



CHALMERS
UNIVERSITY OF TECHNOLOGY



Modelling the effect of vegetation on slope stability

Master's thesis in Infrastructure and Environmental Engineering

Ahmad Al Mahamid
Dolley Alskaf

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

www.chalmers.se

MASTER'S THESIS ACEX30

Modelling The Effect Of Vegetation On Slope Stability

Master's Thesis in the infrastructure and environmental engineering

Ahmad Al Mahamid

Dolley Alskaf

Department of Architecture and Civil Engineering

Division of Geology and Geotechnics

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2024

Modelling The Effect Of Vegetation On Slope Stability

Master's Thesis in the Master's Programme Master's Programme Name

Ahmad Al Mahamid

Dolley Alskaf

© Ahmad Al Mahamid & Dolley Alskaf, 2024

Examensarbete ACEX30

Institutionen för arkitektur och samhällsbyggnadsteknik

Chalmers tekniska högskola, 2024

Department of Architecture and Civil Engineering

Division of Division Name

Research Group Name

Chalmers University of Technology

SE-412 96 Göteborg

Sweden

Telephone: + 46 (0)31-772 1000

Modelling The Effect Of Vegetation On Slope Stability

Master's thesis in the Master's Programme Master's Programme Name

Ahmad Al Mahamid

Dolley Alskaf

Department of Architecture and Civil Engineering

Division of Division Name

Research Group Name

Chalmers University of Technology

ABSTRACT

This thesis seeks to focus on the aspect of vegetation in improving the stability of slopes through modelling and analysis. For this purpose, cross-sectional geometries of the slopes and the effects of various plant species on the mechanical and hydrological response of the slopes are considered by employing Geostudio software and 2D-Plaxis software. This arises through increased cohesiveness and strength offered by roots in the stability of the soil and consequently, the factor of safety thus reducing the disaster of landslides. The results of the work thus support the applicability of vegetation as a cheap and environmentally friendly solution to slope stabilization and vegetation impacts on the mechanical properties of soil and enhancement of infiltration. Suggestions for further research are the investigations of the fourteen species with respect to root cohesion and the combination of vegetarian technologies with standard engineering to create strong slope management plans.

Keywords: vegetation, slope stability, safety factor, root additional cohesion, mechanical effect, hydrological effect, finite element analysis, limit equilibrium analysis, landslide risk, cultivation zone

Table of contents

1	INTRODUCTION	1
2	RESEARCH OBJECTIVES	2
3	LITERATURE REVIEW	3
3.1	Methods of Calculating Slope Stability	3
3.1.1	Limit Equilibrium Method	4
3.1.2	Finite Element Method	6
3.2	Computer software analysis	7
3.2.1	GeoStudio	7
3.2.2	Plaxis 2D	7
3.3	Vegetation effect on slope stability	8
3.3.1	Mechanical and hydrological effect of vegetation	8
3.3.2	Estimation of Root Additional Cohesion	11
3.4	Landslide risk and cultivation zones in Sweden	16
4	METHODOLOGY	21
4.1	Numerical modelling of the conceptual model	21
4.1.1	GeoStudio	21
4.1.2	Plaxis 2D	23
4.2	Mechanical effect of vegetation with varying slope angle	23
4.3	Modelling the hydro-mechanical effect of vegetation on slope stability	24
5	RESULT	29
5.1	Conceptual model	29
5.2	Vegetation effect on slopes with varying angles	33
5.3	Hydro-mechanical effect of vegetation on slope stability	35
6	DISCUSSION	37
7	CONCLUSION AND RECOMMENDATIONS	42
	REFERENCES	44

LIST OF FIGURES

FIGURE 3.1 THE VARIATION OF THE ADDITIONAL COHESION IN SWEDEN'S CULTIVATION ZONES BASED ON PLANT TYPES IN TABLE 3.2.....	20
FIGURE 5.1 VALUES OF SLOPE'S FACTOR OF SAFETY AS A FUNCTION OF THE ROOT ZONE DEPTH FOR VARIOUS TYPES OF VEGETATION, GEOSTUDIO.....	30
FIGURE 5.2 VALUES OF SLOPE'S FACTOR OF SAFETY AS A FUNCTION OF THE ROOT ZONE DEPTH FOR VARIOUS TYPES OF VEGETATION, PLAXIS 2D.....	30
FIGURE 5.3 SLOPE STABILITY ANALYSIS INCLUDING GRASS, SLOPE/W.	31
FIGURE 5.4 SLOPE STABILITY ANALYSIS INCLUDING SHRUBS, SLOPE/W.	31
FIGURE 5.5 SLOPE STABILITY ANALYSIS INCLUDING TREES, SLOPE/W..	31
FIGURE 5.6 SLOPE STABILITY ANALYSIS INCLUDING GRASS, PLAXIS 2D.	32
FIGURE 5.7 SLOPE STABILITY ANALYSIS INCLUDING SHRUBS, PLAXIS 2D.....	32
FIGURE 5.8 SLOPE STABILITY ANALYSIS INCLUDING TREES, PLAXIS 2D.	32
FIGURE 5.9 WATER PRESSURE VS TIME WITHOUT VEGETATION.	
FIGURE 5.10 WATER PRESSURE VS TIME WITH VEGETATION.	35
FIGURE 5.11 SAFETY FACTOR VS TIME WITHOUT VEGETATION.	
FIGURE 5.12 SAFETY FACTOR VS TIME WITH VEGETATION.	36

LIST OF TABLES

TABLE 3.1 DESCRIPTION OF THE HYDROMECHANICAL MECHANISM OF VEGETATION PROVIDED IN FIGURE 3.3.	10
TABLE 3.2 TYPICAL VALUES FOR ROOT ADDITIONAL COHESION C_r . *BASED ON SHEAR TESTS, **BASED ON PERPENDICULAR ROOT REINFORCEMENT MODEL. ***BASED ON THE RIPROOT MODEL.....	16
TABLE 3.3 THE CULTIVATION ZONES AND THEIR CORRESPONDING SUITABLE PLANTS.	19
TABLE 4.1 SOIL PROPERTIES AND SLOPE GEOMETRY USED IN GEOSTUDIO.....	22
TABLE 4.2 VEGETATION COMBINATION USED AT THE TOP, AT THE MIDDLE, AND AT THE TOE OF THE SLOPE.	22
TABLE 4.3 SOIL PROPERTIES USED IN PLAXIS 2D.....	23
TABELL 4.4 THE GEOMETRY OF THE STUDIED SLOPES.....	24
TABLE 4.5 METEOROLOGICAL INFORMATION USED IN THIS ANALYSIS.	25
TABELL 4.6 USED VEGETATION DATA VALUES IN GEOSTUDIO.	26
TABLE 5.1 SAFETY FACTOR VALUES AT DIFFERENT ROOT ZONES AND VARIOUS TYPES OF VEGETATION.....	29
TABELL 5.2 SAFETY FACTOR VALUES FOR SLOPES WITH DIFFERENT ANGLES WITH AND WITHOUT VEGETATION.	33
TABLE 5.3 SAFETY FACTOR VALUES FOR SLOPES WITH DIFFERENT ANGLES WITH AND WITHOUT VEGETATION.	34

Preface

Ahmad Al Mahamid and Dolley Alskaf, authors and proud owners of a master's thesis named "Modelling the Effect of Vegetation on Slope Stability," shall express gratitude that the work in question is dedicated to explaining when, how, and why vegetation can be used to counter landslides and to build safer slopes in general.

By the Grace of God, we have come a long way in civil engineering as students here at Chalmers University of Technology. Thus, our concern with such relationships as nature and engineering led to this topic. Therefore, including vegetation in slope stability analysis is a unique and more sustainable solution to geotechnical engineering.

This writing could not have been completed without the encouragement from our friends and families. We also would like to thank our supervisor and examiner Ayman Abed for his support, directions, and comments on finishing this process. Last but not least, the authors would like to express their appreciation to Chalmers University for having supported the research and development environment for the research work of this paper.

This paper employed numerical modelling with software like GeoStudio and PLAXIS 2D as part of the data analysis. These simulations enabled us to understand the attitude of slopes affected by root systems and vegetative cover. This study suggests that vegetation improves the stability of the slope thereby suggesting that it can be used to prevent landslides.

Although this study provides significant information, the authors identify the need for future studies; more essentially, better knowledge of the additional bonding given by the roots of diverse plants and the particularities of vegetation. They could elaborate and build on our ever-provided procedural knowledge, in a way that would make it more specific and suitable.

In a way, this experiment was thrilling and rather stimulating at the level of intellectual engagement. The decision of deep diving into a relatively new area within civil engineering helped broaden our outlooks and increase the desire to create effective and unique solutions.

Our study will be beneficial for the field of geotechnical engineering and the future research interest in the possibilities to improve the stability of slopes in an environmentally friendly manner.

Göteborg 2024

Ahmad Al Mahamid and Dolley Alskaf

1 Introduction

Given the potential risks that slope failure poses to lives, property, environment, and structures slope stability is an important aspect in geotechnical engineering and Natural hazards management. Some possible factors could be geologic, hydrologic, and anthropogenic related to the instability of the naturally sloping terrain (Hung et al., 2014). Interactions between these variables can be more complicated and could lead to slope failures involving landslides and debris flows, which in the long run may cause adverse impacts to the environment and economy.

For the purpose of avoiding and minimizing the risks associated with slope failures, it is necessary to understand the processes conducive to slope stability. It is defined that a slope can be influenced by such factors as the geometry of the slope, type of soil, water table condition, and external loads (Chowdhury et al., 2009). These elements might have been altered by human intervention or are part of the natural evolution of the slope, however, any changes made to them can have possible impacts on the force balance.

Then it was realized that vegetation plays a part in evaluating slopes and preventing occurrences of slips and landslides (Gray & Sotir, 1996). In this context, there is a positive mechanical role for vegetation where the roots of vegetation improve the cohesion and shear strength of the soil. Similarly, vegetation reduces erosion in the long run by collecting rainwater and preventing surface runoff and in addition to this, vegetation has an ability to stabilize the soil through evapotranspiration hence reducing pore water pressure in a soil profile (Wani & Mir, 2022). These effects assist the slope in receiving a higher safety factor to give it the ability to withstand failure.

Due to the fact that it was widely accepted that vegetation may enhance slope stability and reduce the risks entailed with slope instability, there has been increasing research interest on the role of vegetation on slope stability in recent years (Steinacher et al., 2009). Effective ways of slope stabilize and implementing sustainable land management measures requires the knowledge of how different vegetation species influence the aspects of slope stability and how they achieve this.

These efforts call for improvements in the regular forecasting and the investigations into slope stability with the view of incorporating diverse features that impact on the stabilities of soil masses. In analysing and presenting the measures to mitigate slopes and landslides it becomes mandatory to incorporate the effectiveness and reliability factor in the techniques that involve not only the kind of soil, dimensions of the slope, drainage status, and other regular parameters but also the types of root structures of vegetation.

2 Research Objectives

This work aims to expand the understanding of the characteristics of vegetation and its importance to the stability of slopes through the use of refined modelling and analysis techniques. Therefore, the objectives of this study are to: stipulate the ways through which vegetation influences the stability of slopes and assess the effectiveness of vegetation in minimizing the threats posed by landslides and soil erosions by identifying the relationship between particular types of the plants and the safety factors of slopes. More specifically:

1. Determining the mechanical and hydrological properties that various plant species will have on different slopes with varying geometry and weather conditions given the root pattern of trees and shrubs.
2. An investigation of the potential and feasibility of applying a commercial application to analyse the stability of 2D slopes, from plant attributes.

3 Literature Review

Landslide processes mainly take place because there is an unbalanced force that pushes the soil mass and a resistance that avoids movement on the slip surface. This is in contrast to a system state that is more contained and characterized by a single process or a set and a set of relevant systems. Knowledge of these processes and forces is important in creating needed models, designing appropriate strategies, and evaluating slope stability. Slope stability is obviously one of the most important features in numerical analysis in geotechnical engineering.

Studies on how vegetation affects the stability of a slope can be analysed in many approaches and with different angles of detailed observations. This literature review examines the work that other scholars have done on estimating models on temporal aspects, mathematical models, and ecological models. Therefore, The aim is to make conclusions that focus on improving our knowledge regarding the effect of vegetation on slope stability.

3.1 Methods of Calculating Slope Stability

Geotechnical engineers still perform several common design calculations using the Mohr-Coulomb criteria (ABAQUS, 2004). The Mohr-Coulomb criteria suggest that failure is controlled by peak shear stress τ , which is affected by normal stress σ . One way to demonstrate this concept is by plotting Mohr's circle to represent stress conditions at failure using the minimum and maximum principal stresses. The Mohr-Coulomb failure line is a linear representation that tangentially intersects Mohr's circles; see Figure 3.1.

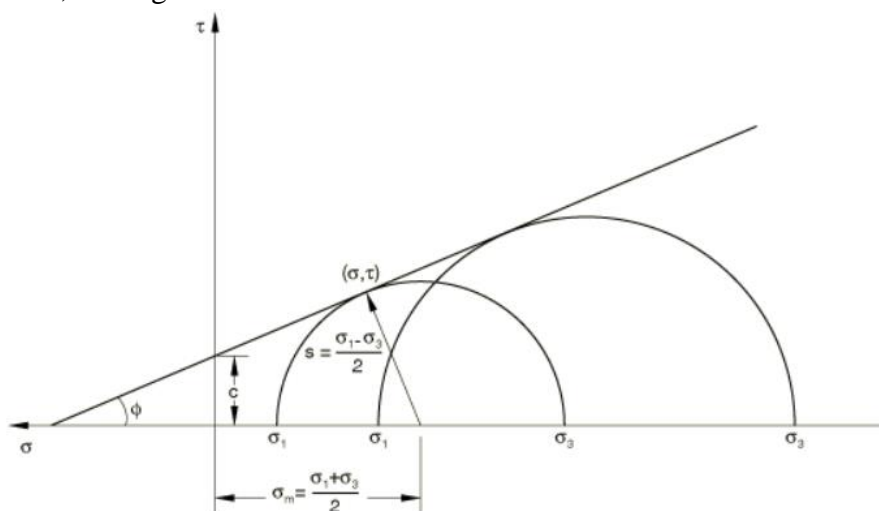


Figure 3.1 Mohr-Coulomb failure criterion (ABAQUS, 2004).

The Mohr-coulomb can be expressed as:

$$\tau = c - \sigma \tan \phi \quad (3.1)$$

where τ is the shear stress, σ is the normal stress, c is the cohesion of the material, and ϕ is the friction angle of the material.

From Mohr-Coulomb circle:

$$\tau = s * \cos \phi \quad (3.2)$$

$$\sigma = \sigma_m + s \sin \phi \quad (3.3)$$

Where s equals half the range between the maximum and minimum principal stresses:

$$s = \frac{1}{2}(\sigma_1 - \sigma_3) \quad (3.4)$$

And σ_m is the mean of the primary stresses at their maximum and minimum values (the normal stress):

$$\sigma_m = \frac{1}{2}(\sigma_1 + \sigma_3) \quad (3.5)$$

The following points outline the fundamental aspects of Mohr's strength theory:

- i) Material experiences failure due to shear forces.
- ii) The maximum strength of the material is defined by the stresses on the plane where failure occurs.
- iii) The intermediate principal stress (σ_2) does not affect the strength of the material when it is exposed to three primary stresses ($\sigma_1, \sigma_2, \sigma_3$).

3.1.1 Limit Equilibrium Method

Geotechnical engineers have long relied on limit equilibrium analysis to assess stability (Krahn, 2003). At the start of the 20th century, there was a proposal to divide an imaginary sliding mass into vertical slices. The Stigberg Quay in Gothenburg, Sweden, underwent stability research in 1916 by Petterson, who assumed a circular slip surface and separated the sliding mass into slices (Krahn, 2003). Fellenius introduced the Swedish, or ordinary, method of slicing throughout the years of the next several decades. Janbu and Bishop advanced the technique in the middle of the 1950s. Equation 3.6 shows that the calculation of the factor of safety involves comparing the total resisting forces and moments to the total driving forces and moments that maintain equilibrium along a specific slip surface.

$$FS = \sum \text{resisting forces, moments} / \sum \text{driving forces, moments} \quad (3.6)$$

This definition assumes that the factor of safety remains constant along the entire length of the slip surface (Kamien, 1997). When the ratio equals one, it signals impending failure, while a factor of safety below one suggests unstable conditions. Thus, the slope is considered stable when the factor of safety exceeds one. The factor of safety's acceptability is dependent on the reliability and confidence of the input material properties in the analysis and the potential consequences of failure. For geotechnical engineering projects related to slope stability, a factor of safety of 1.5 is typically used.

The approaches' solutions vary regarding the equilibrium equations under consideration (Lu, Şener-Kaya, et al., 2012). Only moment equilibrium is satisfied by the ordinary, or Fellenius, method, which eliminates all inter-slice forces, see Figure 3.2b. If manual calculations are the only option, this is the recommended approach. Bishop excluded the inter-slice shear forces and instead added the inter-slice normal forces later; see Figure 3.2c. One more time, only momentary equilibrium is satisfied by Bishop's simplified approach. Similar to Bishop's approach, Janbu's simplified method only meets horizontal force equilibrium, see Figure 3.2d. Advances in computing capacity (see Figure 3.2e) make it possible to perform iterative computations that include all inter-slice and equilibrium equations. The Morgenstern-Price and Spencer procedures are two examples of such methods.

Nevertheless, none of the methods mentioned consider how strain and displacement occur in the soil (Lu, Şener-Kaya, et al., 2012). As a result, calculated stress distributions are often erroneous, and local changes in these values cannot be considered. This does not imply that the safety factor is unreal in its entirety. Stress concentrations caused by the geometry of the slip surface or the interaction between

different soil structures necessitate caution.

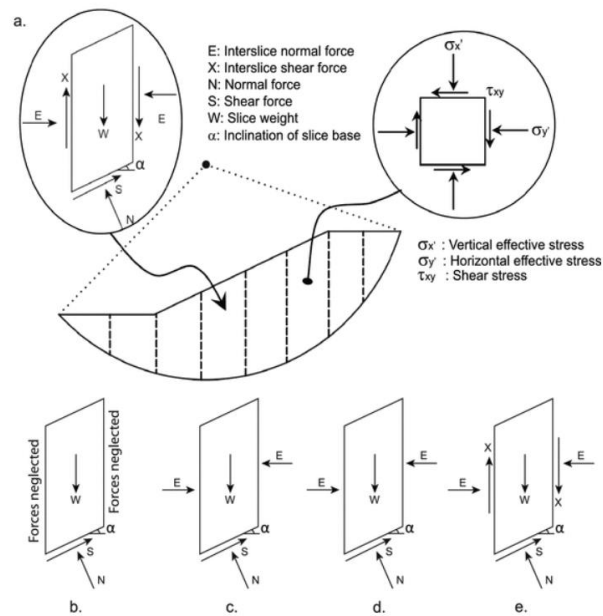


Figure 3.2 (a) slice discretization of a sliding mass and forces on a typical limit-equilibrium slice. Comparing the conventional slice approaches for (b) the ordinary Fellenius Method, (c) Bishop's simplified method (vertical force equilibrium), (d) Janbu's simplified method (horizontal force equilibrium), and (e) Morgenstern-Price Method (Lu, Şener-Kaya, et al., 2012).

3.1.2 Finite Element Method

To address the limitations of limit equilibrium methods, strain-displacement procedures are required. This entails using finite-element techniques such as Janbu's generalized approach or strength reduction methods (SRM).

Using calculated strain and displacement as a basis, the finite element method determines the stress of each element on a discretized slope (Cheng et al., 2007). Complementing the modified Mohr-Coulomb equations or limit equilibrium method allows for precise computation of soil structure interactions, point load impacts, and local safety factors. We use the finite element method when the slope is steep and has sharp edges, or when the geometry and boundary conditions are complicated. On homogenous, smooth slopes with negligible stress concentrations, however, the outcomes could be significantly similar to those from the limit equilibrium method.

Finite element methods, such as SRM (Cheng et al., 2007), can compute complex slope stabilities with accuracy and dependability. Nevertheless, because of the nonlinear solution methods, they have a high computing cost and are often very error-prone and sensitive to initial conditions. The inter-slice shear force assumption, however, places restrictions on limit equilibrium methods. Using one approach over the other does not provide better outcomes because each has its own advantages and disadvantages.

The finite element method is superior to the traditional limit equilibrium methods in the sense that the former does not require you to assume in advance, the shape and location of the critical slip circle (Chok et al., 2015). This is particularly useful when the effect of root reinforcement is being examined because critical slip surface is convoluted and unspecified whenever plants are involved.

3.2 Computer software analysis

Numerous methods have been developed in computers concerning slope stability analysis. These softwares use either the limit equilibrium analysis or the finite element method. It should be noted that we selected GeoStudio and PLAXIS 2D based on the following application:

3.2.1 GeoStudio

GeoStudio is another efficient program which implemented limit equilibrium for analysis of slope stability. The program allows specifying the type of soil and soil layers, geometry of the slip surface, and varying pore water pressures with a large number of soil models. Thus, the input data for problem-solving may be deterministic or probabilistic. Finally, it can also be concluded that the computations involving the limit equilibrium methods can benefit from the stresses computed through finite element analysis to provide a complete slope stability analysis. With all these options integrated together, it is possible for GeoStudio to handle any stability problem of a slope that may be experienced. We selected this software for the study of vegetation on the stability of slopes.

As a result of the problem of the stochastic nature of the input data for analysis, GeoStudio performs probabilistic analyses for slope stability. This study also applied the Monte Carlo simulation in order to calculate the possibility of slope failure. According to the Monte Carlo method probability density and distribution functions are used to find out the safety factor. This method is very useful for sensitivity analysis because it enables the modification of the material parameters such as the unit weight, cohesion, and friction angle.

3.2.2 Plaxis 2D

This software is widely applied in many geotechnical works for deformation as well as stability calculations. Real life situations can be modeled as either a plane stress or a plane strain problem. The program has a convenient graphical shell that enables the user to successfully create the geometry model and the finite element grid with the help of the model of a vertical cross-section of the situation. When carrying out a finite element analysis using Plaxis 2D software then it is required to create a two-dimensional geometry in the x-y plane. In this model one has to incorporate the points which are x, y, and other points or lines through which the geometry of the model has

to be constructed, there are also the material and boundary conditions which has to be defined.

3.3 Vegetation effect on slope stability

In this chapter, a number of researches and study works will be employed to analyse the mechanical and hydrological influence of vegetation on slope stability. This will go a long way in improving our knowledge of the various intricate interactions of vegetation and slope stability. Moreover, this chapter will also provide more additional root cohesion values and describe how each of them can be measured.

3.3.1 Mechanical and hydrological effect of vegetation

Landslides are among the disasters that are caused by natural factors; one of the factors that help in avoiding this calamity is vegetation. John Kim's work for three years gives the soil moisture monitoring measurements, physical properties, and numerical modeling for examining temporal changes of slope stability (Kim et al., 2017). More importantly, trees are known as major stabilizers, and stabilization by trees reduces soil moisture to offer between five and twelve month's worth of stability each year. Yet, the research highlights an important issue: the requirement of more substantial further additions by trees to give a genuine shield against external stimuli such as earthquakes. This information is highly relevant to investigations of slope stability changes over time because of the vegetation, and can greatly help shed light on the dynamic processes of variable relations between vegetation and landslide hazards.

Kokutse goes from time-based considerations of vegetation to numerical uses in a study co-authored with others and entitled "Effect of vegetation on the stability of stream banks in the Volta River Basin" Kokutse et al., 2016, where he utilized the PLAXIS 2D software. This numerical analysis, done using the shear reduction method that is more conventional as earlier noted, goes through various rectilinear slope geometries, various types of soil, and various mechanical parameters of vegetation. The points identified on the root matrix system and the surcharge from trees show essential aspects that determine the stability of the slope. The results of the FE analysis show that the change in the slope angle has a far more significant effect on the safety factor than impacts arising from additional cohesiveness of the soil or its type. What is more, additional cohesion is the second strongest parameter described without relating it to soil type. The study also helps adopters earn insight on the need of numerical modeling approach to unravel issues on vegetation–slope stability.

For the part on the hydrological aspect of vegetation to slope stability, it can be ascertained that the process of evapotranspiration through vegetation results to decrease in soil moisture, thereby having its effect on the hydrological aspect (Ali et al. , 2012). They could cause an increase in the suction pressure of the soil or a

reduction in the pore water pressure and hence our shear strength increased. Plant evaporation not only removes water from the soil, but also lowers the mass, and increases the difference in strength. This research examined the factor of safety for three different tree placements on a slope: at the toe of the slope, at the mid-part, and at the top of the slope. Trees growing on a slope add another layer of resistance to shear forces more than that of shear stress of the soil. This resistance halts the movement of the slope. It was also observed by comparing the factor of safety at different tree positions namely; at the toe, middle, and crest of the slope using SLIP4EX that placement of the tree at the toe results in a much improved stability of the slope compared to the other two positions.

Mulyono et al. examine the effects of vegetation on slope stability, namely the mechanical reinforcing of soils via roots and the reduction of soil water content through hydrological processes. To have a more comprehensive knowledge of the vegetative contribution, it is necessary to take into account the hydrological and mechanical components; see Figure 3.3 for more clarification. Points 1-4 explain the hydrological processes of the vegetation, whereas points 5-9 explain the mechanical processes.

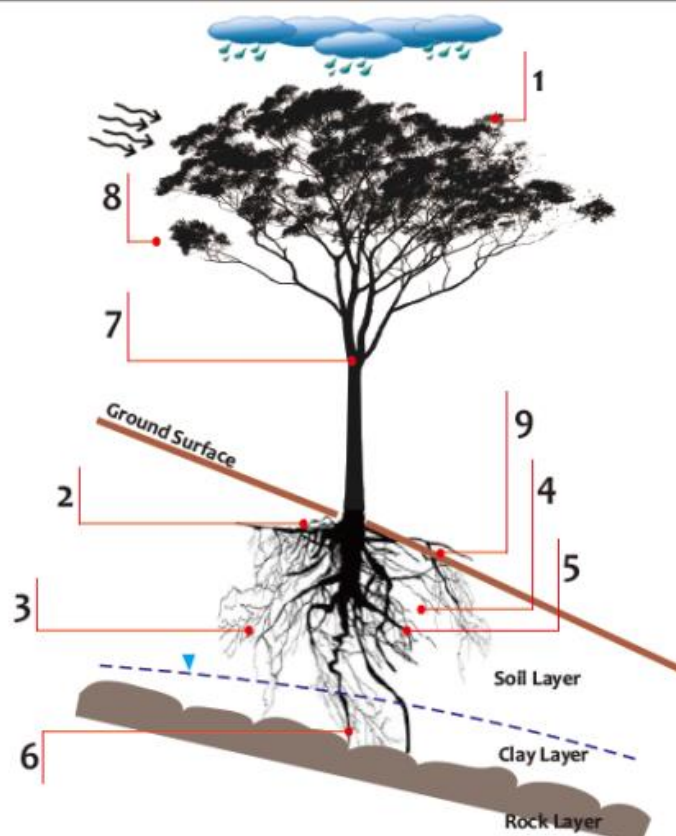


Figure 3.3 The hydromechanical impact of vegetation on slope stability (Mulyono et al., 2018).

The following table describes the code numbers seen in Figure 3.3.

Table 3.1 Description of the hydromechanical mechanism of vegetation provided in Figure 3.3.

Code number	Mechanism
1	When foliage captures rainfall, it leads to losses through absorption and evaporation, which ultimately reduces the amount of precipitation that can seep into the ground
2	Roots and stems enhanced the roughness of the ground surface and soil permeability, consequently increasing the infiltration capacity
3	The roots receive water from the soil and then release it into the atmosphere via transpiration, resulting in a reduction in pore water content
4	The absorption of water by plant roots may lead to a reduction in soil moisture, which in turn can cause the soil to crack and increase its ability to absorb water
5	Roots enhance the stability of the soil by strengthening it and enhancing its resistance to shear forces
6	Vegetation roots secure themselves to the deep layer of soil, providing stability to the soil layer upward by employing buttressing and arching
7	The presence of vegetation adds additional weight to the slope, increasing the normal force components
8	The plant, when subjected to wind, transfers dynamic forces into the slope
9	The roots of plants bind soil particles and decrease their vulnerability to erosion.

The subsequent investigation assessed slope stability by varying the depth of the root zone to 1 m, 1.5 m, and 2 m, considering the presence of vegetation throughout the entire ground surface, on the top of the slope, and only on the slope surface (Noroozi & Hajiannia, 2015). The factor of safety (FOS) was discovered to be higher when vegetation was present across the entire ground surface. It has been observed that as the plant root penetrates deeper or increases in depth, the factor of safety increases. Deforestation increases soil moisture in the affected region, leading to slope collapse.

Expanding on previous research about vegetation's role in slope stability, Mohsen enhances the study with an integrated 2D numerical model (Emadi-Tafti et al., 2021). This research explores the complex relationship between vegetation, soil type, and slope stability in the Kheyroud forest of northern Iran. The study analyzes stability using safety factors concerning different soil conditions and vegetation characteristics. The results emphasize the impact of vegetation, particularly when the depth of the root zone matches the level of the slide body, resulting in a maximum 25% increase in slope stability. Research indicates that vegetation plays a crucial role in mitigating shallow landslides, although its impact is less effective for deep landslides. This study highlights the complex connection between vegetation and slope stability by taking into account various factors such as soil characteristics, tree traits, and slope slowness. The study highlighted the positive impact of roots on enhancing stability and identified a decrease in stability under surcharge load caused by vegetation, with reduced stability observed at 1.2 kPa loading.

3.3.2 Estimation of Root Additional Cohesion

A composite material made up of fibers with a relatively high tensile strength and adhesion contained in a matrix with a lower tensile strength is formed by roots immersed in soil (Coppin & Richards, 1990). This is comparable to the reinforced soil system, in which natural or metallic components are added to stabilize a soil mass. The existence of a root matrix increases the rooted soil mass's shear strength. Because of the binding activity of roots in the soil composite, the mechanical impact of vegetation's roots increases the soil mass strength and resists sliding, but the soil friction angle stays constant, as Figure 3.3 illustrates. Failure may happen via rupture, which is tension failure, or pull-out, which is slippage because of bond failure.

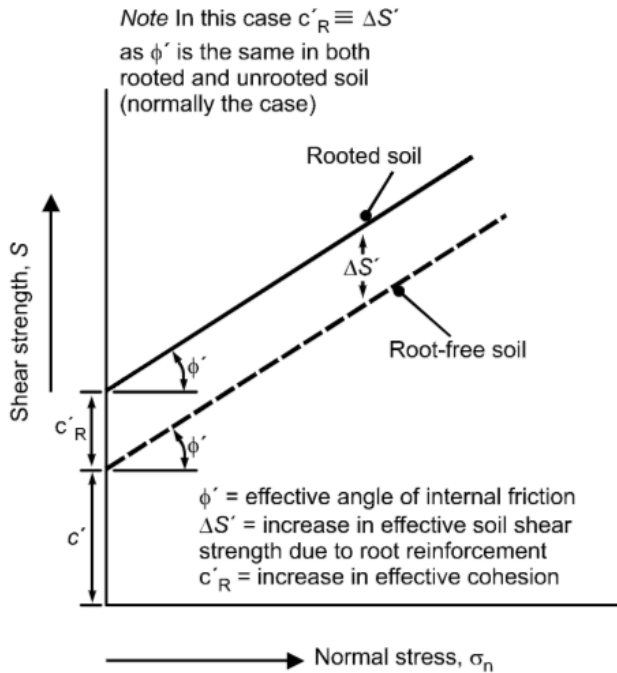


Figure 3.4 The effect of root reinforcement on the soil's shear strength (Coppin & Richards, 1990).

Consequently, the following modification may be made to the Mohr-Coulomb equation for soil shear strength (Coppin & Richards, 1990):

$$s = c' + c_R + (\sigma_n - u)\tan\phi' \quad (3.7)$$

The symbol s denotes the soil's shear strength, effective cohesion, additional soil cohesion, normal stress, pore water pressure, and friction angle.

There are several ways to measure the mechanical parameters of the roots' reinforcement. The following methods will be investigated: (1) the perpendicular root reinforcement model with the available root density and tensile strength information; (2) tests on individual roots; (3) tests on the root-soil matrix; and (4) the RipRoot model.

Wu et al. (1979) developed the first method, the perpendicular root reinforcement model, using the available root density and tensile strength information. The model is dependent on the Mohr-Coulomb equation:

$$s = c + \sigma_n \tan \phi' \quad (3.8)$$

Where s is the shear strength of the soil, c is the cohesion, σ_n is normal stress, and ϕ' is the friction angle of the soil.

Waldron first proposed that roots extend vertically via horizontal shear zones and function similarly to laterally loaded piles, transferring stress to the roots while the soil undergoes shearing (Waldron, 1977). The equation is therefore adjusted:

$$s = \Delta s + c + \sigma_n \tan \phi' \quad (3.9)$$

$$\text{And } \Delta s = T_R (\sin \Theta + \cos \Theta \tan \phi) \quad (3.10)$$

Where Δs represents the increased shear strength due to the roots, T_R is the roots' tensile strength, and Θ identifies the angle to the shear plane. According to Gray, the findings of many investigations on soil including roots revealed that ϕ seemed to be little impacted by the presence of roots (Gray, 1974). Hence, s might be seen as a rise in c . The sensitivity study revealed that, with values ranging from 1.0 to 1.3, the bracketing coefficient ($\sin \Theta + \cos \Theta \tan \phi$) is rather insensitive to the usual changes in Θ and ϕ . Consequently, a value of 1.2 was chosen, and the equation modified to become as the following:

$$\Delta s = 1.2 T_R \left(\frac{A_R}{A} \right) \quad (3.11)$$

RAR ($\frac{A_R}{A}$) stands for the root area ratio. The root reinforcement is solely dependent on RAR. Although this model is user-friendly, it may be overly simplistic because it assumes that the roots are securely anchored and remain attached when under tension (fibre break); the roots are at right angles to the slip plane (perpendicular root); and all roots reach their maximum tensile stress and mobilize their full tensile strength when the soil shears, thus accounting for the forces in the root-soil matrix. Moreover, the diversity in plant life and the impact of root structure may have introduced unreliability in the predictions.

"Methods to measure the mechanical behavior of tree roots: A review" looks at a lot of different experimental methods for testing the mechanical properties of tree roots. It focuses on finding out about root strength and rooted-soil shear-strength data (F. Giadrossich et al., 2017). The report describes field studies on individual roots, such as tensile strength testing and pullout tests. Other studies conducted root-soil matrix tests, such as laboratory shear tests on rooted soils and triaxial tests.

Tensile strength tests evaluate the mechanical characteristics of roots by applying force to the root in a pulling machine until it breaks (F. Giadrossich et al., 2017). Nevertheless, there are difficulties in anchoring the ends of roots in the attachment system without causing damage to the root. Field pullout tests include extracting a root from the soil, and they have shown significant natural variability in root mechanical characteristics. Roots might slide or break during pullout testing due to variables including branching density and direction. Pullout experiments provide

insight into the overall behavior of soil with roots and the specific reinforcing effect of roots on soil as compared to studies conducted on soil without roots. In lab tests using soils with roots, like direct shear tests, there is a noticeable increase in yield stress for rooted soils compared to bare soil. This increase is related to the number of roots present. However, limitations such as a small test size have impacted the practicality of direct shear testing. Triaxial experiments have shown that the presence of roots may enhance soil shear strength and additional cohesion. However, the limited size of roots examined in extremely small soil samples hindered the widespread use of this test in soils with roots.

The scientific article, "New in situ techniques for measuring the properties of root-reinforced soil: laboratory evaluation," discusses the evaluation of four new in situ techniques for tracking mechanical root reinforcement to improve slope stability (G. J. Meijer et al., 2016). The study focused on the development and testing of various methods, including the blade penetrometer, pull-up, pin vane, and corkscrew, as illustrated in Figure 3.4.

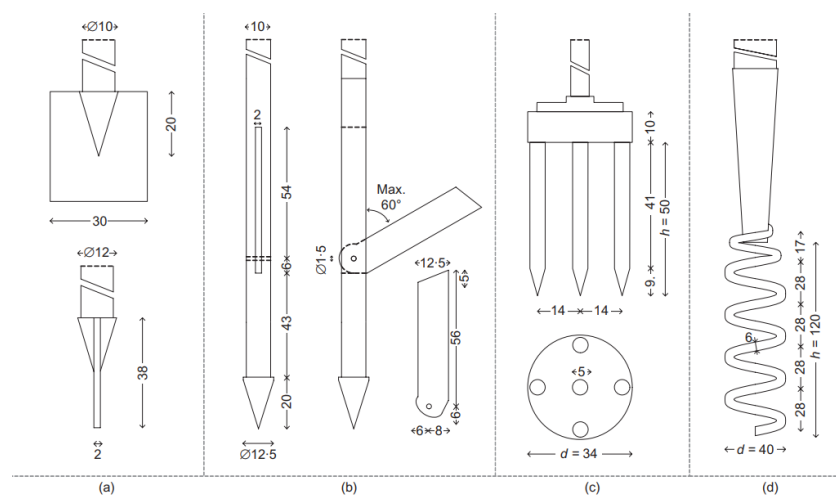


Figure 3.5 (a) blade penetrometer; (b) pull-up; (c) pin vane; (d) corkscrew. The dimensions are in mm (G. Meijer et al., 2016).

The blade penetrometer offers a simplified method for identifying rooted zones and individual roots in the soil (G. Meijer et al., 2016). This method involves a modified penetrometer test that correlates cone resistance with soil strength and type. It's important to differentiate between the behavior of thick individual roots and a dense, fine root network in soil. The blade penetrometer is intended to identify these differences. When conducting the blade penetrometer test, roots in the soil are strained as they are pushed down by the blade until either breakage or slippage of a root end from the surrounding soil takes place. This failure can be seen in the resistance profile as a clear peak at the root depth. Examining the force-displacement plots can help identify whether the main root or side branch has failed. The corkscrew method involves using a device that is installed by being rotated, similar to inserting a corkscrew into a wine bottle, to minimize soil disturbance. The rotational installation

technique ensures that only soil and roots near the screw tip's path are likely to be impacted. When the translational extraction phase occurs, the shear resistance on the outer sides of the cylindrical soil trapped within the screw becomes active. Roots that pass through this interface without disturbance impact this process. The shear resistance of root-reinforced soil comes from the extraction force measurement, assuming tensile forces on the bottom interface are not considered. This method is ideal for directly measuring rooted soil's stress-strain data. It also has to be stated that while using the pin vane method, the blades have been designed to be replaceable with prongs. This design is smooth to pass the roots inside and outside of the prongs without any breakages. The findings made on testing with the pin vane stemmed from different characteristics when there are roots, with the fibrous as well as the thicker roots acting differently relative to stones. The tests provided valuable stress-strain data and proved that it is possible to measure directly the rooted shear strength. As in the case of measured pull-down values, with the pull-up technique, the true root-reinforced penetration profiles can be measured directly by moving upwards instead of downwards like the blade penetrometer. All in all, the pull-up method can be considered quite simple and effective for analyzing the degree of root use and, therefore, the depth and intensity of their development. Cutting and scraping methods were useful in spatially locating the roots and comparing the difference between fibrous and thicker roots with the help of blade penetrometer and pull-up techniques. Declines in resistance not marked on plans pointed to the existence of thicker roots. The two techniques used- corkscrew and pin vane directly measured the rooted shear strength and provided stress-strain data.

The RipRoot model is aimed at calculating the load that roots contribute to the stabilization of stream banks (Pollen-Bankhead & Simon, 2009). It derives parameters for modeling temporal and geographical changes in root reinforcement using root-architecture data. The model considers the quantity and diameter of roots, the strength of roots across potential shear planes, and the spatial diversity of root networks within stream banks. To provide a more realistic picture of root reinforcement, it also considers the ages and dispersion of roots unique to each species. The model also takes into account soil type, pullout, and root breakage. It also offers estimates of root reinforcement using the RipRoot progressive breaking algorithm and the Wu static equation; see Equation 2. Although the model focuses on physical root-growth processes rather than species competition, the user may enter data for numerous species to build a typical species assemblage. In general, the RipRoot model provides estimates of the reinforcement supplied by roots by modeling the effects of root age, species, and distribution on bank stability.

The following table summarizes typical root additional cohesion values gathered from different testing methods (Chok et al., 2015; Capobianco et al., 2021).

Table 3.2 Typical values for root additional cohesion C_r . *Based on shear tests, **based on perpendicular root reinforcement model. ***based on the RipRoot model.

Vegetation	C_r [kPa]
Alder (Japan)*	2.0-12.0
Japanese cedar (Japan)*	1.0-5.0
52-month-old yellow pine (laboratory)*	~ 5.0
52-month-old yellow pine (laboratory)*	3.7-6.4
Conifers (Oregon, USA)**	3-17.5
Conifers (Alaska, USA)**	5.9
River birch (Mississippi, USA)**	8.0
River red gum (Victoria, Australia)**	10.0
Norway spruce (Picea abies)***	5.7
Downy birch (Betula pubescens)***	7.18
Goat Willow (Salix caprea)***	1.37
Mixed grass (Norway)***	0.35

Collectively, the reviewed literature not only enhanced our comprehension of the intricate interactions between vegetation and slope stability, but also highlighted the need for interdisciplinary and contextual approaches to tackle landslide challenges in slope instabilities across diverse environmental conditions. These studies are part of a growing body of knowledge that serves as a guide not only for future studies but also for our current slope stability practices.

3.4 Landslide risk and cultivation zones in Sweden

The Swedish Geotechnical Institute (SGI) and the Swedish Civil Contingencies Agency (MSB) have identified ten areas that are at risk of climate-related events such as landslides, flooding, and shore erosion (Konitzer, 2021). A list of ten national risk areas has been created and ranked based on the projected costs of risk, the level of difficulty in implementing preventive measures, and the interconnections between various risks and the corresponding measures. The risk areas have been categorized into four risk classes. The region of Västkusten-Gota älvdalen is facing a significant and complex set of challenges when it comes to coastal and fluvial flooding, as well as landslides. Nevertheless, all of the identified areas present complex climate-related risks that require immediate attention. A risk area is a specific geographical region vulnerable to various natural hazards such as floods, landslides, or erosion. These hazards can negatively impact human health, the environment, cultural heritage, and economic activities. The figure below presents the identified risk areas; refer to Figure 3.5.

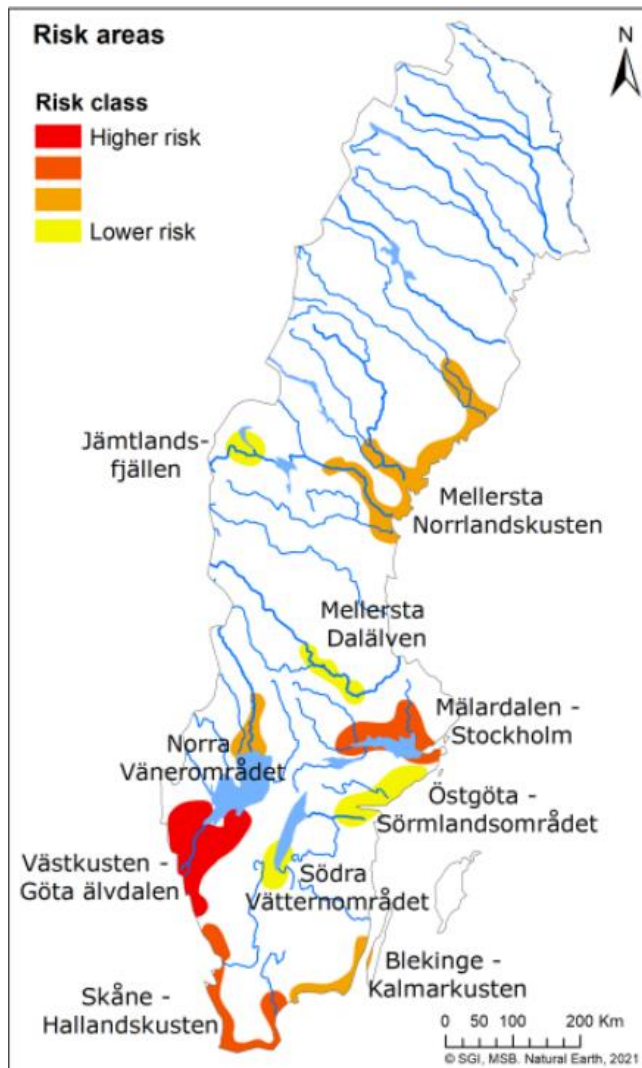


Figure 3.5 Identified risk areas in Sweden (Konitzer, 2021).

In Sweden, landslides covering more than one hectare occur approximately every second or third year (Konitzer, 2021). Landslides can happen in both undeveloped and built-up areas. Throughout the 20th century, there have been multiple significant landslides that have occurred in developed areas. The landslide has caused extensive damage to buildings and facilities, and unfortunately, it has also led to the loss of human life. In modern times, the earth movements in Surte (1950), Göta (1957), Tuve (1977), Vagnhärad (1997), and Småröd (2006) have caused significant damage.

Regarding the cultivation zones in Sweden, the term "Odlingszoner" describes the idea of categorizing the kinds of crops that grow well in various climate zones (RST, n.d.). The phrase is used in Sweden to indicate which crops may be grown in various regions of the country while taking climatic factors like temperature, precipitation, and daylight hours into account. The agriculture zones in Sweden may differ from one zone to another based on factors such as geography and climate. We can broadly classify Sweden into numerous agriculture zones that run north to south, each with unique conditions for different crops. For instance, crops that are more widespread in

southern Sweden can be less resistant to the cold and shorter growing seasons found in the country's north. The Swedish Garden's zone map divides Sweden into eight cultivation zones. Areas 1 and 8, see Figure 3.6, represent the mildest and least productive regions of the country, respectively. The cultivation zones indicate the value "up to" what the plant can handle, meaning a plant labeled zone IV can handle zones I–IV. The higher the zone number, the better suited a plant is for the winter. The zone map focuses on woody plants, including trees and shrubs.

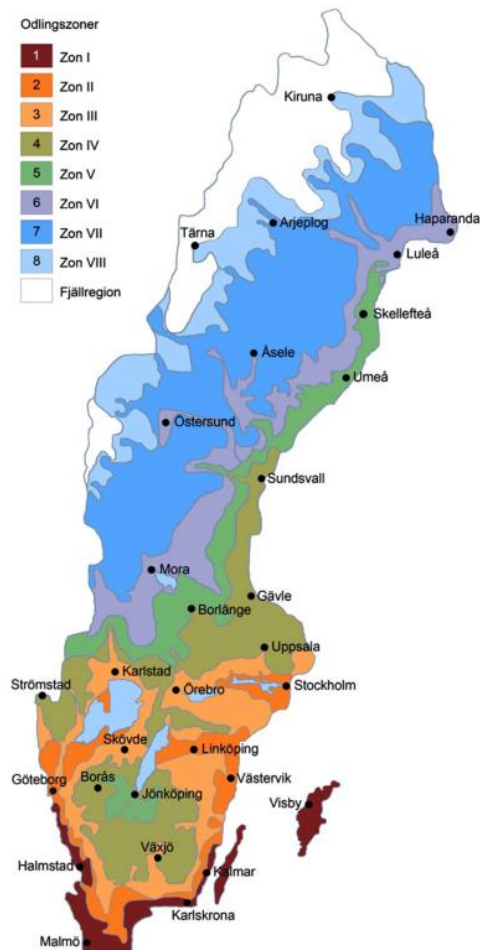


Figure 3.6 Cultivation zones in Sweden (RST, n.d.).

The table below illustrates the different cultivation zones and the corresponding plants suitable for each zone. Table 3.2 includes a list of plants with additional cohesion and determines the plant selection, and plantagen.se offers more plants for each cultivation zone. It is possible to grow grass across Sweden by considering the temperature requirements of each grass species.

Table 3.3 The cultivation zones and their corresponding suitable plants.

Cultivation zone	Suitable plants and their root additional cohesion [kPa]
I	Thuja Brabant (5.9) Norway Spruce (5.7) Japanese cedar (3) River birch (8.0) Downy birch (7.18) Goat willow (1.37) Mixed grass (0.35)
II	Thuja Brabant (5.9) Norway Spruce (5.7) Japanese cedar (3) River birch (8.0) Downy birch (7.18) Goat willow (1.37) Mixed grass (0.35)
III	Thuja Brabant (5.9) Norway Spruce (5.7) Japanese cedar (3) River birch (8.0) Downy birch (7.18) Goat willow (1.37) Mixed grass (0.35)
IV	Thuja Brabant (5.9) Norway Spruce (5.7) Japanese cedar (3) River birch (8.0) Downy birch (7.18) Goat willow (1.37) Mixed grass (0.35)
V	Thuja Brabant (5.9) Norway Spruce (5.7) River birch (8.0) Downy birch (7.18) Mixed grass (0.35)

VI	Norway Spruce (5.7) Conifers forest (3-17.5) River birch (8.0) Downy birch (7.18) Mixed grass (0.35)
VII	Norway Spruce (5.7) Conifers forest (3-17.5) River birch (8.0) Mixed grass (0.35)
VIII	Norway Spruce (5.7) Mixed grass (0.35)

Root cohesion could also be dependent on the type of soil, the climatic conditions, or the type of plant in question. Therefore, the peculiarities of the studied environment should be taken into account while exploring the relationships between plants, roots, and soil to avoid landslides in the future. As illustrated in the following figure, it provides a vague contrast of the additional cohesion in Sweden depending on the data that was gathered from the literature (Chok et al. , 2015).

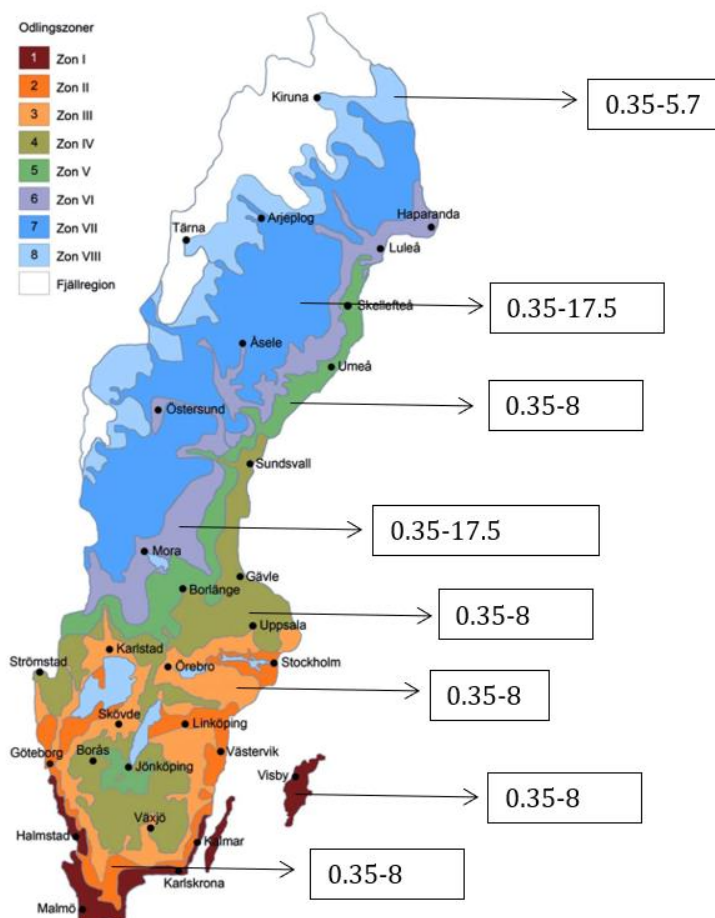


Figure 3.1 The variation of the additional cohesion in Sweden's cultivation zones based on plant types in Table 3.2.

4 Methodology

The methodology of this master's thesis includes reviewing relevant literature on slope stability and vegetation, GeoStudio, and numerical modeling and analysis of slopes using PLAXIS. Initially, we will examine a model that has incorporated only the mechanical aspect of vegetation in its analysis; we will test the safety factor with and without vegetation. The next step is the analysis of a model with varying slope angles which will allow us to investigate the interaction between the slope geometry and slope stability together with vegetation. The last point is to analyze a model to estimate the impact of the vegetation in the destabilization or stabilization of the slope.

One tree species chosen is the downy birch (*Betula pubescens*). The shrub selected was the goat willow (*Salix caprea*), while the grass chosen was a common mixed grass. The vegetation of various types was chosen since they are native to the Swedish environment (The Birch Avenue, 2023; *Salix caprea*, SE: Säl, vanlig säl, DE: Sal-Weide, NL: Boswilg, UK: Goat Willow) (Axelsson & Mattson, 2021). Slope stability was assessed by altering the depth of the root zone to 0.5 m, 1 m, 1.5 m, and 2 m while considering the presence of vegetation throughout the entire ground surface. The design will incorporate the plant roots, providing additional cohesion throughout the root zone.

4.1 Numerical modelling of the conceptual model

A conceptual model is studied using GeoStudio and Plaxis 2D to study the mechanical effect of vegetation on slope stability.

4.1.1 GeoStudio

For slope stability modeling and safety factor calculation, the limit equilibrium method (LEM) from the SLOPE/W package was utilized, assuming Bishop's proposed rotational failure model.

For the sake of simplification in the analyses, we assumed a homogeneous clay slope. This investigation's vegetation primarily impacts the uppermost region of the soil. To streamline the model by incorporating a single material type, a clay material was chosen within GeoStudio. This choice is more reflective of the surface materials that would be observed in the city of Gothenburg, where the soil parameters were selected from various references (Andreasson, 2020; Tornborg et al., 2021). The Mohr-Coulomb model was used for the selected material. The required input parameters for the Mohr-Coulomb model are the unit weight, the friction angle, and the effective cohesion. The primary soil characteristics selected are detailed in the table below.

Table 4.1 Soil properties and slope geometry used in GeoStudio.

Slope and soil parameters	Values
Slope height, H	15 m
Inclination, I	26.57°
Unit weight	17 kN/m ³
Cohesion, c'	4 kPa
Friction angle, φ'	30°

Multiple approaches were available for determining the slip surface for the circular failure, but the entry and exit approach was chosen. The combinations of vegetation considered are detailed in Table 4.2, while Figure 4.1 represents the geometry of the analyzed slope.

Table 4.2 Vegetation combination used at the top, at the middle, and at the toe of the slope.

Vegetation combination			Cohesion at the root zone [kN/m ³]
Top	Middle	Toe	
Bare soil	Bare soil	Bare soil	4
Grass	Grass	Grass	4.35
Shrubs	Shrubs	Shrubs	5.37
Trees	Trees	Trees	11.18

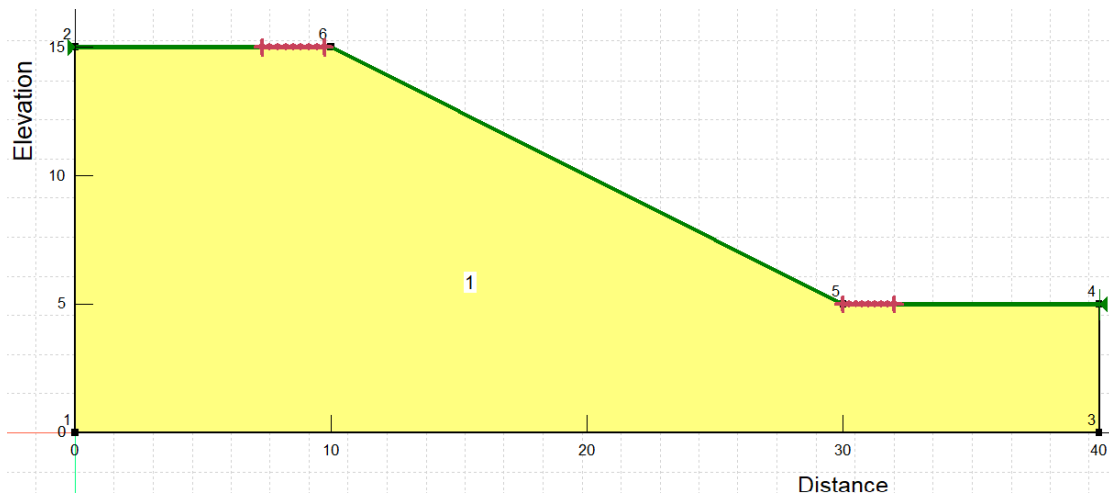


Figure 4.1 The geometry of the analyzed slope.

4.1.2 Plaxis 2D

The safety factor of the same slope is studied using Plaxis 2D which is based on the finite element method. The primary soil characteristics selected are detailed in Table 4.3.

The Mohr-Coulomb model was selected. Elastic qualities of the layers, such as Young's modulus and Poisson's ratio, and strength parameters, such as effective cohesion, effective friction angle, and dilatancy angle, are the input parameters used. Since zero is a fair number, it was assumed that the dilatancy angle was zero for all the layers.

Table 4.3 Soil properties used in Plaxis 2D.

Soil parameter	Value
Poisson ratio, ν	0.2
Young's modulus, E	3000 kN/m ²
Cohesion, c	4 kN/m ²
Friction angle	30°
Unit weight	17 kN/m ³

4.2 Mechanical effect of vegetation with varying slope angle

This chapter will apply the same mechanical characteristics used in Chapter 4.1 to different slopes with varying inclinations. The inclinations that will be examined are 30, 40, 50, 60, and 70 degrees. The primary objective is to analyze the safety factor of slopes without and with vegetation and enhance the factor by introducing appropriate plant species, achieving slope stability. If the safety factor falls below 1.5. to reach a safety factor of 1.5, the analysis will start with the minimum addition of cohesion and root zone depth and will increase gradually until an SF of 1.5 is reached. The same types of vegetation and root zone depths that were used in Chapter 4.1 will be used in this chapter to increase the factor of safety. Figure 4.1 and Table 4.1 illustrate the geometry of the studied slopes.

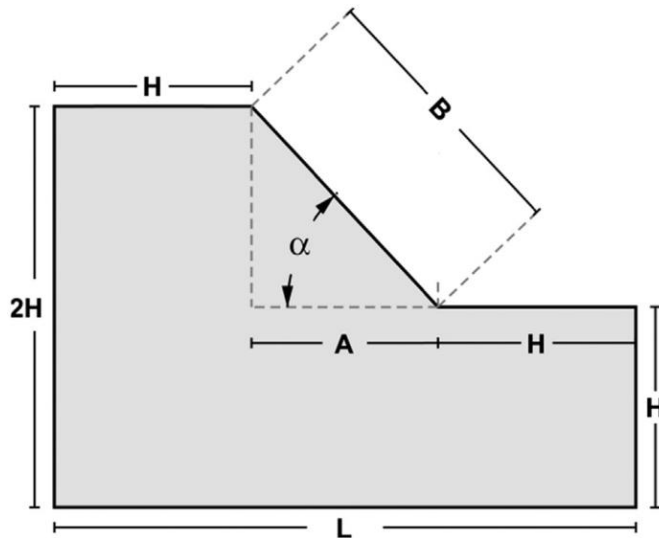


Figure 4.2 The geometries and slope model that were used in the investigations, where α is the slope angle.

Tabell 4.4 The geometry of the studied slopes.

Slope inclination α	H [m]	Slope base length, A [m]	L [m]	Slope length, B [m]
30	6	7	30	12
40	6	7.8	30	9.3
50	6	9.3	30	7.8
60	6	12	30	7
70	6	17.5	30	6.4

4.3 Modelling the hydro-mechanical effect of vegetation on slope stability

Vegetation helps keep the slope stable by blocking rainwater that would have seeped into the slope and taking water from the soil for evaporation. Both methods strengthen the soil by lowering the positive pore-water pressure from water entry and increasing the soil suction through water extraction. This is the major benefit of slope stability.

This chapter will primarily analyze the hydro-mechanical impact of plants on slope stability. The study will focus on a homogeneous clay slope with an inclination of 30 degrees. The mechanical parameters of the clay used for analysis are provided in Table 4.1. The hydraulic parameters for the clay slope have been assumed to exhibit the properties typically associated with clay in Gothenburg.

To examine the impact of vegetation on slope hydrology, the Geostudio software will use a boundary condition known as land-climate interaction. This condition will utilize the Penman-Monteith evapotranspiration method (see Figure 4.3). The Penman-Monteith method is a commonly used technique for estimating

evapotranspiration (ET), which encompasses the simultaneous processes of water evaporation from soil and plant surfaces as well as transpiration from plant leaves (Cai et al., 2007). The Penman-Monteith process estimates PET, and that refers to an ingenious volume of water that can be evaporated and transpired, with outcomes being assessed on a vegetated surface that has direct access to water supplies. The Penman-Monteith method considers the actual energy that can be used in evaporation by adding the influences of incoming solar radiation, temperature, and humidity parameters. In addition to this, wind speed affects the boundary layer, which is that layer of air surrounding the plant and retards evaporation.

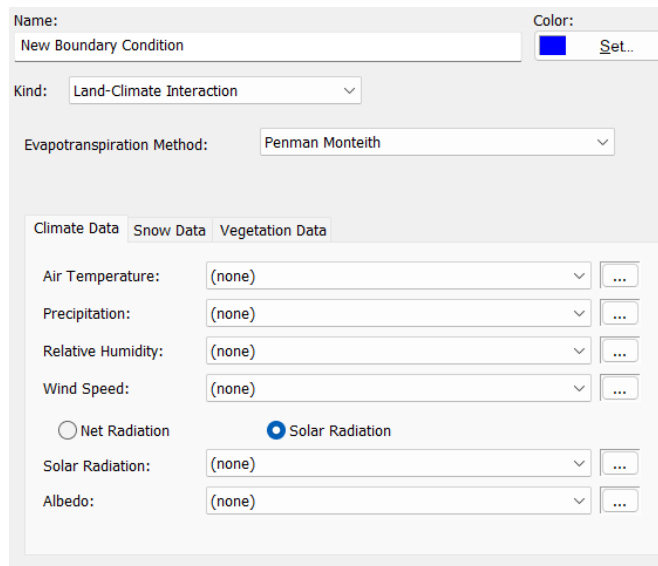


Figure 4.3 The used boundary condition in GeoStudio.

The meteorological variables required for the Penman-Monteith equation, including average air temperature, relative humidity, and wind speed, were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) records. The meteorological data used is listed in Table 4.5. Snow data will be excluded from this investigation since Gothenburg had no snowfall in April 2024. A whole week will be stimulated in GeoStudio with meteorological data from April. The albedo value is assumed to be 0.15, which means 15% of solar energy is reflected and the rest is absorbed.

Table 4.5 Meteorological information used in this analysis.

Month [April]	Average Temperature [°C]	Precipitation [mm/day]	Relative humidity	Wind speed [m/s]	Solar radiation [Wh/m ²]	Albedo
7/4 (day 0)	11.5	2.4	0.80	5.4	5160	0.15
8/4 (day 1)	11	0.5	0.76	6.1	6474	0.15

9/4 (day 2)	10.5	3.1	0.71	5.9	5217	0.15
10/4 (day 3)	8	0.8	0.70	6.4	6648	0.15
11/4 (day 4)	9.5	3.8	0.75	5.7	4920	0.15
12/4 (day 5)	8	4.3	0.77	5.2	4722	0.15
13/4 (day 6)	10	4.3	0.68	6.5	2004	0.15

In this analysis, Downy birch trees will be considered with a root depth zone of 2 meters and additional root cohesion of 7.18 kPa. The plant characteristics included in the Penman-Monteith evapotranspiration calculation, see Figure 4.4, were obtained from previous studies, see Table 4.6.

Figure 4.4 Vegetation data.

Tabell 4.6 Used vegetation data values in GeoStudio.

Vegetation data	Leaf Area Index (LAI)	Plant Moisture Limit	Root Depth [m]	Normalized Root Density	Soil Cover Fraction
Value	3	Data set	2	Data set	0.7
Source	(Wang et al., 1995)	(Rajeev et al., 2012)	(Mauer & Palátová, 2003)	(Ning et al., 2019)	Assumption based on...

The Leaf Area Index (LAI) is a numerical index of the total leaf area per unit ground area. The quantity of light that plants can capture directly correlates with it (Bréda, 2003). This variable is critical in forecasting photosynthetic primary production and evapotranspiration, and it serves as a benchmark for crop growth. The Leaf Area Index (LAI) measures the quantity of leaf material present in a canopy. By definition, it is the ratio of one side of a leaf's surface area to the amount of ground area it covers. The figure below describes how the leaf area index can be estimated.

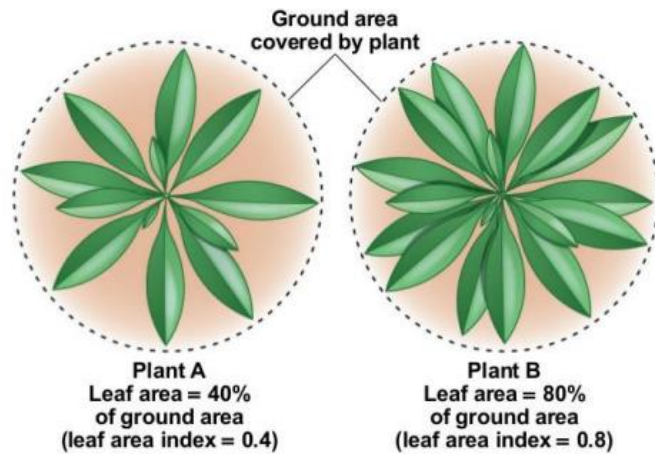


Figure 4.4 Estimation of LAI (Abdellatif & Valdenebro, 2016)

People commonly use the term "plant moisture limit" to describe the minimum amount of moisture a plant needs to survive. Plants' moisture requirements can vary depending on their species, natural habitat, and stage of growth (Rajeev et al., 2012). Since the soil serves as the primary water source for most plants, the moisture limit often correlates with soil moisture levels. When soil moisture decreases below a specific level, it can cause drought stress in plants. If the situation continues, it can lead to wilting, decreased growth, and potentially even death. The PML function refers to the connection between soil suction and the plant moisture-limiting factor. Since the PML function for downy birch on sites is not accessible, we opted to use a typical function from the GEOSLOPE database for different types of vegetation. Figure 4.5 displays this function.

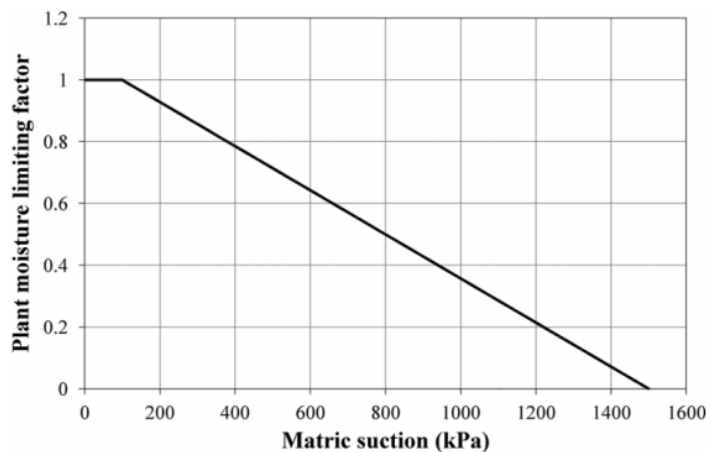


Figure 4.5 The typical PML function used in GeoStudio (Rajeev et al., 2012).

RLD distribution is yet another important aspect that should be considered when evaluating the performance of crops and root uptakes in soil-plant systems (Ning et al., 2019). But, measuring RLD under field conditions is not easy, relatively easy in laboratory conditions. However, it is often the case that many RLD models contain many parameters that can have fluctuations in the course of the crop growth period. While these have their own advantages, they also serve as a hindrance given the fact

that they are somewhat hard to measure. These distribution models of the NRLD do not depend on the growth phase and are effective in estimating the distribution of the RLD with ease and accuracy at any growth phase. This function from a previous study of the relative depth and the normalized root length density was then used in GeoStudio to describe the normalized root density.

The concept of soil cover fraction applies to the ratio of the ground surface area that is occupied by various elements, such as vegetation, residue, or other substances. Mathematicians commonly represent the concept as a fraction or express it as a percentage. The soil cover fraction (SCF) ranges from 0.0, indicating bare ground, to 1.0, which represents a heavily vegetated surface. In this study, the soil cover fraction is assumed to be 0.7.

5 Result

This chapter will illustrate the findings obtained from analyzing slopes using GeoStudio and Plaxis 2D, with and without various types of vegetation.

5.1 Conceptual model

The root system was defined by two primary factors: increased root cohesion (C_r) and depth of the root zone (Z_r). Figure 5.1 and Figure 5.2 clearly demonstrate a substantial rise in the factor of safety (FS) of the slope while transitioning from a grass-covered slope to a tree-covered slope. Undoubtedly, the stability of an unreinforced slope is enhanced when the extra cohesiveness provided by plants' roots is included. The safety factor values derived from GeoStudio and Plaxis 2D are provided in Table 5.1.

Table 5.1 Safety factor values at different root zones and various types of vegetation.

Vegetation type	Depth of the root zone, Z_r [m]	Safety factor, GeoStudio	Safety factor, Plaxis 2D
Bare soil	0	1.596	1.521
Grass	0.5	1.599	1.523
	1	1.601	1.544
	1.5	1.641	1.570
	2	1.643	1.579
Shrubs	0.5	1.606	1.530
	1	1.615	1.576
	1.5	1.653	1.600
	2	1.660	1.642
Trees	0.5	1.643	1.533
	1	1.689	1.580
	1.5	1.718	1.612
	2	1.745	1.644

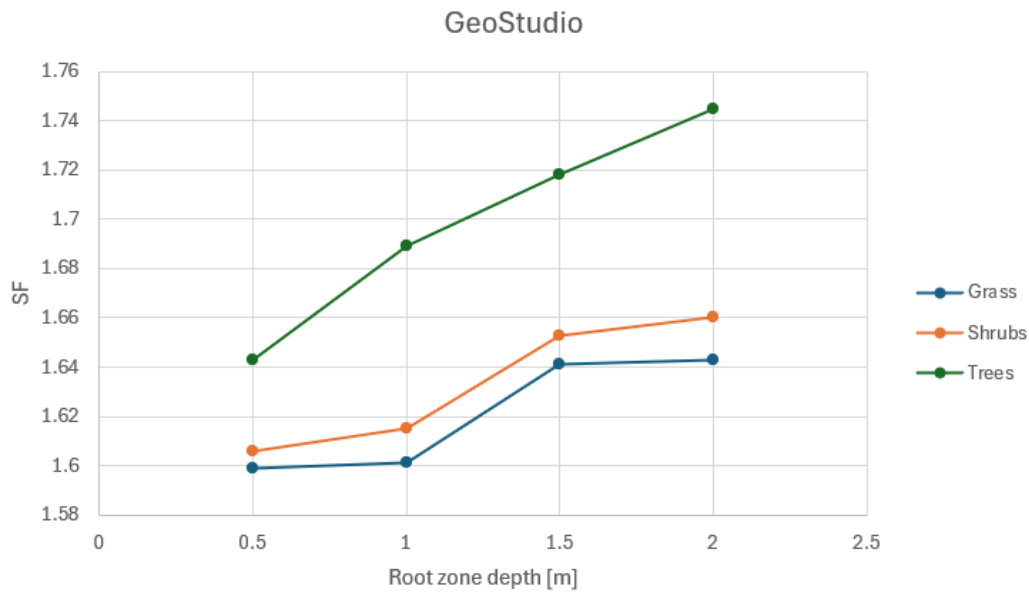


Figure 5.1 Values of slope's factor of safety as a function of the root zone depth for various types of vegetation, GeoStudio.

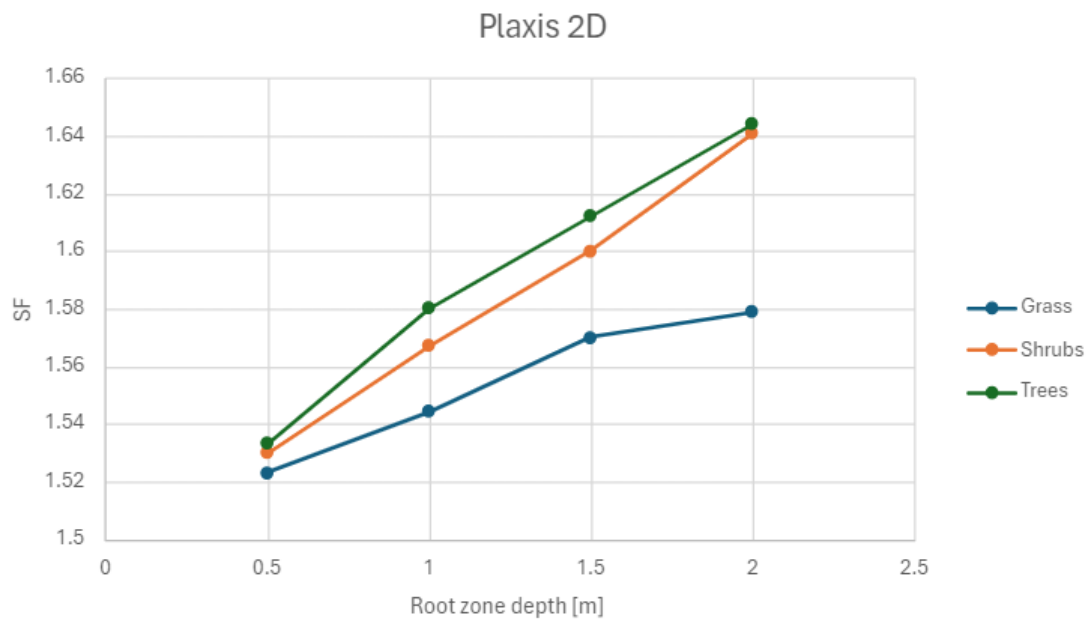


Figure 5.2 Values of slope's factor of safety as a function of the root zone depth for various types of vegetation, Plaxis 2D.

The following figures represent the slope analysis for different vegetation types (grass, shrubs, and trees) with a root zone depth of 2 meters using Slope/W and Plaxis 2D.

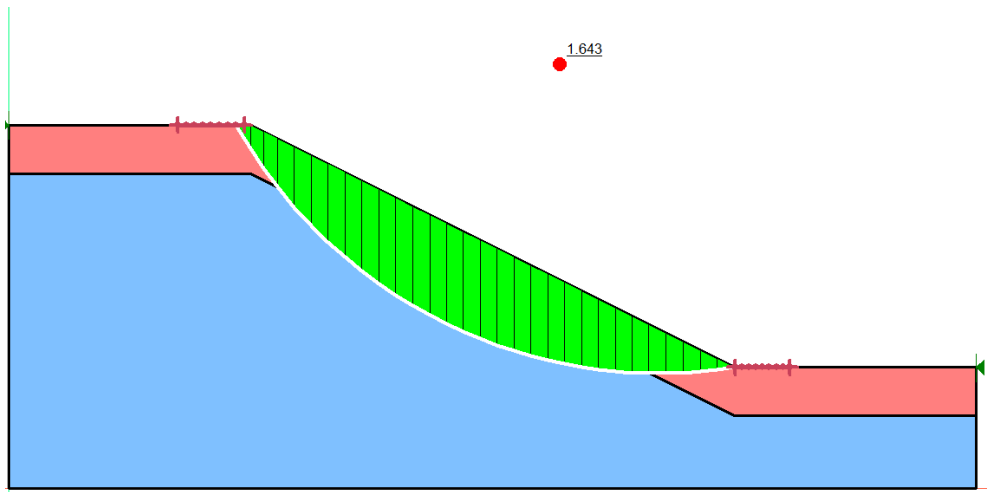


Figure 5.3 Slope stability analysis including grass, Slope/W.

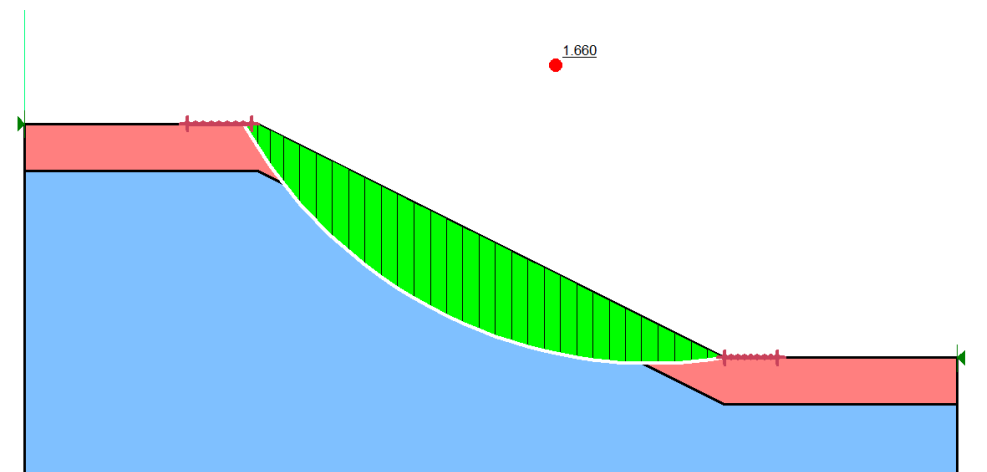


Figure 5.4 Slope stability analysis including shrubs, Slope/W.

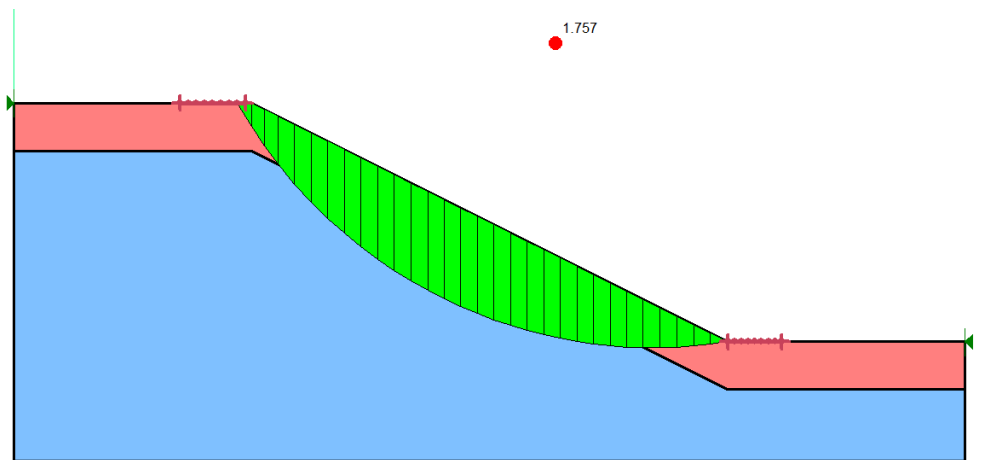


Figure 5.5 Slope stability analysis including trees, Slope/W.

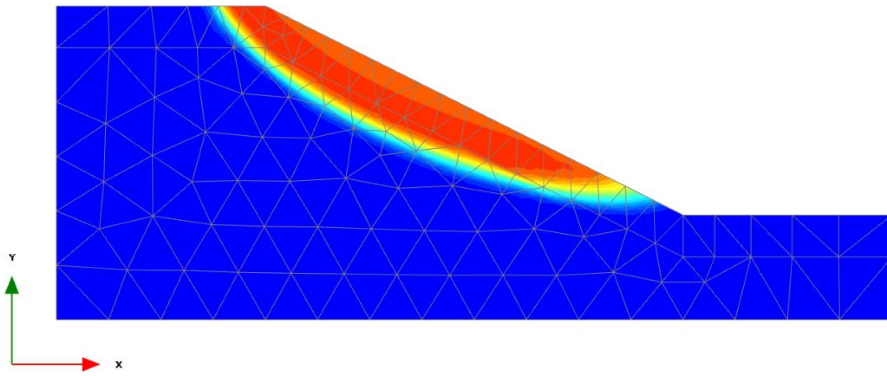


Figure 5.6 Slope stability analysis including grass, Plaxis 2D.

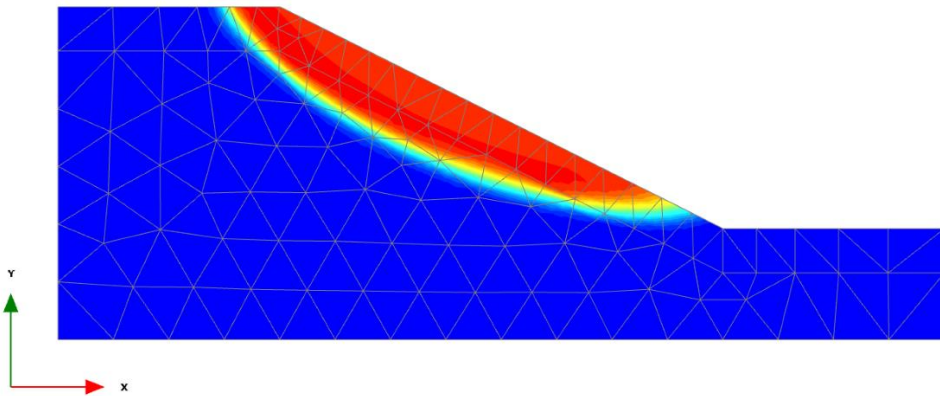


Figure 5.7 Slope stability analysis including Shrubs, Plaxis 2D.

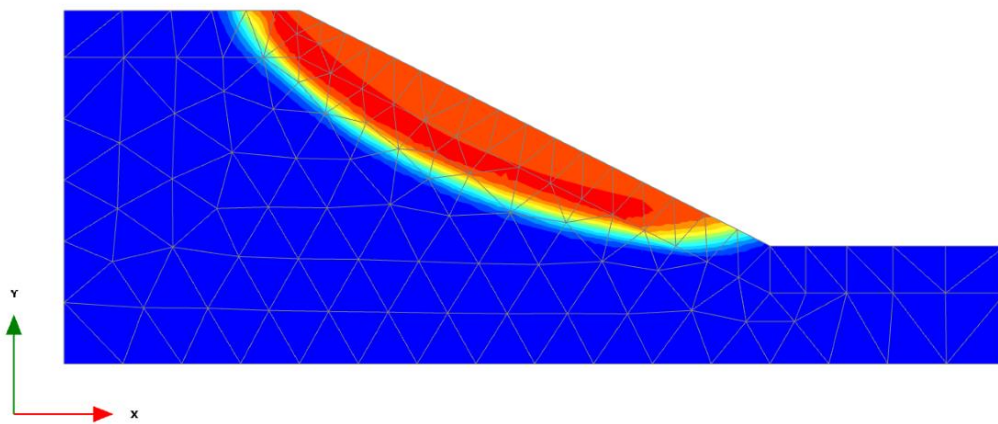


Figure 5.8 Slope stability analysis including trees, Plaxis 2D.

5.2 Vegetation effect on slopes with varying angles

The output generated by GeoStudio is shown in the table provided below. The primary objective is to enhance the safety factor to 1.5 using vegetation.

Tabell 5.2 Safety factor values for slopes with different angles with and without vegetation.

Slope inclination	SF without vegetation	Used vegetation	Root zone depth [m]	Additional cohesion from vegetation [kPa]	SF with vegetation
30	1.798	-	-	-	-
40	1.480	Mixed grass	2	0.35	1.5
50	1.377	Trees (Downy birch)	1	7.18	1.512
60	1.218	Trees (Downy birch)	2	7.18	1.525
70	1.211	Trees (conifers)	1.5	17.5	1.614

The study begins by implementing the minimal root cohesion, which is 0.35 kPa, for mixed grass. It then proceeds to gradually increase the depth of the root zone from 0.5 to 2 meters. If the safety factor remains below 1.5, we will proceed to enhance the root additional cohesion by using shrubs with a root additional cohesion value of 1.37 kPa. Simultaneously, we will increase the root zone's depth from 0.5 to 2 meters. If the additional cohesion provided by the shrubs is not enough to achieve a safety factor of 1.5, we proceed to consider downy birch trees with a root additional cohesion of 7.18 kPa. The safety factor for shrubs at a 2-meter root depth zone on a 50-angle slope is 1.429, which is slightly below 1.5. However, if we wish to implement a root depth zone of less than 2 meters, shrubs are beneficial at a 40-degree incline. With an inclination of 70 degrees, the downy birch trees at a root depth of 2 meters were not adequate enough to raise the safety factor to 1.5. Therefore, an alternative tree species was selected, conifers, which can be found in Sweden and had an additional cohesion of 17.5 kPa.

The output generated by Plaxis 2D is shown in the table provided below. The primary objective is to enhance the safety factor to 1.5 using vegetation.

Table 5.3 Safety factor values for slopes with different angles with and without vegetation.

Slope inclination	SF without vegetation	Used vegetation	Root zone depth [m]	Root additional cohesion [kPa]	SF with vegetation
30	1.731	Mixed grass	-	-	-
40	1.463	Trees (Downy birch)	1	7.18	1.531
50	1.311	Trees (Downy birch)	1.5	7.18	1.520
60	1.217	Trees (Downy birch)	2	7.18	1.501
70	1.157	Trees (conifers)	2	17.5	1.527

In both GeoStudio and Plaxis 2D, the same procedures were used to simulate slopes with varying inclinations and enhance the safety factor to 1.5. In Plaxis 2D, the safety factor for slopes without vegetation is lower compared to GeoStudio. This requires either increasing the depth of the root zone or increasing the additional cohesion of the roots to achieve a safety factor of 1.5. For instance, a slope with a 40-degree inclination requires a combination of grass (0.35 kPa) with a root depth zone of 2 meters to achieve a safety factor of 1.5 on GeoStudio. In contrast, the same slope requires the presence of downy birch trees (7.18) with a root depth zone of 1 meter on Plaxis to get a safety factor of 1.5. For a slope with an inclination of 60 degrees, both software programs employed the same values for root extra cohesion and root zone depth. However, the safety factor after including vegetation in GeoStudio remained greater than in Plaxis.

5.3 Hydro-mechanical effect of vegetation on slope stability

The analyses results will be presented in form of graphs that will indicate the FoS against time and pore water pressure against time. These important parameters are easily compared to each other through the different graphical representations and it is evident how they vary with time throughout the simulation process. The FoS vs. time graphs present the failure and stability of slopes for different conditions, in contrast, pore water pressure vs. time graph reflects on the dynamic behaviour of soil moisture on slopes. Collectively these visualisations proved useful in understanding the extent of the hydro-mechanical effect of vegetation on slopes stability.

The following is an examination of the components and features that can help to predict and monitor the behavior of slopes as influenced by pore water pressure in the soil. Changes in water pressure directly impact the effective stress of the soil and therefore provide variation in the shear strength of the soil mass together with a variability in the occurrence of slope failure. Measuring the pore water pressure over a period enables one to quantify the impact of vegetation on the moisture content of the soil and therefore the stability of the slope. Figures 5.9 and 5.10 The changes in the water pressure were also displayed over time depending on the presence of vegetation. The pressure of the water is found to slightly decrease once vegetation is applied to the slope and this makes it easier to drain.

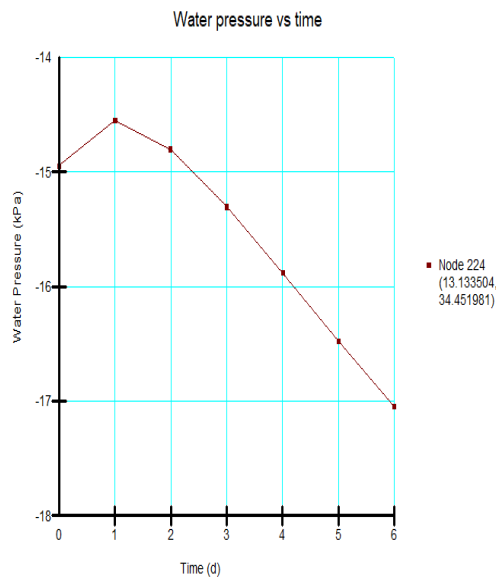


Figure 5.9 Water pressure vs Time without vegetation.

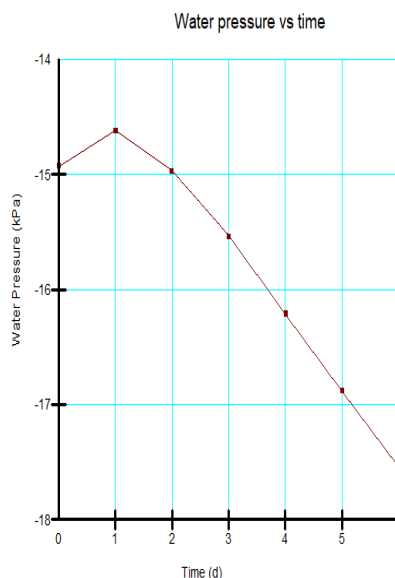


Figure 5.10 Water pressure vs Time with vegetation.

In this work, which utilized GeoStudio to simulate slope stability over a week-long rainfall intensity, the FoS is analyzed for temporal changes. As earlier stated, the results of the survey are described in this chapter and depicted in the following figures; Figure 5.11 and 5.12, which is concerned with the Factor of Safety (FoS) and time depicting the effects of rainfall on slopes. The plotted graphs of the relationships demonstrate, linearity and shift in values that explain the response of the slope under different hydrological conditions.

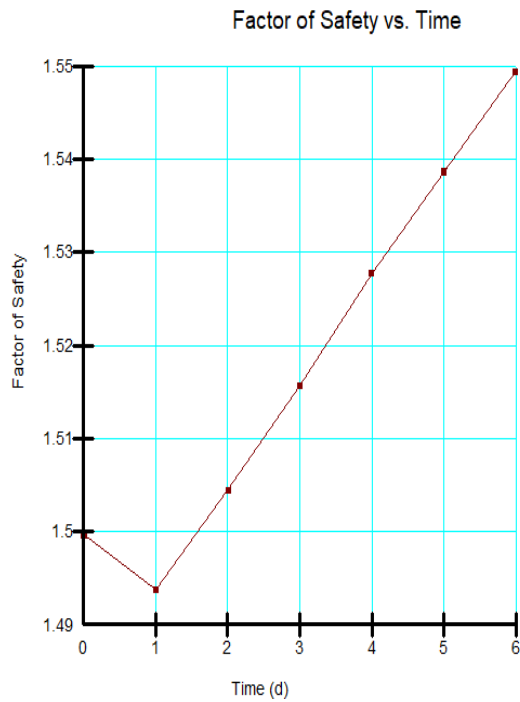


Figure 5.11 Safety factor vs Time without vegetation.

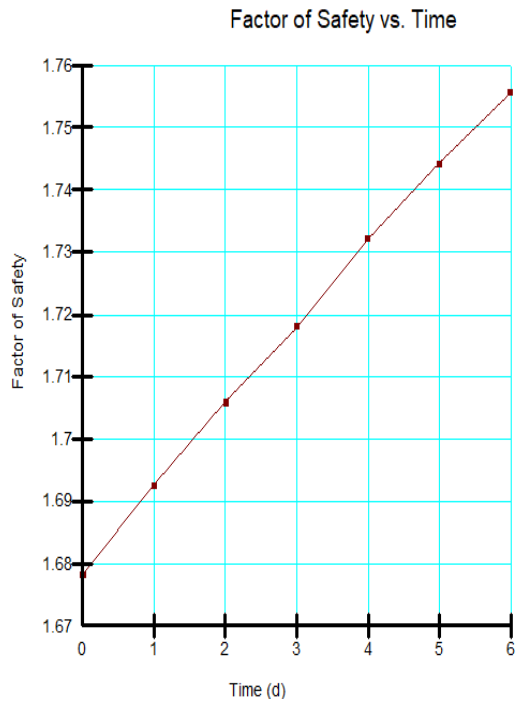


Figure 5.12 Safety factor vs Time with vegetation.

6 Discussion

By examining Figures 5.1 and 5.2, it is evident that, when using the SLOPE/W program, our examination of vegetated slopes yielded a factor of safety ranging from 1.599 to 1.745. The PLAXIS program provided a factor of safety varying from 1.523 to 1.644 for the same vegetated slopes. Based on our examination of slope stability using a factor of safety of 1.5 in geotechnical analysis, it can be concluded that both SLOPE/W and PLAXIS show vegetated slopes with a factor of safety greater than the suggested value of 1.5. Consequently, both programs ensure the safety of the vegetated slopes. The SLOPE/W method yields a greater factor of safety values for the circular failure model than the PLAXIS 2D software does. There are several drawbacks to using limit equilibrium methods to calculate forces, particularly at the crest and toe of a slope where significant concentrations of localized stress are often observed (Aryal, 2008). According to research using different load applications and groundwater changes, the Morgenstern-Price method based on limit equilibrium may have a greater factor of safety (5–15%) when compared to simulations based on finite elements, such as PLAXIS (Aryal, 2006). Our study's findings indicate that SLOPE/W provides a factor of safety that is five to six percent higher than PLAXIS. Comparing this to the range reported by Aryal (2006), the range is acceptable.

When just mechanical reinforcement is taken into account, the presence of roots leads to a maximum increase of 9% in FS. The mechanical impact of roots occurs inside the rooting zone, which is the region of soil penetrated by roots. In this zone, the root-permeated material acts as a composite material, where the stresses are divided between the solid skeleton and the root network. Given that the greatest depth of roots was 2 m, it can be shown that the critical shear surface was often located below the depth at which the roots were present. This explains why the increase in factor of safety (FS) was insignificant when only considering the mechanical reinforcement provided by more root cohesion.

Both software's failure surfaces pass through the root zone. The finite element study of non-reinforced hillslopes revealed that the failure mechanism is characterized by a shallow planar failure. This failure mechanism may be prevented by consistently reinforcing a slope using the roots of plants. As the level of root cohesion and the depth of the root zone grow, the critical slip surface moves farther down below the surface of the ground (see Figures 5.6–5.7).

The analysis of slope with different inclinations (see Chapter 5.2) indicated that the inclination angle had the most significant influence on the variability of the factor of safety. Additional cohesion is considered the second-most important aspect affecting the safety factor. Combining these two elements is crucial in causing shallow slope collapses and has a considerable impact on slope stability. After examining the rooting depth and additional root cohesion of various vegetation species in Tables 5.2 and 5.3, it becomes apparent that having a deeper root system with lower additional

cohesion is more crucial than having a deeper root system with higher additional cohesion in some cases.

The purpose of the hydro-mechanical analysis, which was performed using GeoStudio, was to evaluate how slopes behave when different amounts of precipitation occur over time, with and without vegetation. Our main objective was to comprehend the dynamic changes in water pressure and safety factors, which are important indicators of slope stability. The graph showing the relationship between water pressure and time without vegetation (see Figure 5.9) showed a consistent pattern of water pressure decreasing throughout the simulation period, with a peak at day 1. The decrease in pressure, which begins at -15 kPa and ends at -17 kPa, indicates a slow release of water within the slope. The trend we observed suggests that drainage processes are happening in the soil. These processes help to gradually remove excess water, which in turn reduces the pressure in the pores. This phenomenon is in line with well-known principles of slope hydrology. Excess pore water pressure can be a major concern for slope stability, and it is crucial to eliminate it to prevent potential failure mechanisms. On the other hand, the graph that shows the safety factor over time showed a different pattern. It showed that the safety factor increased consistently throughout the simulation. The increase in safety factor indicates that the slope's stability conditions have been getting better as time goes on. If the water pressure decreases, the effective stress in the soil increases, which makes the slope more stable. However, it is important to mention that on day 1, there was a temporary decrease in the safety factor. The anomaly may be caused by various factors, such as changes in precipitation intensity.

The precipitation decreased significantly from 2.4 mm on day 0 to 0.5 mm on day 1, see Table 4.5, indicating a significant reduction in the amount of water entering the slope system. The abrupt drop in rainfall probably caused a decrease in the rate at which water was being drained from the soil. This led to a temporary buildup of water and a subsequent rise in water pressure on the first day. The reason for this accumulation might be because of the leftover effects from the rain that happened the day before. The soil had not completely dried out by the start of the simulation on day 1. The reason why the safety factor decreased on day 1 is because the water pressure temporarily increased and the effective stress within the slope decreased. When the water pressure increases, it puts more pressure on the soil particles, which makes them less able to resist sliding or deformation. As a result, the safety factor temporarily decreases because the slope becomes more prone to failure in these conditions.

The presence of vegetation has led to decreased water pressure values when compared to situations where vegetation is absent (see Figures 5.9 and 5.10). The decrease in water pressure can be explained by the vegetation's ability to improve soil structure and encourage water to seep through, which helps to decrease surface runoff and lessen the amount of water on the slope. The peak in water pressure that was observed

on day 1, even though there was vegetation, indicates that the drainage processes took longer to respond due to the leftover effects of previous rainfall events. Nevertheless, it is worth noting that the size of this peak is significantly smaller when compared to situations where there is no vegetation. This emphasizes how vegetation plays a crucial role in regulating changes in water pressure and enhancing the stability of slopes. Further, the aspect of the safety factor by using vegetation has been rising from the initial stage of the simulation. As in the case with no vegetation, the safety factor does not depress even on the first day when evaluated; refer to Figs. 5. 11 and 5. 12. Next is the ability to recover its strength quickly, this can be explained by the fact that vegetation helps to reinforce the slope area. Plantation plays an important role in improving the strength of the soil, controlling erosion, and the stability of the slope to outside force. In one way, vegetation makes the soil stronger and helps to interlock the root onto the slope hence reducing chances of the slopes to fall. This helps to retain higher safety factors incorporating the rainfall amount or lack of it.

Vegetation cover has demonstrated some beneficial effects towards the mechanical and the hydrological aspects of the slope stability. Thus, providing a more elaborate form of managing slopes in a sustainable manner. However, in the procedure of applying vegetation to enhance the capability of the slope to resist failure, several factors should be taken into consideration including age and type of vegetation. First of all, the mechanical benefits of vegetation are: strengthening of the roots and fastening of the ground. This is because in mature trees the root biomass is greatly developed and as a result they offer better mechanical support. Therefore it is necessary to look at the age and the growth stage of the vegetation in relation to the relieve factor when assessing the mitigation of slope instability. Thus, the state of mechanical reinforcement shall be evaluated with reference to the concentration and the species characteristics of vegetation. Due to the angle that the slope is, the support offered by vegetation is likely to be less as compared to the vegetative cover that has deeper root systems Therefore, in reference to vegetation type, the right type of vegetation must be chosen and well maintained in order to guarantee slope stability. From the point of view of the hydrology, vegetation has the function of lowering water pressure and of soil permeability. However, the successful process of regulation of hydrological processes depends on different aspects such as the canopy interception, evapotranspiration rates, and soil permeable factor. The young vegetation often has less tree crowning area and transpiration index, this implies it can't decrease the water thrust created by rainfall as effectively. Besides, vegetation formation is characterized by a transition phase where optimization of hydrological functions might not have been attained. Thus, the temporal dimension should be taken into consideration in slope management because, despite the positive influence of vegetation in minoring hydrological risks of slope failure, the time factor plays a significant role in the overall hydrological efficiency in management strategies for slopes. However, one might find it rather challenging when it comes to employing vegetation for the enhancement of the stability of slopes. Irrigation, trimming or removal of species that encroach on the slopes, this is an additional cost and work

input to be incurred or undertaken in the management of slopes. Also, it can be concluded that the application of vegetation-based solutions requires regular assessment and management in order to provide for its long-term stability. This entails issues such as disease, pest attacks, and deterioration of vegetation. In some cases due to the high population density in the areas or the lack of space, layout vegetation to create slope stability might prove difficult due to other uses of the land. In other words, vegetation may contribute to positive changes in slope stability from a Mechanical perspective and Hydrological perspective. Nonetheless, more information is necessary in regards to the characteristics, age, as well as obstacles linked to vegetation for application to take place.

Risk is inevitably part of any geotechnical study and our work, exploring the factors affecting slope stability under vegetation, is not an exception. The three sources of uncertainty in our work are as follows. Such factors are limitations of the data that are available in our study and assumptions that were made while undertaking the analysis. The variation of root depth concerning the set vegetation is another source of error. Due to a lack of sufficient information on the root depth of the vegetation that we examined in this research, we adopted random root depth. Vegetation roots add variation to the mechanical structure where their effect is to alter slope stability as evaluated by us. Also, there are a number of questions concerning the definition of the vegetation parameters, such as how far plant water deficit is valid or the normalizing density of the roots employed in the hydro mechanic evaluation. In fact, this research mainly revolved around the downy birch vegetation type; however, there were some issues related to data collection and availability of complete data specifically of downy birch vegetation type. Because of this, we relied on information from various sources of vegetation resulting into uncertainty as to how accurate and relevant these parameters are to our study. Another cause which contributes to the variability of the hydraulic property is dealing with it with respect to the rooted soils. An association between vegetation and the hydraulic conductivity has a complex relationship, which is largely not realized. It should be noted that for the sake of simplifying as well as for the incapability of acquiring the hydraulic properties data for rooted soils, it was assumed that the hydraulic properties of rooted soil are similar to that of regular soil. These are factors in formulating Implications for research and practice, and, in understanding these limitations, these uncertainties should be acknowledged in order to grasp the findings of this study. What our analysis allows us to understand is how slopes remain stable when there is different vegetation and rainfall. However, all is not well and a look at the following uncertainties is enough to paint a picture that there is still more work to be done and areas to improve in. Future work can involve refining matters concerning the description of vegetation attributes, improving the simulations of the root-soil processes, as well as expanding the understanding of how vegetation impacts hydraulic conductance. In conclusion, it is worthy to note while uncertainty poses challenges to the current analysis, it also shows opportunities for the investigation's advancement. For more effective application of assessments of stability of slopes with vegetation cover, it is necessary to investigate methods that

allow reducing the indeterminacy and applying stronger data. This will enable us to come up with the right decision concerning geotechnical engineering practices.

7 Conclusion and recommendations

This thesis establishes the importance of vegetation in the improvement of slope stability as evidenced by the findings in the research part. According to the review of mechanical and hydrological impacts of vegetation, it is concluded that vegetation plays an ability to significantly enhance the safety factor of slopes and, thus, minimize the possibilities of landslides and erosion. It was shown by the numerical models that were developed using GeoStudio and PLAXIS 2D that vegetation of different types plays a very crucial role by providing root reinforcement and by helping in restructuring the soil mass of the slope. These models proved that vegetation, especially 'large' and well-developed trees, helps improve already compacted soils bearing pressure and capacity for resisting against water pressure by improving the slopes' cohesion and strength.

Our findings underline the dual benefits of vegetation: mechanical reinforcement due to the roots and hydrological benefits due to better ability of the soil to infiltrate water and to resist water pressure. Apparently, vegetation enhances slope stability and therefore the inclusion of vegetation in the management of slopes is a sustainable method of preventing slope failures.

Based on the findings of this study, we recommend the following actions for future research and practical implementation:

Species Selection and Vegetation Management: Choose and provide vegetation species that provide sound mechanical support and good water regulating properties or functions. The degree of the tree's ability to influence soil stability thus indicates that mature trees with extensive root systems should be given priority over young plant growth.

Site-Specific Vegetation Plans: Formulate site-specific vegetation plans based on the soil characteristics available in the site, the slope geometry of the land and the climatic conditions of the area. Thus, such an approach will help to select the suitable type of vegetation in relation to the certain environmental conditions and will help to provide for the highest level of slope stability.

Long-Term Monitoring: Recommend the adoption of long-term monitoring of vegetated slopes to determine the continued impact of vegetation on slope stability. The information, collected with this purpose, will advance the knowledge about the stability of the slopes covered with various types of vegetation and their spatial arrangement.

Integration with Engineering Solutions: Pair with vegetative measures traditional engineering control structures like retaining wall and the system of drain. This integrated approach has the creativity of using the advantages of both natural and engineered solutions.

Further Research on Root Cohesion: Carry out a survey to quantify the added cohesiveness of different root systems as well as the specialty of vegetative parts. New such studies will improve the accuracy of current slope stability models so as improve the practices of vegetation management.

Through the adoption of these guidelines, practitioners will have an effective method of converting vegetation into a natural way of stabilizing and controlling slopes and make contribution towards safer and more sustainable slope management.

REFERENCES

- ABAQUS. (2004). In *ABAQUS Theory Manual Version 6.5*.
- Abdellatif, M., & Valdenebro, E. (2016). Storm-water Management: Evapo-transpiration & Cooling with Water.
https://www.researchgate.net/publication/323959785_Storm-water_Management_Evapo-transpiration_Cooling_with_Water
- Ali, N., Farshchi, I., Mu'azu, M., & Rees, S. W. (2012). Soil-root interaction and effects on slope stability analysis. *Electronic Journal of Geotechnical Engineering*, 17, 319-328.
- Andreasson, M. (2020). *Göteborgs kommun, Helgered 32:1. Kompletterande geoteknisk undersökning inför detaljplan*.
- Aryal, K. (2008). Differences between LE and FE methods used in slope stability evaluations. 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG),
- Aryal, K. P. (2006). Slope stability evaluations by limit equilibrium and finite element methods.
- Axelsson, K., & Mattson, H. (2021). *Geoteknik. Författarna och studentlitteratur 2016*.
- The birch avenue*. (2023). <https://www.botan.uu.se/learning/learning-resources-for-schools/heritage-trees-in-uppsala/the-birch-avenue/>
- Bréda, N. J. (2003). Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *Journal of experimental botany*, 54(392), 2403-2417.
- Cai, J., Liu, Y., Lei, T., & Pereira, L. S. (2007). Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages. *Agricultural and Forest Meteorology*, 145(1-2), 22-35.
- Capobianco, V., Robinson, K., Kalsnes, B., Ekeheien, C., & Høydal, Ø. (2021). Hydro-mechanical effects of several riparian vegetation combinations on the streambank stability—A benchmark case in southeastern Norway. *Sustainability*, 13(7), 4046.
- Cheng, Y. M., Lansivaara, T., & Wei, W. (2007). Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods. *Computers and geotechnics*, 34(3), 137-150.
- Chok, Y., Jaksa, M., Kaggwa, W., & Griffiths, D. (2015). Assessing the influence of root reinforcement on slope stability by finite elements. *International Journal of Geo-Engineering*, 6, 1-13.
- Chowdhury, R., Bhattacharya, G., & Flentje, P. (2009). *Geotechnical Slope Analysis*. Taylor & Francis Group.
- Coppin, N. J., & Richards, I. G. (1990). *Use of vegetation in civil engineering*. Ciria Butterworths.

- Emadi-Tafti, M., Ataie-Ashtiani, B., & Hosseini, S. M. (2021). Integrated impacts of vegetation and soil type on slope stability: A case study of Kheyroud Forest, Iran. *Ecological Modelling*, 446, 109498.
- Giadrossich, F., Schwarz, M., Cohen, D., Cislighi, A., Vergani, C., Hubble, T., Phillips, C., & Stokes, A. (2017). *Methods to measure the mechanical behaviour of tree roots: A review*.
- Giadrossich, F., Schwarz, M., Cohen, D., Cislighi, A., Vergani, C., Hubble, T., Phillips, C., & Stokes, A. (2017). Methods to measure the mechanical behaviour of tree roots: A review. *Ecological Engineering*, 109, 256-271.
- Gray, D. H. (1974). Reinforcement and stabilization of soil by vegetation. *Journal of the Geotechnical Engineering Division*, 100(6), 695-699.
- Gray, D. H., & Sotir, R. B. (1996). *Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control*. John Wiley & Sons.
- Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. *Landslides*, 11, 167-194.
- Kamien, D. J. (1997). Engineering and design: introduction to probability and reliability methods for use in geotechnical engineering. *Corps of Engineers Washington DC*.
- Kim, J. H., Fourcaud, T., Jourdan, C., Maeght, J. L., Mao, Z., Metayer, J., Meylan, L., Pierret, A., Rapidel, B., & Rouspard, O. (2017). Vegetation as a driver of temporal variations in slope stability: The impact of hydrological processes. *Geophysical research letters*, 44(10), 4897-4907.
- Kokutse, N. K., Temgoua, A. G. T., & Kavazović, Z. (2016). Slope stability and vegetation: Conceptual and numerical investigation of mechanical effects. *Ecological Engineering*, 86, 146-153.
- Konitzer, K. (2021). Riskområden för ras, skred, erosion och översvämning.
- Krahn, J. (2003). The 2001 RM Hardy Lecture: The limits of limit equilibrium analyses. *Canadian geotechnical journal*, 40(3), 643-660.
- Lu, N., Şener-Kaya, B., Wayllace, A., & Godt, J. (2012). *Analysis of rainfall-induced slope instability using a field of local factor of safety*.
- Lu, N., Şener-Kaya, B., Wayllace, A., & Godt, J. W. (2012). Analysis of rainfall-induced slope instability using a field of local factor of safety. *Water Resources Research*, 48(9).
- Mauer, O., & Palátová, E. (2003). The role of root system in silver birch (*Betula pendula* Roth) dieback in the air-polluted area of Krušné hory Mts. *J. For. Sci*, 49(5), 191-199.
- Meijer, G., Bengough, A., Knappett, J., Loades, K., & Nicoll, B. (2016). New in situ techniques for measuring the properties of root-reinforced soil—laboratory evaluation. *Géotechnique*, 66(1), 27-40.
- Meijer, G. J., Bengough, A. G., Knappett, J. A., Loades, K. W., & Nicoll, B. C. (2016). *New in situ techniques for measuring the properties of root-reinforced soil – laboratory evaluation*.

- Mulyono, A., Subardja, A., Ekasari, I., Lailati, M., Sudirja, R., & Ningrum, W. (2018). The hydromechanics of vegetation for slope stabilization. IOP Conference Series: Earth and Environmental Science,
- Ning, S., Chen, C., Zhou, B., & Wang, Q. (2019). Evaluation of normalized root length density distribution models. *Field crops research*, 242, 107604.
- Noroozi, A. G., & Hajiannia, A. (2015). The effect of vegetation on slope instability as predicted by the finite element method. *EJGE*, 20(28).
- Pollen-Bankhead, N., & Simon, A. (2009). Enhanced application of root-reinforcement algorithms for bank-stability modeling. *Earth Surface Processes and Landforms*, 34(4), 471-480.
- Rajeev, P., Chan, D., & Kodikara, J. (2012). Ground-atmosphere interaction modelling for long-term prediction of soil moisture and temperature. *Canadian geotechnical journal*, 49(9), 1059-1073.
- RST. (n.d.). *Zonkartan*. Riksförbundet Svensk Trädgård. <https://svensktradgard.se/tradgardsrad/zonkartan/>
- Salix caprea*, SE: Sälgl, vanlig sälgl, DE: Sal-Weide, NL: Boswilg, UK: Goat Willow.). http://www.flowersinsweden.com/Salixcaprea_page.htm
- Steinacher, R., Medicus, G., Fellin, W., & Zangerl, C. (2009). THE INFLUENCE OF DEFORESTATION ON SLOPE (IN-) STABILITY. *Austrian journal of earth sciences*, 102(2).
- Tornborg, J., Karlsson, M., Kullingsjö, A., & Karstunen, M. (2021). *Modelling the construction and long-term response of Göta Tunnel*.
- Waldron, L. (1977). The shear resistance of root-permeated homogeneous and stratified soil. *Soil Science Society of America Journal*, 41(5), 843-849.
- Wang, T., Tigerstedt, P., & Viherä-Aarnio, A. (1995). Photosynthesis and canopy characteristics in genetically defined families of silver birch (*Betula pendula*). *Tree Physiology*, 15(10), 665-671.
- Wani, K. S., & Mir, B. (2022). Application of bio-engineering for marginal soil improvement: an eco-friendly ground improvement technique. *Indian Geotechnical Journal*, 52(5), 1097-1115.
- WU TH, M. W., & SWANSTON, D. (1979). Strength of tree roots and landslides on Prince of Wales Island. *Alaska*, 16(1), 19-33.