	1.621	2.215	P22	1.583	2.215	P35	1.557	1.804	P48	1.523	1.153
12	T1	P10	1.526	4.638	P23	1.492	4.639	P36	1.488	3.031	P49	1.485	1.517
	T2	P11	1.635	2.638	P24	1.598	4.295	P37	1.557	2.055	P50	1.523	1.377
	T3	P12	1.621	1.951	P25	1.583	1.951	P38	1.557	1.737	P51	1.523	1.153

Figure 4.2: Existing water table Analysis

Figure 4.2 illustrates the tabulated critical global & local FOS obtained using SLOPE/W analysis for existing water table. Figure 4.3 to Figure 4.10 show a clearer illustration on the plotted global FOS and local FOS against the number of bars and the types of arrangement. The minimum allowable FOS (1.5) is indicated as a red dotted line. T1 is the reduction of bars from toe level one by one and is indicated as blue colour. The orange colour represents T2 arrangement, which is the reduction of the bottom bars from each terrain. Meanwhile, the green colour indicates T3 arrangement, which is the reduction of the upper bar from each terrain.

If the design chooses 12 m, it is possible to reduce the number of bars to 12 bars for all arrangement (T1, T2, T3) while retaining the minimum allowable FOS for reinforcement of slope (FOS = 1.5). If 10 m and 8 m design of soil nail length are chosen, it is also possible to reduce to 12 bars of reinforcement while maintaining both Global FOS and Local FOS above 1.5. However, this only applies to T2 and T3 arrangement.

Meanwhile if the design chooses 6 m soil nail, it is only possible to reduce to 14 bars for T2 and T3 arrangement. However, it is not advisable to use all 6 m soil nail as the Global FOS and Local FOS barely passes the minimum allowable FOS of 1.5.

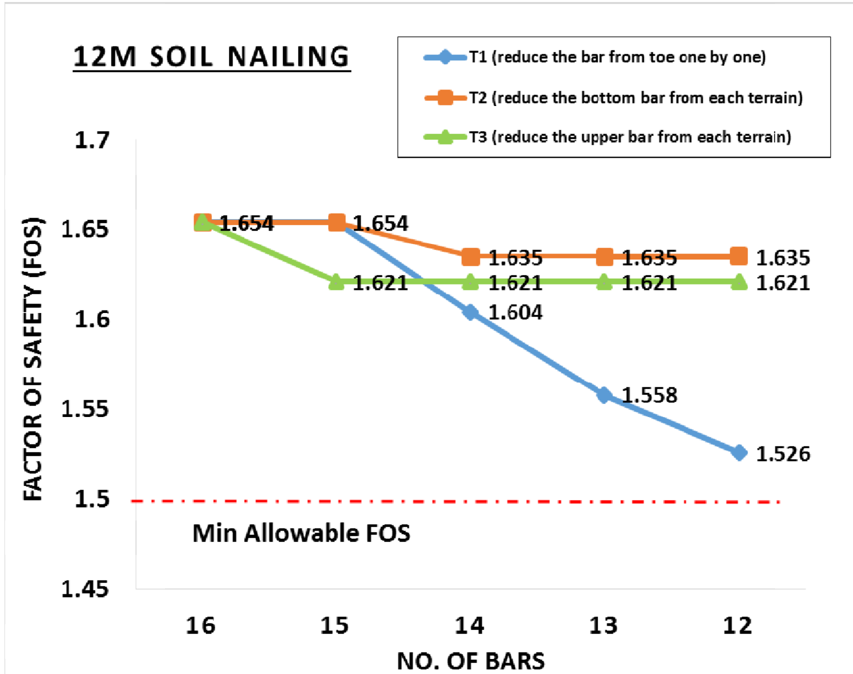

Figure 4.3: Global FOS (12 m nail, existing water table, reduction of bars, different arrangement)

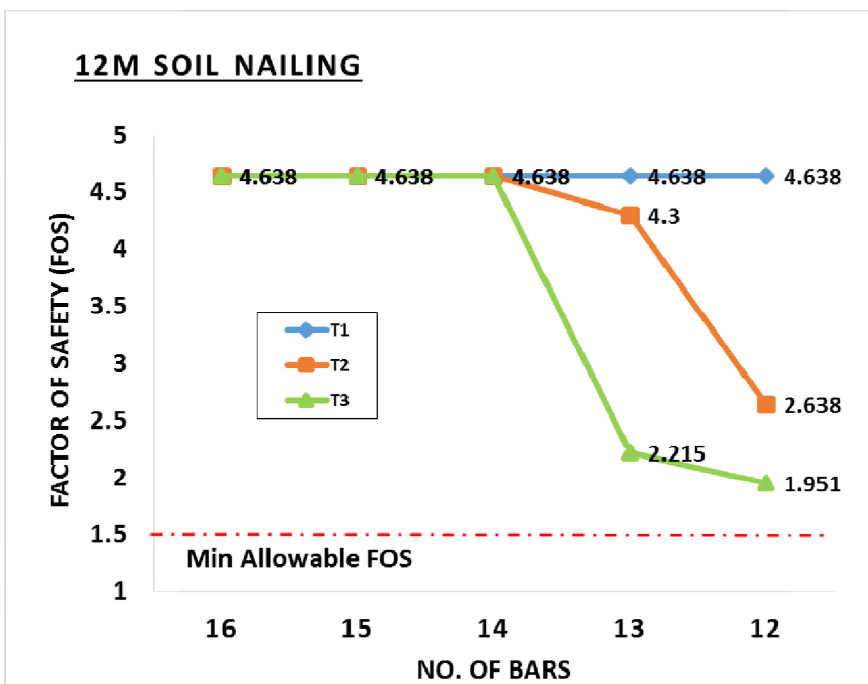

Figure 4.4: Local FOS (12 m nail, existing water table, reduction of bars, different arrangement)

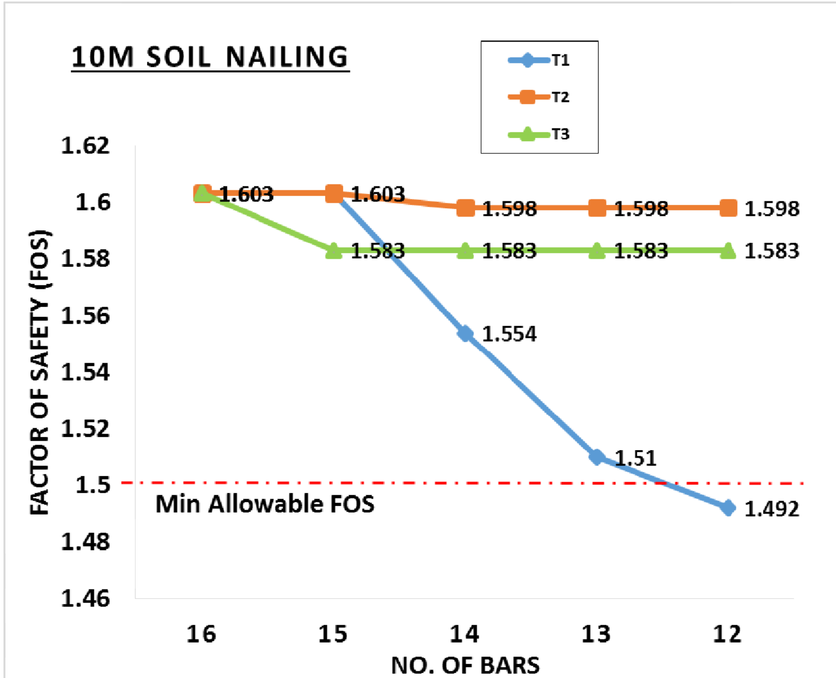

Figure 4.5: Global FOS (10 m nail, existing water table, reduction of bars, different arrangement)

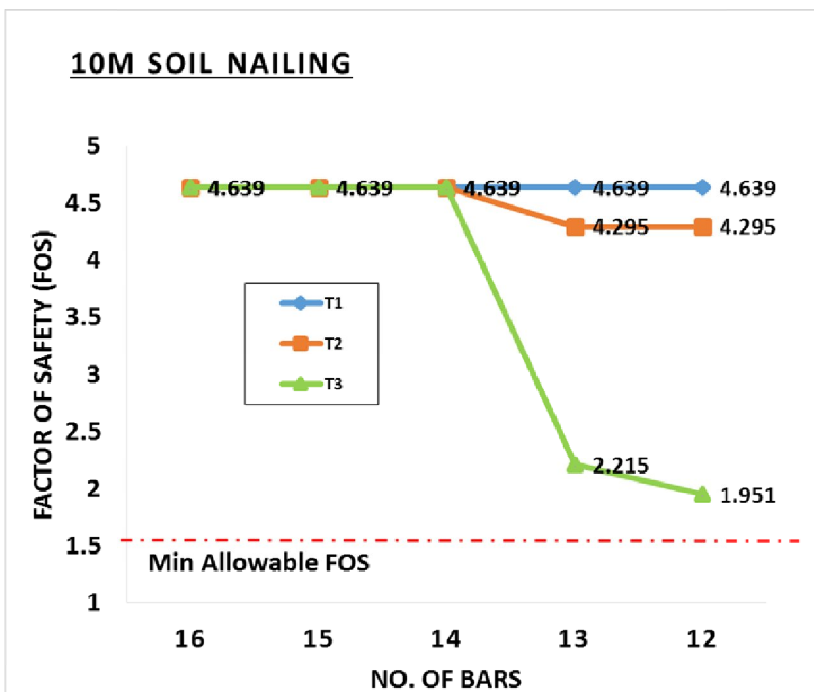

Figure 4.6: Local FOS (10 m nail, existing water table reduction of bars, different arrangement)

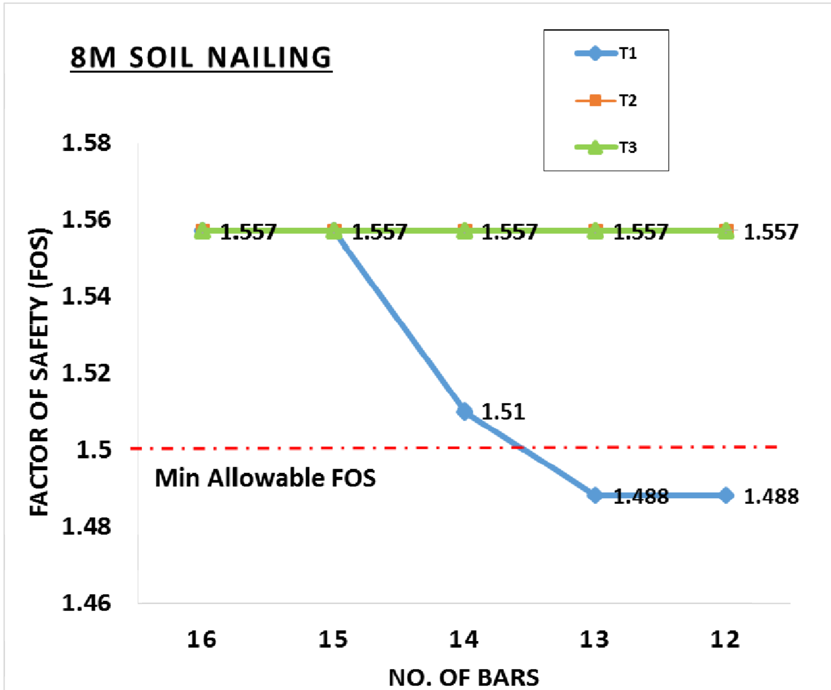

Figure 4.7: Global FOS (8 m nail, existing water table, reduction of bars, different arrangement)

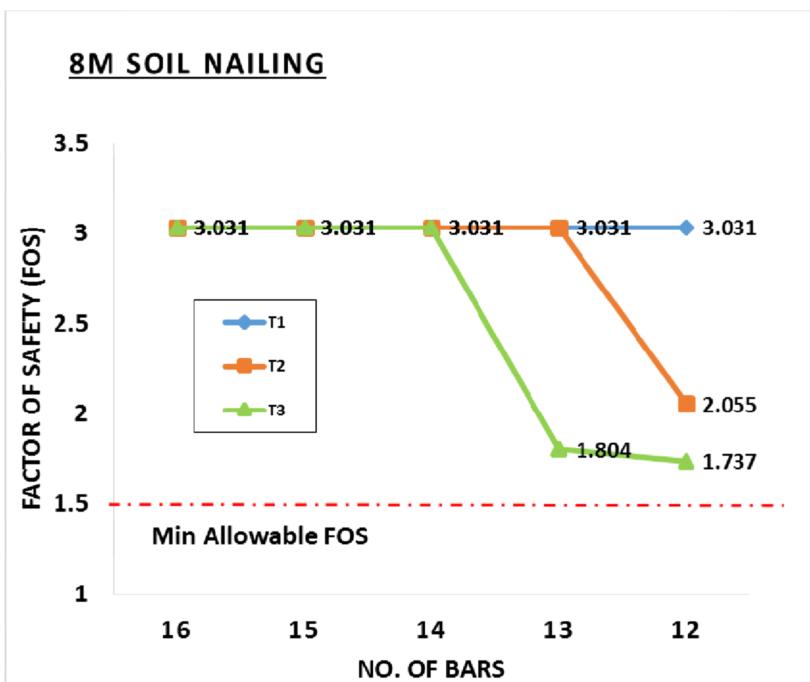

Figure 4.8: Local FOS (8 m nail, existing water table reduction of bars, different arrangement)

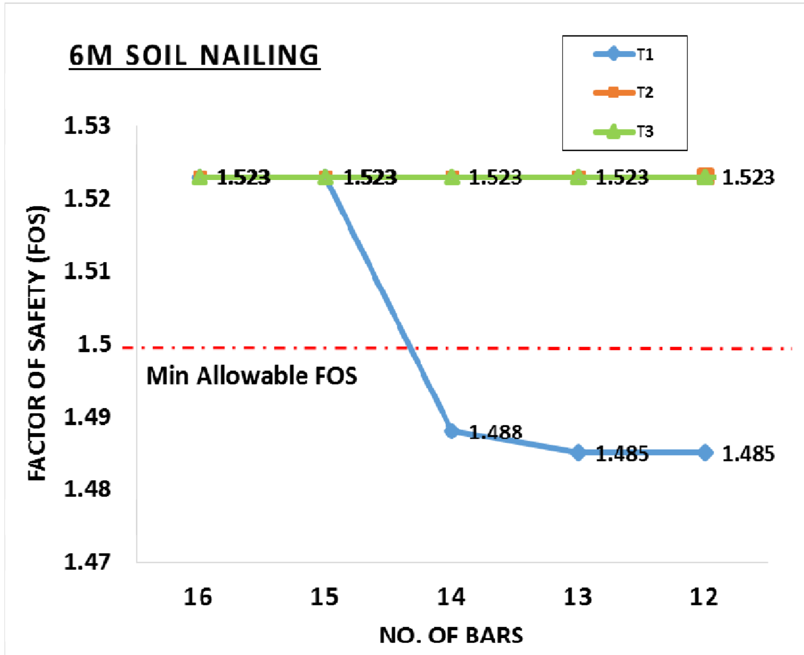

Figure 4.9: Local FOS (6 m nail, existing water table reduction of bars, different arrangement)

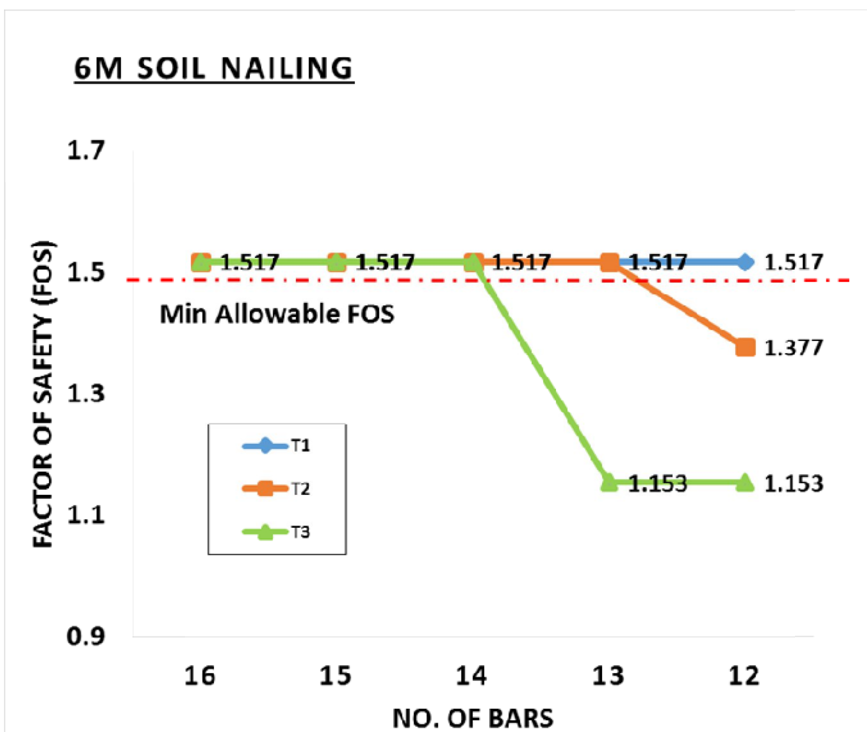

Figure 4.10: Local FOS (6 m nail, existing water table reduction of bars, different arrangement)

4.2 Flooded Water Table

		Flooded water table													
		Length = 12m			Length = 10m			Length = 8m			Length = 6m		
No of bars (Nos)	Types of Arrange-ment	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS	Analysis Code name	Global FOS	Local FOS
16	/	C2			P64			P77			P90		
15	T1	P52	1.648	3.64	P65	1.592	3.642	P78	1.546	2.348	P91	1.513	1.147
	T2	P53	1.648	3.64	P66	1.592	3.642	P79	1.546	2.348	P92	1.513	1.147
	T3	P54	1.61	3.64	P67	1.572	3.642	P80	1.546	2.348	P93	1.513	1.147
14	T1	P55	1.604	3.64	P68	1.543	3.642	P81	1.5	2.348	P94	1.478	1.147
	T2	P56	1.623	3.64	P69	1.587	3.642	P82	1.546	2.348	P95	1.513	1.147
	T3	P57	1.61	3.64	P70	1.572	3.642	P83	1.546	2.348	P96	1.513	1.147
13	T1	P58	1.553	3.64	P71	1.5	3.642	P84	1.478	2.348	P97	1.47	1.147
	T2	P59	1.623	3.64	P72	1.587	3.642	P85	1.546	2.348	P98	1.513	1.147
	T3	P60	1.61	1.7	P73	1.572	1.7	P86	1.546	1.379	P99	1.513	0.837
12	**T1**	**P61**	**1.516**	**3.64**	**P74**	**1.482**	**3.642**	**P87**	**1.478**	**2.348**	**P100**	**1.47**	**1.147**
	T2	**P62**	**1.623**	**2.035**	**P75**	**1.587**	**3.642**	**P88**	**1.546**	**1.576**	**P101**	**1.513**	**1.012**
	T3	**P63**	**1.61**	**1.478**	**P76**	**1.572**	**1.478**	**P89**	**1.546**	**1.324**	**P102**	**1.513**	**0.837**

Figure 4.11: Flooded water table Analysis

Figure 4.11 illustrates the tabulated critical global & local FOS obtained using SLOPE/W analysis for flooded water table. Figure 4.12 to Figure 4.19 show a clearer illustration on the plotted global FOS and local FOS against the number of bars and the types of arrangement. The minimum allowable FOS (1.5) is indicated as a red dotted line. T1, T2 and T3 are indicated by the same colours in the graph as describe earlier in Section 4.1.

If the design uses 12 m soil nail, it is possible to reduce the number of bars to 13 bars for all arrangement (T1, T2, T3) while retaining the minimum allowable FOS for reinforcement of slope (FOS = 1.5). It is also possible to reduce to 12 bars except for T3 arrangement. For T3, the global FOS obtained is 1.61, however, the local FOS obtained is 1.478 which is below the minimum allowable FOS of 1.5. Thus, T3 arrangement is not chosen for 12 bars of 12 m design. If the design opt for 10 m soil nail length, it is possible to reduce the number of bars to 13 bars while maintaining both Global FOS and Local FOS above 1.5 for T1, T2 and T3 arrangement. However, if 8 m soil nail length is used, it is possible to reduce the number of bars to 15 bars too while maintaining the minimum allowable FOS.

Meanwhile, for flooded water table condition, it is not advisable to use all 6 m soil nail design. Even though 16 arrangements are provided, the global FOS obtained is 1.513 which barely passes the minimum allowable FOS for a reinforced slope (1.5). However, it is a shame to know that the local FOS obtained for 16 arrangement is 1.1447 which is below 1.5. Thus, 6 m design is not recommended in this case.

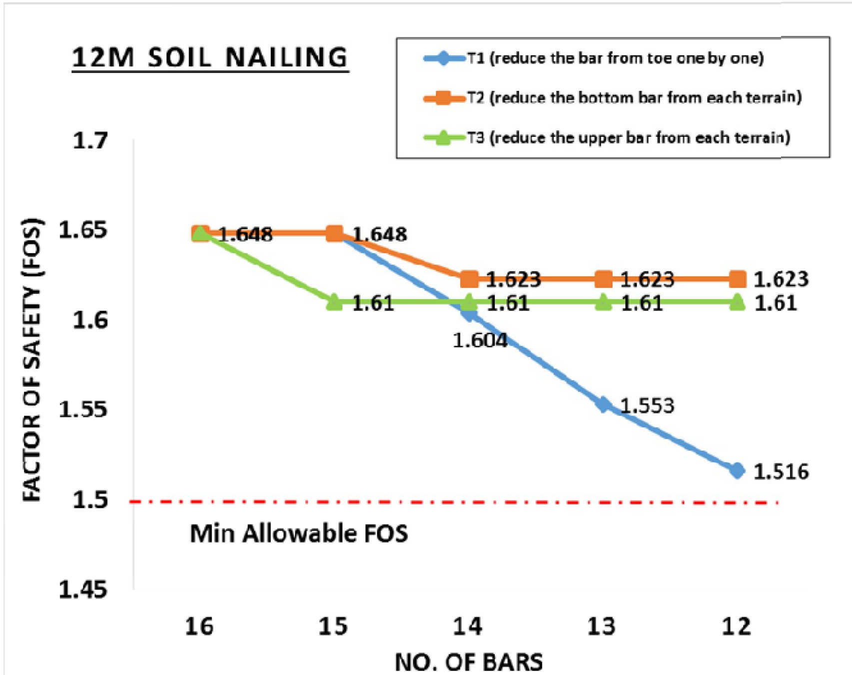

Figure 4.12: Global FOS (12 m nail, flooded water table reduction of bars, different arrangement)

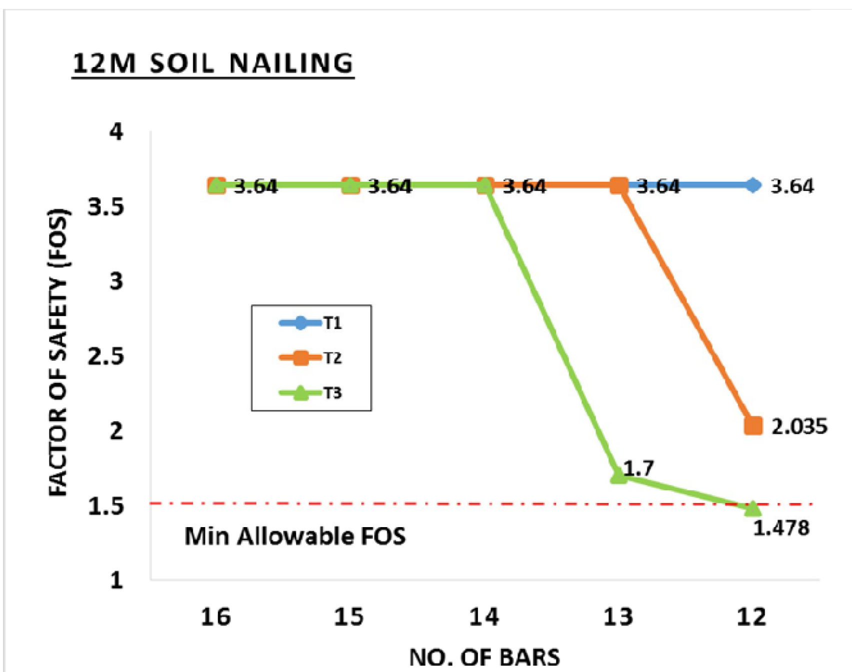

Figure 4.13: Local FOS (12 m nail, flooded water table reduction of bars, different arrangement)

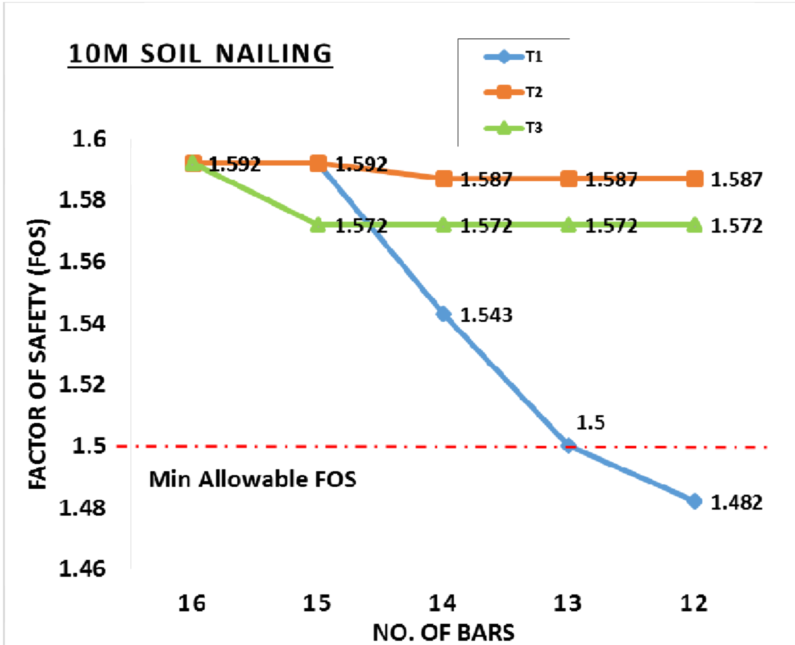

Figure 4.14: Global FOS (10 m nail, flooded water table reduction of bars, different arrangement)

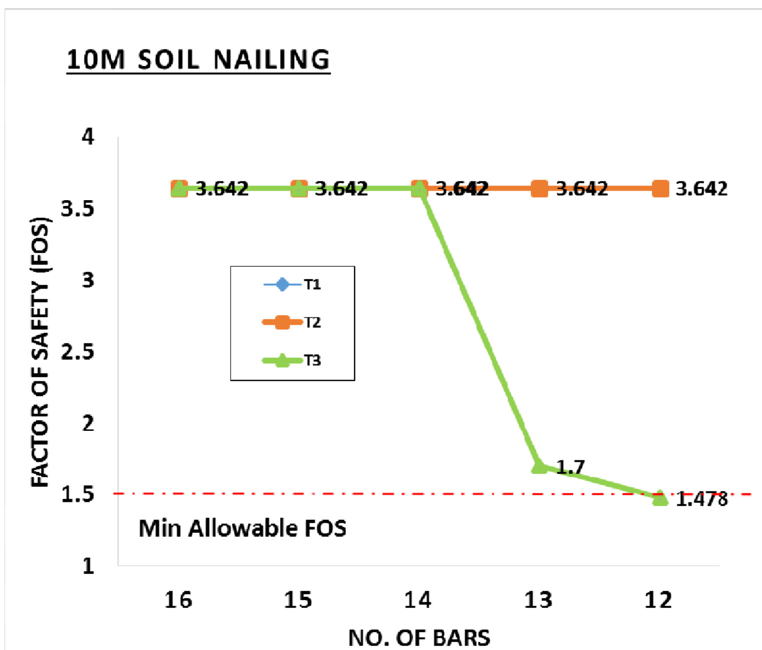

Figure 4.15: Local FOS (10 m nail, flooded water table reduction of bars, different arrangement)

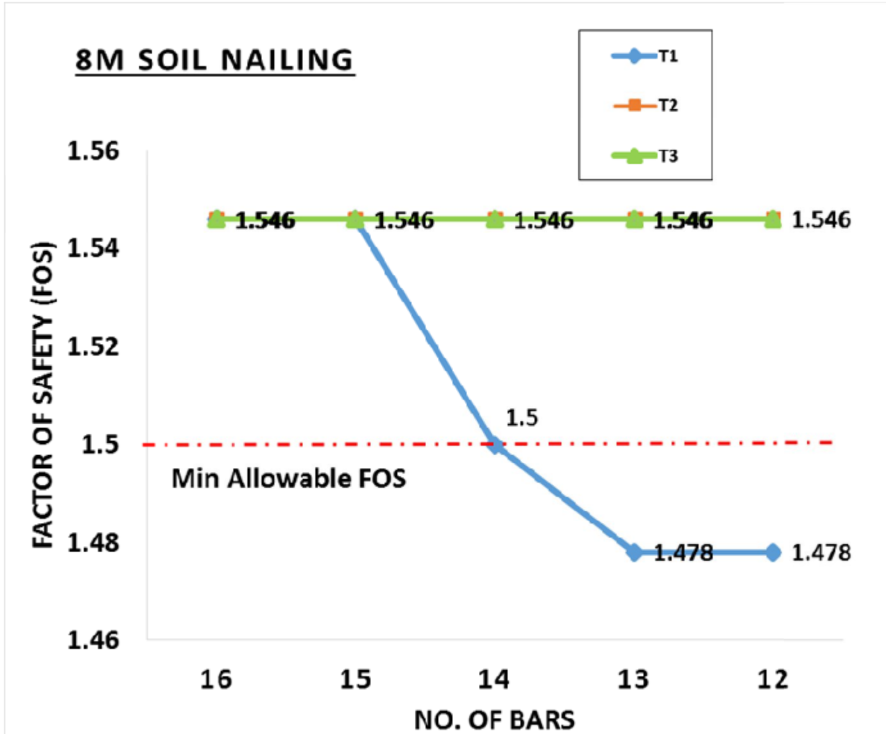

Figure 4.16: Global FOS (8 m nail, flooded water table reduction of bars, different arrangement)

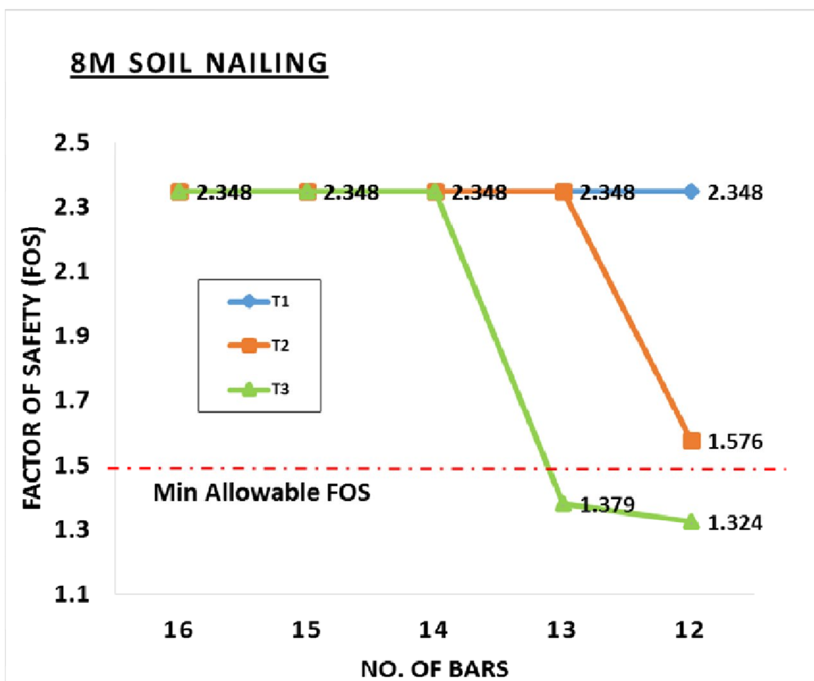

Figure 4.17: Local FOS (8 m nail, flooded water table reduction of bars, different arrangement)

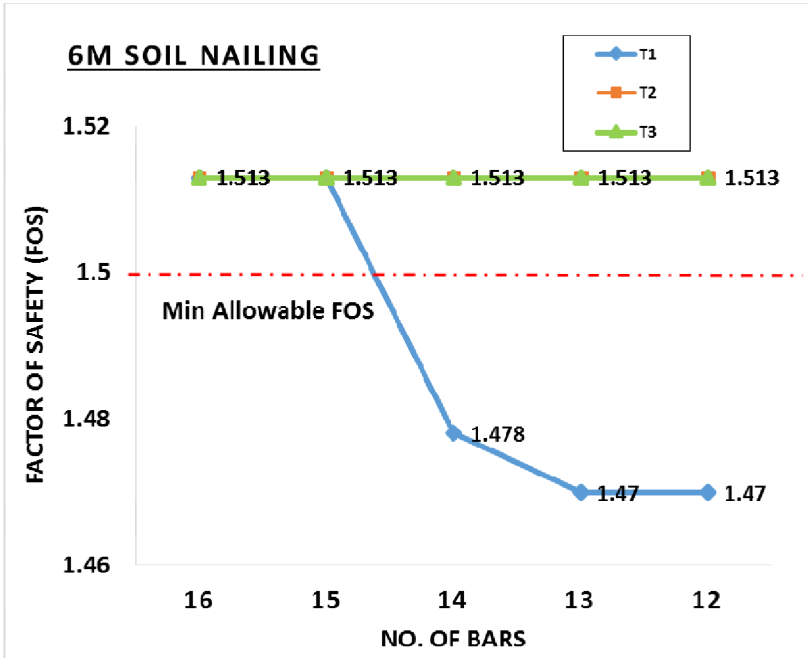

Figure 4.18: Global FOS (6 m nail, flooded water table reduction of bars, different arrangement)

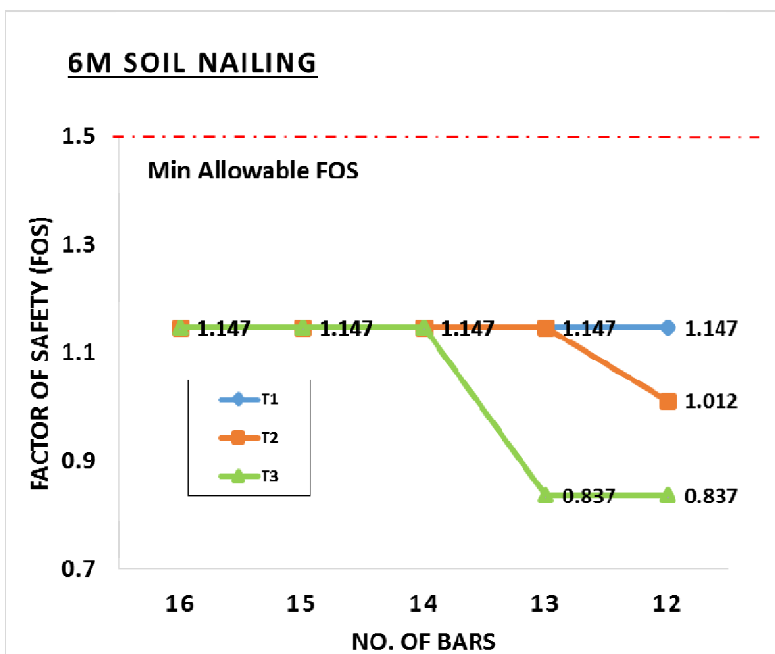

Figure 4.19: Local FOS (6 m nail, flooded water table reduction of bars, different arrangement)

4.3 Estimation of Costing

In any Civil Engineering projects, materials cost about more than half the total project costing. There are some common materials used in any civil engineering projects, such as rebars, cement, concrete, coarse aggregates, fine aggregates, steel, formwork etc. Other factors which contributes to the project costing are human resources, tendering and a lot more which will not discuss here.

In this chapter, the focus is on the cost optimization in terms of the installation of soil nailing alone. A brief method about the construction of soil nail wall is discussed. The soil nail wall is a top to bottom construction method.

The basic elements and materials used in soil nailing are explained in this section. Figure 4.20 shows the basic materials and costing per unit material for the installation of soil nailing alone. The cost listed below is just an estimation for research purposes, actual costing of the materials and elements are considered as confidential pricing among the contractors.

Subject A is drilling, where the cost is RM 800 per metre drilling. Subject B is referring as rebar which is exactly the soil nail used for soil nail wall project. For "Slope A", the diameter of rebar used is T32. Based on the pricing given by Quantity Surveyor Online and CIBD, rebars are usually manufactured and shipped as a package of 1 tonne, the pricing for 1 tonne of T32 rebars is estimated as RM 2050. There are 13 T32 rebars in one tonne package, so dividing by 13 bars, it should cost around RM 158 per T32 rebar. Subject C is cement grouting which is estimated at RM 80 per metre. Cement grouting is necessary to apply after the drilling and installation of rebar to strengthen the rebar and also to provide protection to the rebar away from rusting. Lastly, subject D refers to the pile head which is installed to provide protection to the tip of the rebar. It is estimated as RM 200 – 300 per unit, thus assuming the largest value which is RM 300 per unit.

By using the basic cost in Figure 4.20, "Slope A" at cross section of RL256.5 (CH 4060 - CH 4140) with 16 arrangement of 12 m bars is estimated at RM 176 288.

Subject		Cost		Slope A estimated cost (RM)
		RM	per	
A	Drilling	800	metre	176,288 (12 m, 16 bars)
B	Rebar	158	Nos	
C	Cement grout	80	metre	
D	Pile Head	200 - 300	Nos	

(*1 tonne = 13 T32 = RM 2050, one T32 = RM158)
Figure 4.20: Basic costing for installation of soil nailing alone

Figure 4.21 shows the proposed design of soil nail arrangement for existing and flooded water table and the total cost optimization compared to "Slope A" design based on the results tabulated in Section 4.1. In order to achieve cost optimization, parametric analysis are carried out based on the original design of "Slope A". The proposed designs for existing water table condition are design 1, 2, 3 and 4, whereas the proposed designs for flooded water table condition are design 5, 6 and 7.

For the 1st proposed design, 12 arrangement of 12 m soil nail bars are chosen, and is 25% less than the original "Slope A" design at RL256.5 (CH 4060 - CH 4140). Design 2 consists of 12 arrangement of 10 m soil nail bars and is 36.98% less than the original design used. Meanwhile, design 3 refers to 12 arrangement of 8 m bars, which is 48.96% less than the initial design. On the other hand, design 4 consists of 14 arrangement of 6 m soil nail bars, costing 55.06% less than the initial design. However, design 4 is not recommended due to the FOS obtained which is merely above the marginal line of the minimum allowable FOS of 1.5. The explanation is discussed in Section 4.1.

Design 5 to 8 show the proposed design for soil nail arrangement under flooded water table level. Design 5 has 13 arrangement of 12 m soil nail bars, which is 18.75% less than the original "Slope A" design at RL256.5 (CH 4060 - CH 4140). Design 6 consists of 13 arrangement of 10 m soil nail bars which is 31.73% less than the original design. Meanwhile, design 7 has 15 arrangement of 8 m bars which is 36.2% less than the initial design. 6m design is not recommended in this case and is explained in Section 4.2.

Design	Water Table	Soil Nail Arrangement	Subject				Total Cost (RM)	Remarks
			A	B	C	D		
1	Existing	12m, 12 bars	115,200	1,896	11,520	3,600	132,216	Save 25%
2		10m, 12 bars	96,000	1,896	9,600	3,600	111,096	Save 36.98%
3		8m, 12 bars	76,800	1,896	7,680	3,600	89,976	Save 48.96%
4		6m, 14 bars	67,200	1,106	6,720	4,200	79,226	Save 55.06%
5	Flood	12m, 13 bars	124,800	2,054	12,480	3,900	143,234	Save 18.75%
6		10m, 13 bars	104,000	2,054	10,400	3,900	120,354	Save 31.73%
7		8m, 15 bars	96,000	2,370	9,600	4,500	112,470	Save 36.2%

Figure 4.21: Proposed design of soil nail arrangement for existing and flooded water table and the total cost optimization compared to "Slope A" design

Chapter 5 CONCLUSION

Based on the control analysis and parametric analysis carried out, it is possible to optimize the design in terms of soil nail length and soil nail arrangement. A more economical slope condition is proposed in this research by optimizing the soil nail configuration (length and arrangement). For existing water table, it could be reduced to 8m with 12 arrangement (T2 & T3 arrangements), whereas for flooded water table, it could be reduced to 8m with 15 arrangement (T1, T2 and T3 arrangement).

Various parameters such as slope geometry, different water table level and different soil nail configuration are studied on how they affect the type of failure mechanism and FOS. For global failure, T1 arrangement shows a significant decline in FOS with the decrease of reinforcement bar. This is because T1 arrangement is the reduction of the bars from the toe level one by one. The more bars from the toe level are taken out, the lesser the FOS would be because the toe reinforcement is important to support the whole slope in terms of global failure. T1 arrangement is actually not recommended in practice because toe reinforcement is very important as it supports the whole slope in terms of sliding, however for this research, it is used to study the effect on the FOS.

Besides, cost optimization on the installation of soil nailing alone in terms of length & arrangement of soil nailing are studied as well. For existing water table condition, cost optimization can be achieved around 25% to 50% if compared to the original “Slope A” at cross section of RL256.5 (CH 4060 - CH 4140). Meanwhile, under flooded water table condition, cost optimization can be achieved around 18% to 36% if compared to the initial design.

Chapter 6 RECOMMENDATION

Based on the preliminary results obtained, it is suggested that more parameters such as weaker soil parameters, different slope geometry, various water table and various soil nail configuration should be considered in future as case study and comparison of the type of failure mechanism and the possible cost optimization obtained.

Furthermore, more time should be allocated for this research. Besides conducting this research study, the author needs to cope with his academic studies at the same time, which at some point, the author finds it hard to concentrate and cope with the given timeline.

Moreover, a better understanding on the fundamentals of slope stability analysis and soil nailing design is required to enhance this research in terms of cost optimization. FOS results alone are not that convincing in determining the stability of a slope as there are other uncertainties for geotechnical issues. Hence, the compiled FOS results should be checked and compared with risk and reliability analysis of slope stability. By determining the risk and the probability of failure on the slope, we can have a better insight on the slope failure and the risk it possess.

Besides, a better understanding on the international codes for soil nailing reinforcement such as BS 8006:1995, HA 68/94, FHWA 1998 and FHWA 2003 –IF-03-017 are essential for further research. A fundamental knowledge in slope stability as well as the design procedure and method would help the author in carrying out analysis in the future. For Malaysian slopes practices, FHWA 1998 and FHWA 2003-IF-03-017 manuals are recommended due to its ease of construction method. Besides, FHWA recommends the “slip surface” method which can be easily adopted in practical applications with the aid of slope stability analysis software.

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APPENDICES

Design Issues

There are a lot of design issues, but only a few will be discussed. Juran and Ellias (1991) discussed the basic steps which involved in soil nail wall design are as follows:

i. For the specific structural geometry, ground profile, and boundary loadings, the working nail forces and location are estimated.
ii. The reinforcement type and stability at each reinforcement level are selected, that is, the nail resistance is verified whether it is sufficient to withstand the estimated working forces with an acceptable factor of safety.
iii. Verify that global stability of the nailed soil structures and the surroundings ground is maintained during and after excavation with an acceptable factor of safety.
iv. The system of forces acting on the facing is estimated and the facing for specified architectural and durability criteria are designed
v. For permanent structures, select the corrosion projection related to site conditions
vi. The drainage system for groundwater piezometric levels is selected (example : horizontal drain, bench drain)

Besides, Neoh (2004) argued that soil nail designers have to understand the following basic engineering behavior and fundamental design concepts of soil nailing in slopes stabilization.

i. Soil nailing is a proven cost effective technique widely used to stabilize cut slopes or support deep excavation by reinforcing the insitu ground. It generally consists of drilling, inserting rebar, grouting and nail head construction/facing/gunitng.

ii. The most important design issue concerns the pull out resistance of the reinforcing element. In practice, it is usually estimated based on soil data with reference to empirical observations including pull out test results derived from full scale verification/sacrificial tests on site.

iii. Some slope movement is required to mobilize load tension in the soil nail (rp to 30mm).

iv. Soil nails need to extend to a sufficient length beyond the active zone or any plane of weakness to overcome external stability including (1) overturning, (2) sliding, (3) bearing, and (4) overall slope instability, modes of failure.

v. Three internal failure modes must be checked in order to ensure factor of safety, example (1) nail pull-out resistance, (2) nail material tensile capacity, and (3) nail head/facing capacity.

Construction Issues

In constructing soil nail walls, equipment type, construction technique and construction sequence can significantly influence the performance of soil nails for most geotechnical engineering works. Firstly, emphasis is given on construction method and QC for drilling, inserting rebar, grouting, nail head construction and slope protection. Next, the engineer should be clear on whether the specialist soil nailing contractor complies with the specification and specifics and also fit for the job with experienced and certified nozzle man. Also, effective supervision by site personnel is a must to check regularly on the contractor's Method Statement for completed soil nailing which compiles with the design specification as well. Besides, the type and model of equipment or machine, material and manpower must be clearly identified in a complete method statement. Meanwhile, sequence of works, output of the proposed resources and quality control tests (type and frequency of tests/ observations/ measurements), together with the respective acceptance criteria should be clearly stated. (Neoh, 2004)

Pull Out Test

Soil nailing is an in situ soil reinforcing technique implemented for stabilizing existing slopes in Malaysia and in many other countries and regions. In the design of a soil nail system, pull-out capacity of a soil nail is an important design parameter. Field pull-out tests are then carried out to verify the pull-out resistance assumed at the design stage. However, the pull-out capacity of a soil nail in the field is influenced by a number of factors, such as variation in the soil properties, variation in the installation procedures, types of soil nail, and stress levels.

Verification tests are completed on non-production, "sacrificial" nails prior to construction. In addition, verification testing may be required during production to verify capacities for different in situ conditions encountered during construction and/or different installation methods. Although it would be optimal for verification tests to reach the point of pullout failure, this may not be possible in some cases. Verification tests provide the following information:

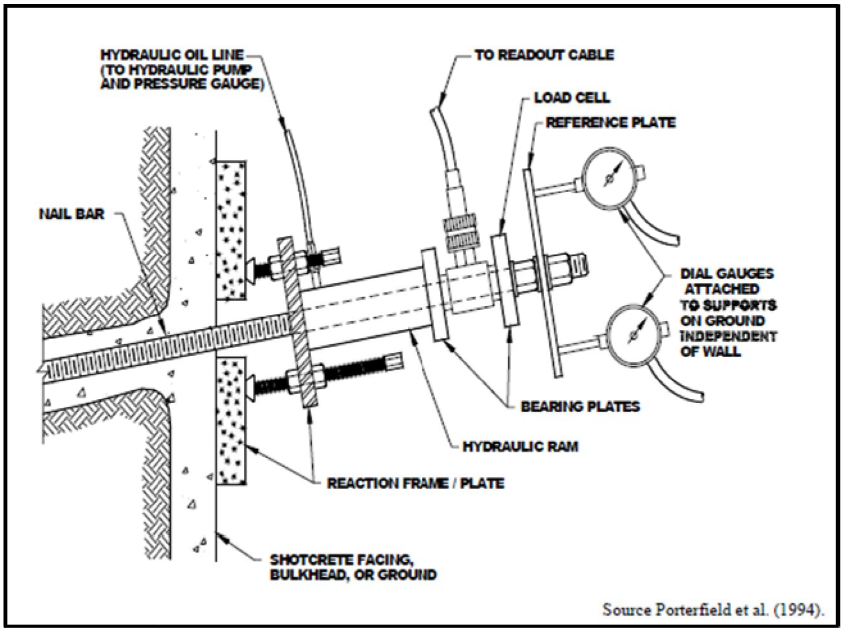
i. determination of the ultimate bond strength (if carried to pullout failure)
ii. verification of the design factor of safety
iii. determination of the soil nail load at which excessive creep occurs.

As a minimum, verification test loading must be carried out to a load defined by the pullout factor of safety times the design allowable pullout capacity. If the factor of safety for pullout is 2.0, then the test load must verify 200 percent of the allowable pullout capacity. Test loads in excess of this minimum, and preferably to failure, are recommended as they provide considerably more information and may lead to more economical drilling installation methods. The test acceptance criteria require that:

i. no pullout failure occurs at 200 percent of the design load where pullout failure is defined as the load at which attempts to further increase the test load increments simply results in continued pullout movement of the tested nail; and

ii. the total measured movement (ΔL) at the test load of 200 percent of design load must exceed 80 percent of the theoretical elastic movement of the unbonded length (UL). This criterion is expressed as heoreΔrite, where Δ whe is the minimum acceptable movement defined as:

$$\Delta L_{min} = 0.8\ PUL/EA$$



Appendix 1: Hydraulic Jack Used for Soil Nail Load Testing (FHWA0-IF-03-017)

Gantt chart and key milestone

FYP 1															
No.	**Activity**	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**	**W13**	**W14**
1	**Selection of Project Topic**														
2	**Briefing session**														
3	**Preliminary Research Work**														
4	**Submission of Extended Proposal**														
5	**SLOPE/W Analysis (Preliminary)**														
6	**Proposal Defence**														
7	**Project work continues (Analysis of Data)**														
8	**Submission of Interim Draft Report**														
9	**Submission of Interim Report**														
FYP 2															
10	**Project work continues**														
11	**Submission of progress report**														
12	**Project work continues**														
13	**Pre-SEDEX**														
14	**Submission of draft report**														
15	**Submission of dissertation report (soft bound)**														
16	**Submission of technical paper**														
17	**Oral presentation**														
18	**Submission of dissertation report (hard bound)**														

Appendix 2: Gantt chart and key milestone for FYP