A Comparative Study on Slope Stability Analysis by Limit Equilibrium and Finite Element Methods

Thesis

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By

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Pantnagar **_(Arju Rawat)_**
October, 2022 *Authoress*

CERTIFICATE–I

This is to certify that the thesis entitled **"A Comparative Study on Slope stability Analysis by Limit Equilibrium and Finite Element Methods"** submitted in partial fulfillment of the requirements for the degree of **Master of Technology in Civil Engineering** with major in **Soil Mechanics and Foundation Engineering** of the College of Post Graduate Studies, G. B. Pant University of Agriculture & Technology, Pantnagar, is a record of bona fide research carried out by **Ms. Arju Rawat,** Id. No. **56668** under my supervision and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been acknowledged.

Pantnagar
October, 2022

(Ajit Kumar)
Chairman
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CERTIFICATE–II

We, the undersigned, members of Advisory Committee of **Ms. Arju Rawat** Id. No. **56668,** a candidate for the degree of **Master of Technology in Civil Engineering** with major in **Soil Mechanics and Foundation Engineering** agree that the thesis entitled **"A Comparative Study on Slope Stability Analysis by Limit Equilibrium and Finite Element Methods"** may be submitted in partial fulfillment of the requirements for the degree.

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Member

(Sunil Kumar)
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LIST OF ABBREVIATIONS AND SYMBOLS

C	Cohesion
CSS	Critical shear surface
E	Young's modulus of Elasticity
FDM	Finite Difference Method
FEM	Finite Element Method
FOS	Factor of safety
H	Height of slope
JSM	Janbu's Simplified Method
LEM	Limit Equilibrium method
M-PM	Morgenstern-Price's Method
μ	Poisson's Ratio
γ	Unit weight
ϕ	Angle of internal friction

Introduction

Chapter 1 INTRODUCTION

1.1 General

A slope is an inclined surface of a mass, such as earth, that may be supported or unsupported. Both natural and artificial slopes exist. These can be cuttings or embankments that are above or below ground. In order to reduce the chances of slope collapse and landslides, an analysis of slope stability is done. Many people have died and been destroyed as a result of both man-made and natural slope failure (landslides). In order to ensure that the specified slopes remain stable, engineers must provide careful thought before any work and then development is carried out. Slope failure can be identified through accurate slope stability measurement and slope analysis. Engineering solutions to slope instability issues necessitate a thorough understanding of analytical techniques, investigation equipment and stabilization techniques. The core objective of slope stability evaluations is to aid in safe and efficient excavation, embankment and earth dam design.

Any slope created by nature or by man must undergo a stability study to identify the failure surface with the minimum factor of safety. To find the minimum factor of safety for the stated slope, it is important to identify the critical failure surface. Various search and optimization techniques have been employed in the past but they all share the same drawback, which is the issue with doing computations by hand. The effect of soil parametric values on the failure surface and the factor of safety of the slope will be investigated throughout this study. By comparing the factor of safety from various slip surfaces, the critical failure surface for a given slope can be found. The surface of critical failure is the slip surface which has the smallest factor of safety.

1.2 Common Causes of Slope Failure

Each slope has unique geology, soil composition, vegetation and a variety of other characteristics. Therefore, any slope rehabilitation method must be specifically tailored to the slope on which it is to be implemented and the factors contributing to that slope’s instability if it is to effectively reduce the threat of landslides and mudslides. Here are a few typical reasons for slope failure.

1.2.1 Steepness of the slope

It is well known that a slope gets more unstable the steeper it is. The natural inclination of steep slopes is to shift some of their materials downward until the natural angle of repose is established. The stability of a slope will be affected by any type of slope modification, including natural processes like a stream cutting across the banks of a river or human actions like workmen excavating a portion of the slope's base to build roadways.

1.2.2 Water and drainage

Compared to air, water is much heavier. The soil on slopes gets significantly heavier during periods of heavy rain because the soil becomes saturated and water replaces the air between the soil grains and when the earth is being held back by a retaining wall at its base, this becomes an issue. In particular, if the weight of the earth behind the retaining wall exceeds the capability of retaining wall structural, the retaining wall will buckle and fail, releasing the earth behind it in a disastrous deluge. Similarly, water decreases grain-to-grain contact which lowers cohesiveness. Water saturation already raises the likelihood of downslope mass movement which is in addition to changes in the groundwater fluid pressure in slope rocks during the rainy season (Iravanian and Shlash, 2020).

1.2.3 Soil composition

When it comes to preventing slope collapse, the soil composition of the slope is a crucial factor to take into account. When it comes to frictional erosion resistance and grain cohesion, different types of soil will exhibit quite varied properties. For instance, sand or loose soil has minimal cohesiveness and will disintegrate when submerged in water. On the other hand, soils with a lot of clay will typically expand when wet and will make them heavier and gradually tends to move (Aaron & Mcdougall, 2019).

1.2.4 Vegetation

The strength of soil is also proportionally correlated with the quantity and variety of vegetation present. The soil is held in place and becomes more erosion-resistant by the roots of vegetation. The ability of plants to hold the soil in place increases with size; the larger the vegetation, the more widely dispersed its roots.

Additionally, more vegetation means that the slope will probably be more stable. This is the main cause of slope failures during the rainy season that have had their vegetation burned off or destroyed by bushfires.

1.2.5 Joint and Fractures

Natural cracks in the rocks forming a slope are known as joints and fractures. These are brought on by the erosion of the rocks that are above them or the natural expansion of rocks brought on by cooling. The cohesiveness between the rocks that make up the slope is significantly decreased as a result of these cracks, raising the risk of a landslide on the slope (Aaron and Mcdougall, 2019).

1.2.6 Sudden Shocks

The sudden mass movement of soil on slopes may also be caused by sudden shocks like earthquakes, storms, volcanic eruptions, the passage of heavy vehicles, blasting and others (Iravanian and Shlash, 2020).

1.3 Types of Slope Failure

1.3.1 Translation failure

Translation failure happens when slopes are infinite; in this situation, the failure surface is parallel to the slope surface. The week topsoil will form a parallel slip surface when it fails if the soil along the slope has similar properties up to a certain depth and the soil underneath this layer is a strong or hard stratum. Slopes made of layered materials or naturally occurring slope formations can exhibit this type of failure.

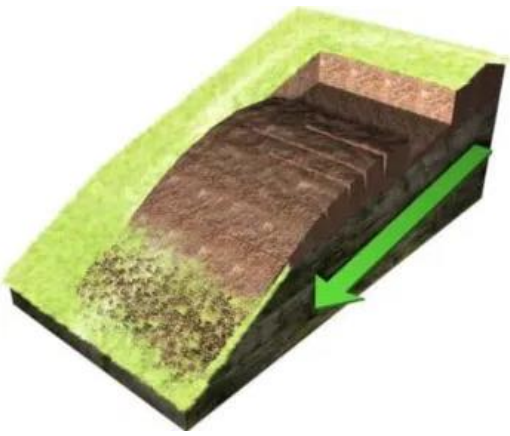

Fig. 1.1 Translation failure (Source: https://theconstructor.org)

1.3.2 Rotational failure

When a rotational failure occurs, the slip surface takes on a curved shape as a result of rotation along it. Failure surface slides downward and outward. When the soil is homogeneous, it has a circular shape, however, when the soil is non-homogeneous, it has a non-circular shape.

Rotational failure may occur in three different types:

1. Face failure or slope failure: This type of rupture occurs when the slope angle is very steep and the soil near the toe has a high resistance. The surface arc meets the slope above the slope toe.
2. Toe failure: In this type of failure, the rapture plane passes through toe of slope.
3. Base failure: It happens when the failure plane passes through the base of the slope and there is a weak soil stratum under the toe.

Fig. 1.2 Types of Rotational failures (Source: https://theconstructor.org)

1.3.3 Wedge failure

A failure plane that is inclined is created by wedge failure, sometimes referred to as block failure or plane failure. This kind of failure happens when a slope has cracks, joints, weak soil layers or is built of two different materials. It is more akin to translational failure, however wedge failure can happen on both infinite and finite slopes, whereas translational failure only happens in the case of infinite slopes.

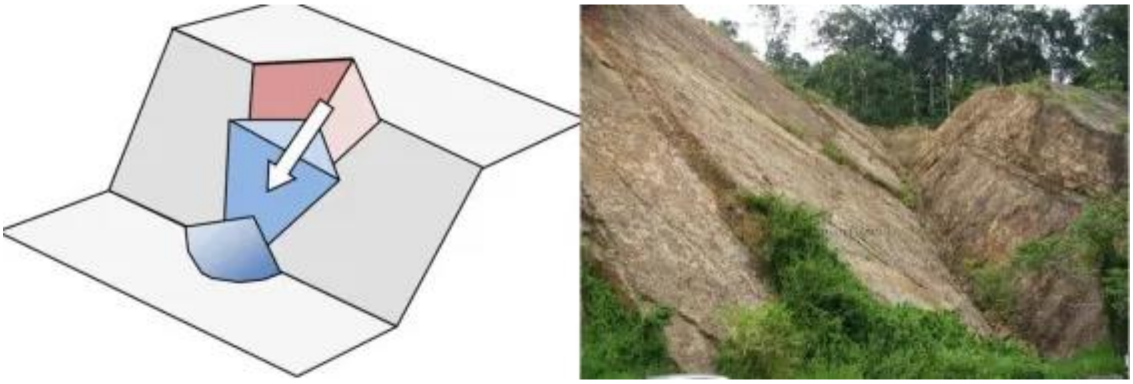

Fig. 1.3 Wedge failure (Source: https://theconstructor.org)

1.3.4 Compound failure

This type of failure is a combination of a translational slide and a rotational slide. The slip surface in this instance is flat in the middle, similar to a translational failure and curved at both ends, similar to a rotational slip surface. When there is a hard soil layer at a significant depth from toe, the slip surface becomes flat.

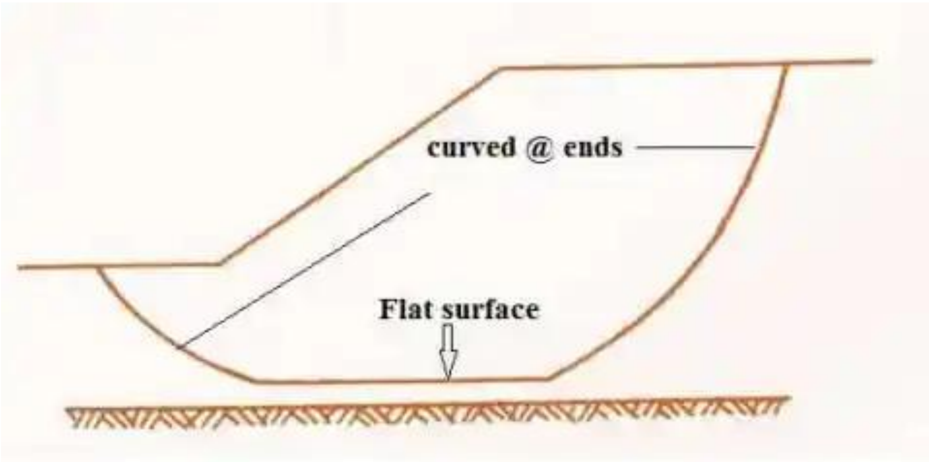

Fig. 1.4 Compound failure (Source: https://theconstructor.org)

1.4 Factors Affecting Slope Stability

1.4.1 Slope geometry

The geometric design of the slope is based on three main parameters: height, overall slope angle and surface area of failure. With an increase in slope height, the slope's stability rapidly declines. As the overall slope angle increases, the risk of failure increases. The instability is also strongly influenced by the curvature of the slope. In slope design, convex slope sections should be avoided. With the higher and steeper slope, there is less stability.

1.4.2 Geological structure

The major geological structure of any structure (building, retaining wall, railroad, highways, *etc*.) that affects the stability of slopes is as follows**:**

1. Dip quantity and direction.
2. Zones of shear intra-formational
3. Joints and interruptions
4. Faults

If strata dip in the excavations, instability of the slope increases. Faults give a very low strength lateral or rear release plane therefore the strata are highly disturbed. The stability will be severely hindered if there is a clay or soil band between two rock bands. Joints and bedding planes weaken the surface as well. The strength of the shear along the surface, its orientation with respect to the slope and the impact of water pressure on the surface all play a role in the slope stability.

1.4.3 Lithology

The strength of the rock mass affected by faulting, weathering, discontinuities, previous operations and folding is determined by the rock materials that form a pit slope. Pit slopes with alluvium or weathered rocks on the surface have poor shear strengths and the strength will be further diminished if water flows through them. It is necessary for these slopes to be flatter.

1.4.4 Ground water

The following changes are caused by the presence of ground water:

a) It modifies the cohesiveness and frictional characteristics.

b) It decreases normal stress.

It has a very negative effect on the stability of the slopes and may result in increased thrust or even destructive forces. Water in joints can have both physical and chemical impacts that alter the friction and cohesiveness of the surface of discontinuity. Physical influence increases the frictional resistance which lowers the shearing resistance along a failure plane. Therefore, the normal stress on the joints is reduced.

1.4.5 Dynamic forces

The vibration brought on by blasting increases shear stress which maximizes the material's dynamic acceleration and leads to slope plane instability. This accelerates ground motion which causes rock fracturing. Bench instability is the main cause of the effects of poor blasting techniques. These factors, such as bench face angle and blasting vibrations also affect rock mass failure because of back break and blast damage. Many soft blasting techniques have been used to lessen these effects on minor slopes.

1.4.6 Angle of internal friction

It is the angle between the resulting force and the normal force when the shearing stress causes the failure to occur. Angle of internal friction is a measurement of any material which can tolerate a certain amount of shear stress. The grain size, quartz concentration and roundness of the soil grains all have an impact on this. A large angle of internal friction is produced by reduced roundness and a bigger median particle size.

1.4.7 Cohesion

It is the characteristic property of a rock or soil that measures how effectively it resists being deformed or broken by forces like gravity. Negative pore pressure, capillary pressure and electrostatic forces for over-associated clay are additional factors that contribute to the loading process. Less stable slopes are those with weaker cohesion.

1.5 Factor of Safety

FOS is the ratio of the resisting force to the driving force. In the case of a stable slope with no structures on it, the ratio of the shear strength to the force required to maintain stability. Any slope can collapse if the sliding block shear resistance is insufficient to withstand the shear forces. The value by which the stability state of the slopes is checked is safety action.

The factor of safety recommendations for various values of slopes are shown in Table 1.1.

Table 1.1 Recommended value of factor of safety for slopes (Iravanian and Shlash, 2020)

Value of factor of safety	Slope details
FOS < 1	Unsafe
FOS = 1 - 1.25	Quit satisfying
FOS = 1.25 - 1.4	Satisfying
FOS > 1.4	Acceptable for all slopes

There are several ways to calculate the factor of safety and typically each approach of analysis has its own formula for the FOS. However, the most widely used formula assume that the FOS is constant and can be separated into two types: Momentum equilibrium and force equilibrium.

1.6 Softwares Overview

For analyzing slope stability, there are various computer programs available. Both limit equilibrium analysis and the finite element approach are employed by these programs. SLOPE/W and PLAXIS 2D are two different geotechnical programs that will be employed in this study on slope stability analysis.

1.6.1 SLOPE/W

SLOPE/W is a smart programme that employs limit equilibrium to address slope stability issues. With the help of a wide range of soil models, it has the capacity to model different soil types, intricate stratigraphic patterns, slip surface geometry, and conditions with fluctuating pore water pressure. Input data for addressing problems might be either deterministic or probabilistic. The ordinary (Fellenius) approach, the Bishop's Simplified technique, the Spencer's method, the Janbu's method, the Morgenstern-Price's method, the generalized limit equilibrium method and finite element stress are the methods used by SLOPE/W to analyze stability issues. SLOPE/W performs probabilistic slope stability analysis to take variability and uncertainty in the input data for analysis into account. The Monte Carlo's Method is used in this analysis to statistically evaluate the probability that a slope would fail. Factor of safety for probability density and distribution functions is found by using the Monte Carlo's method. Varying material parameters like unit weight, cohesion and angle of internal friction facilitate sensitivity analysis in this method (Omari, 2012).

1.6.2 PLAXIS 2D

For many geotechnical applications, deformation and stability analysis are carried out using the two-dimensional finite element programme PLAXIS 2D. An axis-symmetric model or a plane strain model can both be used to simulate real-world scenarios. Based on a typical vertical cross-section of the current scenario, the program's user-friendly graphical user interface enables users to quickly produce a geometry model and finite element mesh. The user can construct a two-dimensional geometry model in the X-Y plane, consisting of points, lines and other components and describe the material properties and boundary conditions in order to utilize the PLAXIS 2D tool to perform a finite element analysis.

The phi/c reduction method is used by PLAXIS 2D to calculate the global factor of safety. The load advancement number of stages is used in this procedure. The incremental multiplier is used to specify the increment of the strength reduction of the first calculation step. The strength parameters are successively reduced automatically until all the additional steps have been performed. Similar reductions in interface strength also occur. A completely established failure mechanism should be produced by the last phase. The calculation is performed more than once with more additional steps if a failure mechanism has not yet fully developed (Omari, 2012).

1.7 Objectives of the Study

The main objectives of this study are as follows:

- To determine the effects of soil factors (cohesion, unit weight, angle of internal friction) on factor of safety and length of arc.
- To calculate the factor of safety by varying slope geometry (slope height and slope angle).

- To calculate the relationship of soil parameters and slope geometry with factor of safety and also find the relation between the failure arc's length and soil parameters.
- To employ two slope stability analysis software programs namely SLOPE/W and PLAXIS 2D and Swedish circle method will be used.
- Compare the outcomes of the various analyses of slope stability used in this study.

1.8 Importance of Study

When computers were not yet available, modeling soils with heterogeneous and variable characteristics that changed with ambient conditions were very challenging. However, with the rapid advancement of science and the advent of computers, using programming that relies on numerical methods has become simpler and helps to solve many geotechnical problems. The use of contemporary computers and software is essential to the completion of the design in its best form for the complicated installations of our day. The goal of this study, which focuses on theory and practice, is to close the gap between the two by promoting the use of the best modeling software packages currently in use by geotechnical engineers worldwide. This will help other engineers use the programs and understand how to handle the results that are produced by the software. It will be easier to avoid any geotechnical collapse both during design and construction if slope stability analysis is integrated into the plan.

1.9 Organization of Thesis

This thesis is made up of 5 chapters:

Chapter 1 presents general information on slope stability in addition to its factors, types and common cases of slope failure and software overview. The objectives and scope of the study are also described.

Chapter 2 includes a brief review of the various conventional methods of slope stability analysis. It also presents a comprehensive literature review on slope stability analysis based on numerical modelling.

Chapter 3 represents a detailed description of the methodology and discusses software programs and methods that were used in this study.

Chapter 4 presents the results of the study which include the effect of each soil strength parameter, cohesion, unit weight and angle of internal friction (c, γ and ϕ) both jointly and independently on the factor of safety. Figures were drawn to show the effects of the factors on the failure surface and factor of safety after all the models had been generated and analyzed.

Chapter 5 summarizes the thesis by providing conclusions drawn out from the study and discusses the further scope of the study.

Review of Literature

Chapter 2 REVIEW OF LITERATURE

2.1 General

In this part, a study will be presented on the stability of the slope analyzing methods and a brief review of the literature on slope stability analysis.

2.2 Limit Equilibrium Methods

The majority of methods for evaluating slope stability are based on limit equilibrium analysis. All limit equilibrium analyses have as their conclusion that the final findings may be expressed as a factor of safety. The factor of safety is defined as the ratio of the sum of driving forces or moments to the sum of resisting forces or moments that bring the slope into an equilibrium along a specific slip surface as given in equation 2.1.

$$FOS = \frac{\sum \mathrm{Re}\,sisting\,Forces, Moments}{\sum Driving Forces, Moments} \qquad (2.1)$$

The three primary limit equilibrium analysis techniques that are frequently employed in practice are the method of slices, the wedge method and the infinite slope approach. The software used for the limit equilibrium analysis for slope stability uses the method of slices which is one of the three approaches mentioned above (Omari, 2012).

2.2.1 Methods of slices

The normal stress acting at a place on a potential sliding surface should be impacted by the soil weight resting above that place. The equilibrium of each slice is calculated in terms of forces and moments by first dividing the potential sliding mass into many vertical slices. Consequently, it is possible to calculate the minimum factor of safety of slide mass. Now-a-days, the majority of computer programs that employ the limit equilibrium approach have search engines that help in determining the critical slide mass and provide the least factor of safety for that slide.

2.2.1 Ordinary method of slices

This technique is also known as the Swedish Method of Slices or the Fellenius Method. This approach ignores all interslice forces and unable to achieve force equilibrium for both the slide mass and the individual slices. It simply takes into account moment equilibrium and ignores force equilibrium. However, depending on the method of slices, this is one of the easiest operations (Punmia, B.C., 2017).

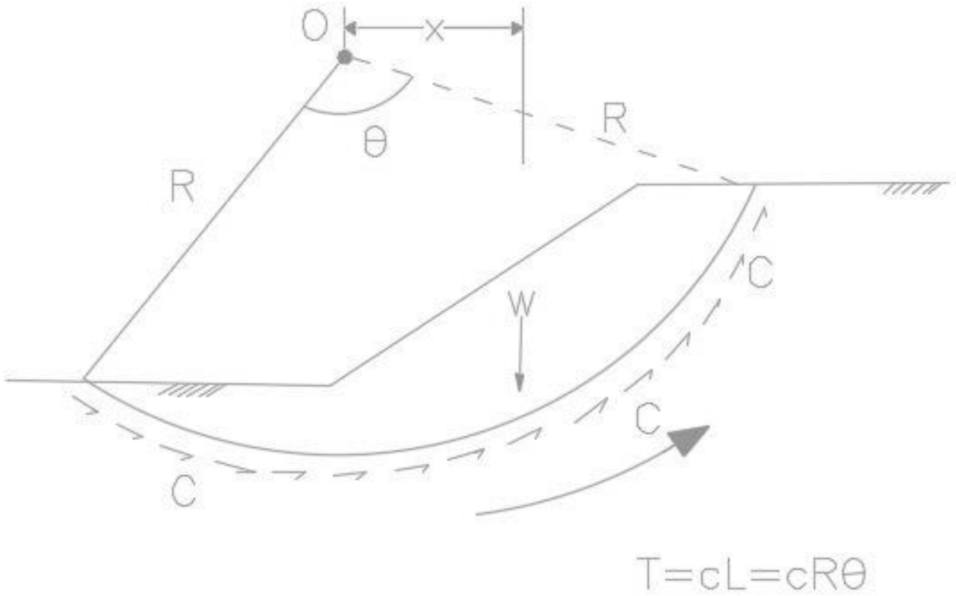

Fig. 2.1 Swedish slip circle

The algorithm for Swedish method is presented in the following equations

$$S = C + \sigma' \times \tan\phi \qquad (2.2)$$

$$\text{Frictional force} = \sigma' \times \tan\phi = N\tan\phi \qquad (2.3)$$

$$\text{Resisting force} = \sum(C \times L) + \sum(N\tan\phi) \qquad (2.4)$$

$$\text{Disturbing force} = \sum T \qquad (2.5)$$

$$\text{Resisting moment} = R\left\{\sum(C \times L) + \sum(N\tan\phi)\right\} \qquad (2.6)$$

$$\text{Disturbing moment} = \sum T \times R \qquad (2.7)$$

$$T = W\sin\alpha \qquad (2.8)$$

$$N = W\cos\alpha \qquad (2.9)$$

$$FOS = \frac{\sum(C \times L) + \sum(W\cos\alpha \times \tan\phi)}{W\sin\alpha} \qquad (2.10)$$

Where:

S = Shear stress

σ′ = Effective stress

L = Length of arc

W = Weight of the slice

α = Angle between the tangent of the centre of the base of the slice and the horizontal

2.2.1.2 Simplified Bishop's Method

Bishop's Method (1955) considered the vertical interslice shear forces are zero and the resulting interslice force is horizontal which was neglected in the Swedish circle method. It satisfies the moment equilibrium but not the force equilibrium. This approach takes into account the pore pressure acting on the slices as well as the normal inter-slice forces but ignores the shear inter-slice forces. This is one of the flexible approaches for figuring out the factor of safety of slope.

Let, E_L and E_R = Resulting horizontal forces on the left and right section respectively

X_L and X_R = Resulting vertical forces

W = Weight of slice

P = Total normal force acting at the base of the slice

l = Length of the arc

b = Horizontal width of the slice

θ = Angle of base of slice with horizontal

The equation for normal forces is given below:

$$P = \frac{W - \left(\frac{1}{F}\right)(cl - ul \times \tan\phi)\sin\theta}{ma} \tag{2.11}$$

$$ma = \cos\theta + \frac{(\sin\theta \times \tan\phi)}{F} \tag{2.12}$$

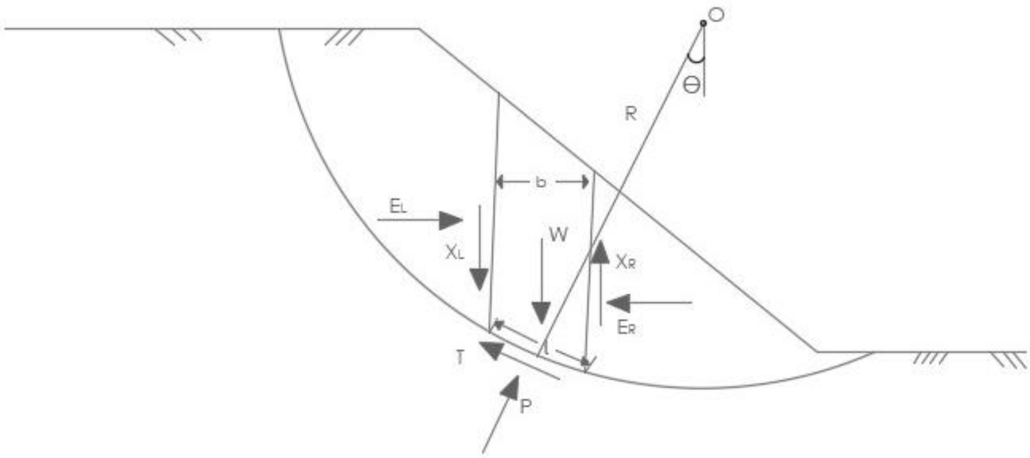

Fig. 2.2 Bishop's simplified method of slices

By taking moment around the centre of circle:

$$FOS = \frac{\sum \dfrac{cl \times \cos\theta + (w - ul \times \cos\theta)}{\cos\theta + \left(\sin\theta \times \dfrac{\tan\phi}{F}\right)}}{\sum W \sin\theta} \qquad (2.13)$$

2.2.1.3 Janbu's Simplified Method

Janbu's method suggested a method to calculate the factor of safety by using the horizontal forces equilibrium equation. Although interslice forces are not considered in the analysis, their impact is taken into account using a correction factor. Cohesion, angle of internal friction and failure surface form are all factors that affect the correction factor (Albataineh, N. 2006).

2.2.1.4 Morgenstern-Price's Method

Morgenstern-Price's Method (1965) took into account the moment equilibrium for each slice in circular and noncircular slip surfaces in addition to the normal and tangential equilibrium. In this approach, the interslice shear forces (X) and the interslice normal forces (E) are assumed to have the following simplified relationship:

$$X = \lambda \times f(x) \times E \qquad (2.14)$$

Where λ is an unknown scaling factor which is solved as one of the unknowns and f(x) is an assumed function that fluctuates continuously across the slip. The horizontal interslice force (E), the position of the interslice forces (line of thrust), the scaling factor (λ), the normal forces on the base of the slice (P) and the factor of safety (F) are the unknowns that need to be solved for in the Morgenstern-Price's technique. After calculating the above unknowns using the equilibrium equations, the vertical component of the interslice forces (X) is determined using the above equation.

2.2.1.5 Spencer's method

Spencer (1967) provided a method that works for any form of slip surface and it is a very accurate approach that satisfies the equilibrium of forces and moments. The fundamental assumption is that all of the slices have the same angle of the side forces. One of the unknowns in the explanation of the equilibrium equation is the precise angle of the forces between the slices. Spencer's method also includes the concept that the normal force (N) is applied at the mid of base of each slice. If a practically large number of slices are utilized, essentially all planning using Spencer's approach is completed by computer and a sufficiently big number of slices is easily performed. This postulation has little effect on the calculation values for unknowns.

2.3 Finite Element Method

Although the FEM was initially created to be employed in the study of stresses on structures of complex aircraft constructions, it has now been modified to be widely applied in a variety of engineering domains. The mass being considered is represented by an arrangement of elements connected at a finite number of nodal points using the finite element method which is a numerical procedure. It is not necessary to estimate the failure geometry when using the finite element method as opposed to the limit equilibrium approach. The stress-strain behaviour of the material under investigation can be used to determine the corresponding strains when you are aware of the stress circumstances. The outcome of the finite element analysis displays a mesh with a stress or deformation vector.

2.4 Potential Slope Failure Surface and Soil Parameters

The impact of soil parameters on the factor of safety has been the subject of numerous research, but their influence on the surface of the slip has rarely been considered. In one of the handful of studies (Lin and Cao, 2011), the relationship between those parameters and the possible slip surface and their effects on the failure surface is discussed. This work investigates the function of angle of internal friction, cohesion, unit weight and slope height (h) as follows:

$$\lambda = \frac{C}{(\gamma \times h \times \tan\phi)} \tag{2.15}$$

Additionally, a higher value of λ indicates a deeper failure slide and a lower value of λ brings the failure surface closer to the top of the soil (Lin and Cao, 2012).

2.5 Previous Study on Slope Stability Analysis

Ghosh and Biswas (2012) investigated the slope stability evolutions using limit equilibrium (LE) approaches are compared to those obtained using the GEOSLOPE program. The factor of safety (FOS) obtained from various conditions with simplified slope geometry and assumed input values is used to compare the LE based approaches. The Morgenstern-Price's technique (M-PM) is contrasted with the Bishop's simplified Method (BSM) and Janbu's simplified Method (JSM). In the circular shear surface (CSS) analysis, the simplified Janbu's (JSM) technique delivers the most conservative value of the FOS while the M-PM approach is better for normal conditions, according to the comparative research of the limit equilibrium methods. The Bishop's Simplified Method approach either over or underestimates the FOS.

Rabie (2014) compared the limit equilibrium method and finite element method in order to determine the factor of safety of slope under the influence of rainfall. The findings of a finite element analysis of a case study are compared with those of other well-known traditional methods, including the simplified Bishop's Method (1955), simplified Janbu's Method (1954) and Fellenius Method (1927). Additionally, the stability of the slope under rainfall and infiltration is examined. Particularly, saturated and unsaturated infiltrations are taken into consideration. The water table rises to the ground surface and water flows practically parallel to the slope's direction during periods of heavy rainfall or snowmelt. The influence of the change in shear strength, density, pore-water pressure and seepage force in soil slices on the slope stability is discussed. In the end, it is discovered that traditional limit equilibrium approaches are far more conservative than the finite element method. The shape or position of the failure surface, the slice side forces and their orientations do not need to be predetermined in order to assess the factor of safety for slope using the later technique. The study also highlights capabilities of FEM for slope stability analysis.

Tang and Jiang (2015) determined the effect of different soil nailing properties on the factor of safety of a slope. The GeoStudio programme was used in this study to assess the slope stability using a number of analysis methodologies. The Morgenstern-Price's method is used to examine soil nailing characteristics that affect slope stability including nail inclination, horizontal spacing between nails, diameter and length. The slope has the highest factor of safety when the soil nailing angle is around 15 degrees, the factor of safety reduces as the horizontal space between the soil nails grows, with a clear permissible space range of 2 metres or less and increases linearly as the diameter and length of the soil nails increase. But the factor of safety starts to slowly rise when the length of the soil nail reaches a point where it roughly corresponds to the height of slope. For field engineers these findings may serve as a design foundation.

Chakrabarti and Shivananda (2017) examined one of the most significant areas that needs to be appropriately addressed in the field of slope stability analysis. The major goal of this study was to calculate the soil slope factor and displacement in both the vertical and horizontal directions. Here, the Finite Element Method has been used to analyze the slope stability while using PLAXIS-2D. A number of sequence modeling were used in this investigation. Every model sequence was examined for stability analysis purposes taking into consideration different slope angles and varying slope heights. The findings of this investigation demonstrated that the factor of safety had varying values depending on the sequence and comparison with displacement. Angle of internal friction and cohesion values are held constant in this paper and findings for soil with changing slope but a consistent two-dimensional model is compared.

Jampani and Bhupathi (2017) investigated the best slope stabilisation method for each soil type by analysing a slope of 30 m height and 50° inclination with various soil types, including clay, silty clay and gravel. The stability of the slope is examined in relation to surcharge, water table and seismic stress. Stability analysis was carried out by using SLOPE/W software (Geostudio 2007). Berming, soil nailing and a combination of both stabilization methods were used in this investigation. The study analyses the impact of surcharge and water table in addition to berm angle, width, angle, length and spacing. With horizontal and vertical seismic coefficients of 0.18 and 0.09 respectively, seismic analysis is carried out using a pseudo-static technique. The study found that in comparison to water table and seismic load, the influence of surcharge on slope stability is minimal. Gravels were more severely affected by seismic activity and water table. Based on the results, it is also possible to draw the conclusion that soil nailing is a suitable slope stabilization technique for gravelly soil and that clayey soil benefits from a combination of soil nailing and berming.

Sarkar *et al.* (2018) discussed the stability analysis and recommended control measures of one active landslide along the National Highway (NH-58) Rishikesh Badrinath road near Pipalkoti. Samples were taken to investigate the physical and engineering aspects of the landslide site in order to determine its geotechnical characteristics. Different tests were conducted, including particle size analysis, moisture content, Atterberg limits, specific gravity, bulk density, dry density, void ratio, relative density and direct shear testing. Slope stability study was performed on two of the slide area portions. Using the GeoStudio software (SLOPE/W), factors of safety were computed under various moisture conditions, both with and without earthquake loading. To determine the effectiveness of the nails, stability analyses were performed using GeoStudio software and the SLOPE/W module limit equilibrium approach. After the slope material was reinforced with soil nails, analysis revealed a considerable improvement in the slope stability. This suggested that one option for reducing the ongoing landslide activity would be soil nailing.

Sharma *et al.* (2018) examined how the use of various types of soil backfill affects slope stability. This investigation looks at the effects of changing the soil parameters (cohesiveness and angle of internal friction) on steep slope embankments of various heights (6, 12, 18, 24 and 30 meters). Since very high and steep slope embankments were taken into consideration for the study, a tiered structure or berm was taken into consideration. Thus also into consideration the effect of berm width on slope stability as an additional parameter. The detected trends in the results were further matched with the literature that was at hand and with earlier research. The findings indicated that the factor of safety for the overall stability increased when soil factors like cohesiveness (c) and angle of internal friction (ϕ) increased. The analysis revealed that the soil type with the highest angle of internal friction and lowest cohesion was the most ideal, as increasing soil cohesion increased both the horizontal displacements and axial pressures acting on the geogrids while also increasing global stability.

The use of a tiered structure or the addition of a berm reduced forces and horizontal displacements on the lowest tier greatly while simultaneously increasing the factor of safety for overall stability, according to the results. It was decided that the available soil fill should only be used for short height embankments in absence of the recommended granular soil. Only recommended granular soils should be utilized for high embankments.

Desai and Joshi (2019) conducted the project work separated into two sections for the two conditions: dry season and wet season. Tests were carried out on the soil to establish its parameters, including cohesion, angle of internal friction and unit weight. Laboratory testing is used to determine additional input soil strength values. These parameters are employed in the analysis phase which was carried out using the Finite Element Method (FEM) with the PLAXIS software and the Limit Equilibrium Method (LE) with the GEOSTUDIO (SLOPE/W) programs. All LE methods estimate higher FOS than FE analysis in PLAXIS, with the exception of Janbu's methods. When compared to FE, the Janbu's approach may understate FOS by 10–12%. However, when compared to the FE analysis, the correction factor used in the Janbu's approach computes nearly identical FOS. External loads, complex geometry, more realistic normal stress distributions and the consequent FOS are best handled using FE methods. When compared to the FE analysis, the Morgenstern-Price's method for the pore pressure case may overestimate FOS by up to ±10%.

Alateya and Asr (2020) studied the effect of cavities on slope stability in earth dams under rapid drawdown conditions. The goal of investigation is to examine the effects of several elements including cavity diameter and location. Using PLAXIS 2D, a series of finite element simulations were carried out to create models and analyze slope stability in earth dams while taking the impact of subsoil cavities into account. Additionally, the combined effect of slope strength parameters and cavities on stability were examined and parametrically analyzed. The report showed that for all locations under study, the existence of cavities and an increase in the diameter of those holes significantly reduced the stability of the upstream face in a horizontal direction; however, this effect was less pronounced on the downstream side. The findings also demonstrated that the stability is more sensitive to changes in cavity position in the horizontal direction than in the vertical direction. According to the results, when cavities are located in critical areas of an embankment, raising their shear strength parameters does not reduce the impact they have on stability.

Arun *et al.* (2020) presented results of experiments on a land slide-prone location in the district of Thrissur is the Kuranchery slope. The samples of soil were collected from two slopes (slope 1 and slope 2), to determine the index properties of soil. Sieve analysis, Light compaction, Atterberg limits, Specific gravity and Direct shear test were conducted. This study involved the analysis of data using two separate programmes (GEO5 and PLAXIS 2D) and the observation of stability characteristics. FOS for slope 1 is 1.78 from PLAXIS 2D and 1.71 from GEO5 and FOS for the slope 2 is 1.56 from PLAXIS 2D and 1.49 from GEO5. The outcomes of the study concluded that Plaxis 2D provides more value of factor of safety than Geo5.

Iravanian and Shlash (2020) determine the slope stability and the critical slip surface of failure using the PLAXIS, FLAC/Slope and SLOPE/W software programs respectively. Two limit equilibrium and finite element approaches have also been utilized. To examine the effectiveness of these techniques, various shear strength parameter values were used. The factor of safety was studied in relation to various unit weight, cohesiveness and angle of internal friction values. When the findings for the factor of safety were examined, it became clear that PLAXIS for finite element calculations produced values that were 0.5 percent more conservative than those from the SLOPE/W programme. The most complex software was found to be FLAC/Slope and the finite difference approach typically provided the lowest result for the factor of safety when compared to other methods. The effects of angle of internal friction, unit weight and cohesiveness on the length of the failure arc were also assessed. However, no connection between the length of the failure arc and the factor of safety was found.

Lindberg (2020) examined the three-dimensional effects in slope stability for slopes with cohesive soils and slopes that involve three-dimensional excavations and compared the outcomes with method provided by Swedish commission on slope stability. The results from the methodologies corresponding to two-dimensional geometry were also compared as well as the factors of safety and slip surfaces are formed. Models developed in the limit equilibrium programme GeoStudio (SLOPE/W) and the finite element programme PLAXIS 3D were used to conduct the analysis. For three different geometry groups in PLAXIS 3D, three-dimensional excavations with variable slope lengths, external loads and slope angles were examined. SLOPE/W was used to model the corresponding two-dimensional geometries and the Swedish commission of slope stability three-dimensional effect approach was used to recalculate the results.

The study showed that the methods are effective for slopes with inclinations of 1:2 and 1:1 when an external force is present on the slope edge and the factor of safety is higher and not very near to 1. The approaches are not well matched for an excavation with vertical walls or in the absence of an external load. The results also indicate that for a long unloaded slope, the factor of safety approaches the value determined by a two-dimensional study that is simplified. According to the results, conventional cohesive slopes can be easily calculated using the recommendations from the Swedish commission on slope stability.

Nasiri and Hajiazizi (2020) reported that the two and three-dimensional Finite Element Methods (FEM) and the Finite Difference Methods (FDM) are more significant in this regard as a result of the increase in numerical techniques. In this study, the effects of angle of internal friction and cohesion on factor of safety of slope were examined and the outcomes of 2D and 3D FD analyses were compared with those of FE studies. Because the findings of 2D & 3D analyses were identical with a difference of less than 0.3 percent in cohesive soils (friction angle equal to zero) it was not necessary to assess the slope in the 3D study. The factor of safety derived in the 2D analyses (both FEM and FDM) were similar on granular slopes (cohesion equal to zero). The values in the 3D state were greater and this showed that except for cohesive soils, the results of the 2D analysis were more conservative in this situation. It should be noticed that the factor of safety values for the fine and medium mesh types in the 2D FDM for pure granular soils were close. However, the values are higher for the coarse mesh and in pure cohesive slopes the outcomes were similar for all three states (fine, medium and coarse mesh types).

Sungkar *et al.* (2020) described the analysis of slope stability that intended to calculate the factor of safety for landslide for both the reinforced and unreinforced conditions. The study case was in West Aceh Regency, Aceh Province, Indonesia, along STA 84+910 of the National route Meulaboh-Geumpang. Due to the terrain in the area and the condition of the Meulaboh-Geumpang route, landslides frequently occur and are also brought on by rainfall. Bishop's technique which assumes a circular failure surface was used to perform the analysis of factor of safety for the existing conditions. 2D Plaxis version 8.6 software was used to check the calculations. The nonlinear relationship for the factor of safety, however, necessitates repeated methods of computation. Bishop's method calculations for the current situation produced a result of 1.08 while Plaxis software produced a result of 1.10, indicating that the slopes are unstable and require reinforcement to prevent landslides. Sheet pile was used as an alternative form of reinforcement and calculations were made using 2D Plaxis version 8.6 software. The upper and middle of the slope have different sheet pile placements. The factor of safety after reinforcement was calculated and the values were 1.57 (with a 12m sheet pile depth at the upper slope) and 1.48 (with a 10m sheet pile depth in the middle of the slope).

Firomsa and Tsige (2021) compared the factor of safety of several trial slip surfaces, it is possible to identify the critical failure surface for a given slope. It is important to obtain the critical failure surface for the specified slope in order to determine the minimum factor of safety. In this investigation, the failure surface and factor of safety were examined in relation to the soil parameters cohesion (c), angle of internal friction (ϕ) and unit weight. The length of the failure arc and the critical failure surface were calculated using the GEO5 software application. With the use of slope geometry and soil strength characteristics, an equation was developed to identify the critical failure surface. The study revealed that variations in soil unit weight, angle of internal friction and cohesion affect the slope's factor of safety. Additionally, the dimensionless function which is linked to cohesion, angle of internal friction and unit weight has an impact on the slip surface. A model was developed to identify the critical failure surface using the slope geometry and soil parameters.

Salih (2021) described the soil slope model assessments in PLAXIS-2D software using finite element analysis method (FEM). The parameters of the soil layers that were fed into these slope models were determined by laboratory testing using drained triaxial compression on residual soil samples that had been remoulded at a 200 kPa moulding pressure. By identifying the failure surface and the related factor of safety while taking into account the influence of different slope geometries, this work seeks to present numerical simulations of natural slope stability. The observed (FOS) values were compared with earlier findings from slope models with a comparable slope that was computed by the limit equilibrium analysis method (LEM) using the SLOPE/W software. The assessed results showed that the computed FOS could be significantly impacted by a change in slope geometry. Additionally, the factor of safety determined by the FE approach was nearly identical to but marginally higher than the outcomes determined by the LE method. However, both approaches are successful in identifying the optimal mechanism behind slope failure behavior. However, the use of FEM presents an attractive replacement for conventional methods for the issue, particularly for LEM.

Yuan *et al.* (2021) described the laws of slope displacement and the shifting positions of the sliding surface throughout the filling process using the strength reduction approach. The finite element programme PLAXIS creates the multistage fill slope model. Under the same working conditions, the slopes with and without reinforcement are evaluated. The two components considered in sensitivity analysis are internal factors and external factors. According to the results of the finite element study, the settling of a multistage fill slope without reinforcement is primarily concentrated on the right side of the slope and gradually gets smaller as filling height rises.

The reinforcement has the optimal impact on the sliding surface. It goes without saying that strengthening can give the slope a better sliding surface position which is beneficial for the slope stability. According to the sensitivity analysis, the factor of safety is adversely linked with unit weight, slope ratio and grade height. In addition, there is a positive correlation between the factor of safety and the platform width, cohesiveness and angle of internal friction. The slope stability is most greatly impacted by the angle of internal friction. Additionally, each grade's platform width and height should be kept under 4 meters. The multistage filling slope design can be guided by sensitivity analysis.

Belew *et al.* (2022) studied the Ribb embankment dam seepage and slope stability. For its intended function to be maintained throughout its service life, an earth-filled dam needs to be stable against seepage and slope failure. An embankment dam stability is determined by its shape, parts, materials, individual components qualities and the forces that are applied to it. The analyses were carried out using the PLAXIS 2D program. The Mohr-Coulomb criterion was employed in the analysis to describe how the dam body and foundation behaved which includes the full dam body and its 20 m of foundation depth. The amount of seepage through the main body of the dam and several critical loading conditions were examined.

This study established the flow rate, pore water distribution and position of the phreatic line. Under the toe of dam, the phreatic line has surfaced. This may indicate that the dam is resistant to sloughing issues which are the most typical reason for dam failure downstream. The simulation results showed that at normal pool level, the average rate of seepage through the dam body was 5.05×10^{-6} m^3 /s/m, while the average rate through the foundation was 3.00×10^{-6} m^3 /s/m. According to expression, the seepage results are within the acceptable range.

2.6 Concluding Remarks

The review of the literature described above reveals that,

- Various researchers have computed value of FOS taking into consideration various soil parameters like cohesion, friction angle and unit weight.
- Various software programs work on the mathematical simulation in a way similar to well established conventional methods of slope stability analysis.
- SLOPE/W also works on the principles as adopt in the conventional methods but PLAXIS software is based on Finite element method.
- Different techniques are used to determine the FOS in which the Finite element method gives the higher values than the other traditional methods except Janbu's method.
- According to above studies the SLOPE/W software gives the higher values than PLAXIS 2D for the factor of safety of slopes.

Materials and Methods

Chapter 3 MATERIALS AND METHODS

3.1 Introduction

The software programs and their methodologies for slope stability analysis are described and discussed in the following sections.

3.2 Methodology

For each slope, there are driving and resisting forces should be considered. Driving forces are mostly caused by the weight of the soil, which is directly proportional to the unit weight of soil while resisting forces are primarily caused by the cohesion and angle of internal friction of the soil. The first part of the study will examine how the cohesion (c), angle of internal friction (ϕ) and unit weight (γ) of soil affect the calculation of the factor of safety (FOS) and length of arc.

The second part of this study will analyze and model a sufficient number of slopes with the same soil parameters, cohesion, unit weights and angle of internal friction in addition to slope geometry by varying the angles and heights of the slope in order to analyze the effect of the calculation of safety factor for these slope parameters. First two parts in the study will be analyzed by using SLOPE/W software. Then reanalyze the previous models with the same properties and conditions on another software package PLAXIS 2D version 8.6 and manually by Swedish circle method using Microsoft Excel 2010. Then compare the outputs with the results of SLOPE/W in order to check and control the accuracy of SLOPE/W results.

3.3 Materials

3.3.1 Soil

Different soil types with various soil parameters have been assumed for the analysis. Different soil types with slight variations in the soil characteristics were assumed in order to create models that could be used to accurately determine the relationship between the failure surface and the soil parameters.

3.4 Softwares and Programs

3.4.1 SLOPE/W Software

SLOPE/W software using the Limit Equilibrium approach determines the factor of safety for slopes made of rock, soil and earth. The version SLOPE/W 2018 R2 has been used in this study. Although SLOPE/W software is based on the Limit Equilibrium method, it also computed stress from finite element method for some slopes. The details of soil properties are presented in Table 3.1.

Table 3.1 Soil properties required for SLOPE/W

Property	Symbol	Units
Unit weight	γ	kN/m^3
Cohesion	c	kN/m^2
Angle of internal friction	ϕ	°

3.4.1.1 The Methodology of SLOPE/W Analysis

Figure 3.1 shows the model units, properties of the soil and the slip surface scale for the model so that the axes can be drawn afterward.

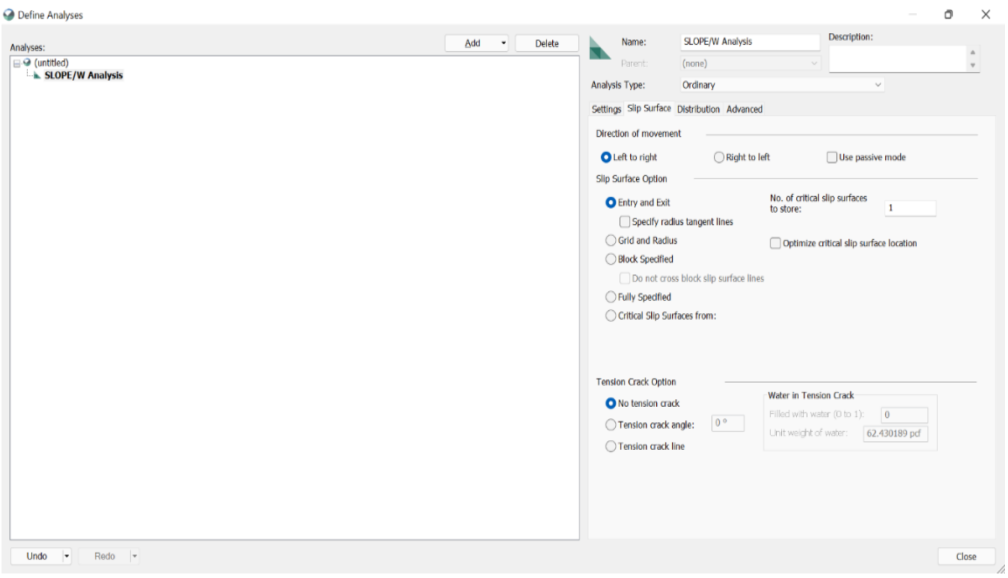

Fig. 3.1 Units in SLOPE/W

To draw the model, software needs to input the coordinates (X, Y) of each point of the slope. After that assign and create the properties of material, as shown in Figure 3.2.

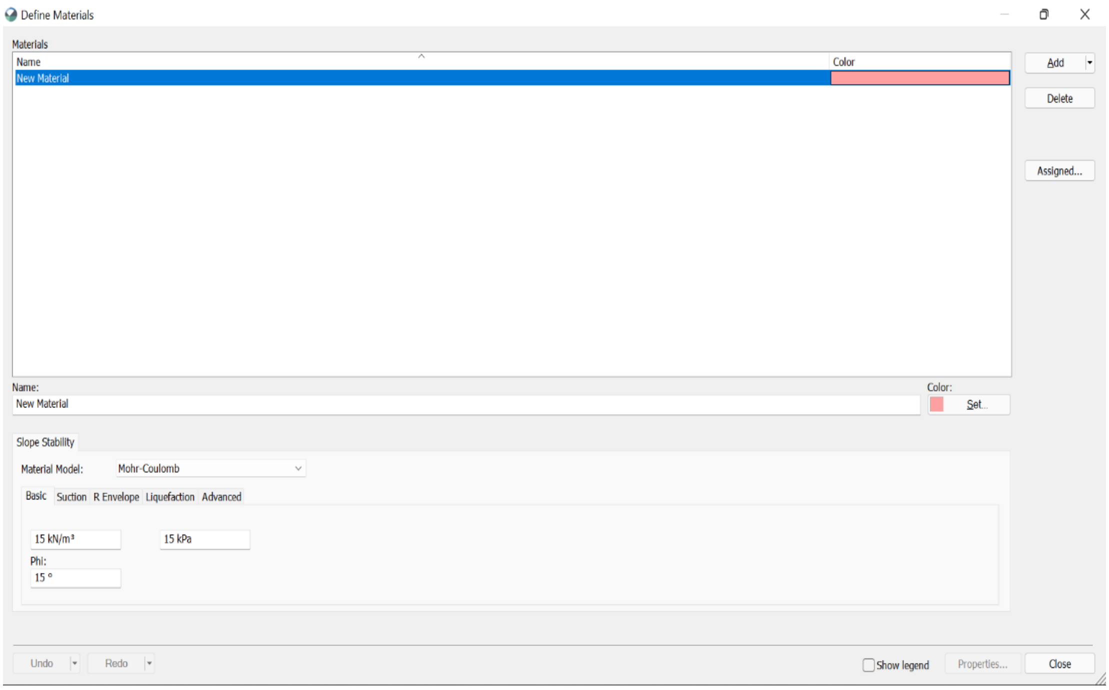

Fig. 3.2 Properties of the soil used in SLOPE/W

The amount of time it requires to analyze the slope depends on the number of increments and the type of mesh used when establishing the soil parameters in the software and then starting to compute the minimal factor of safety of the slope by clicking the “start” button.

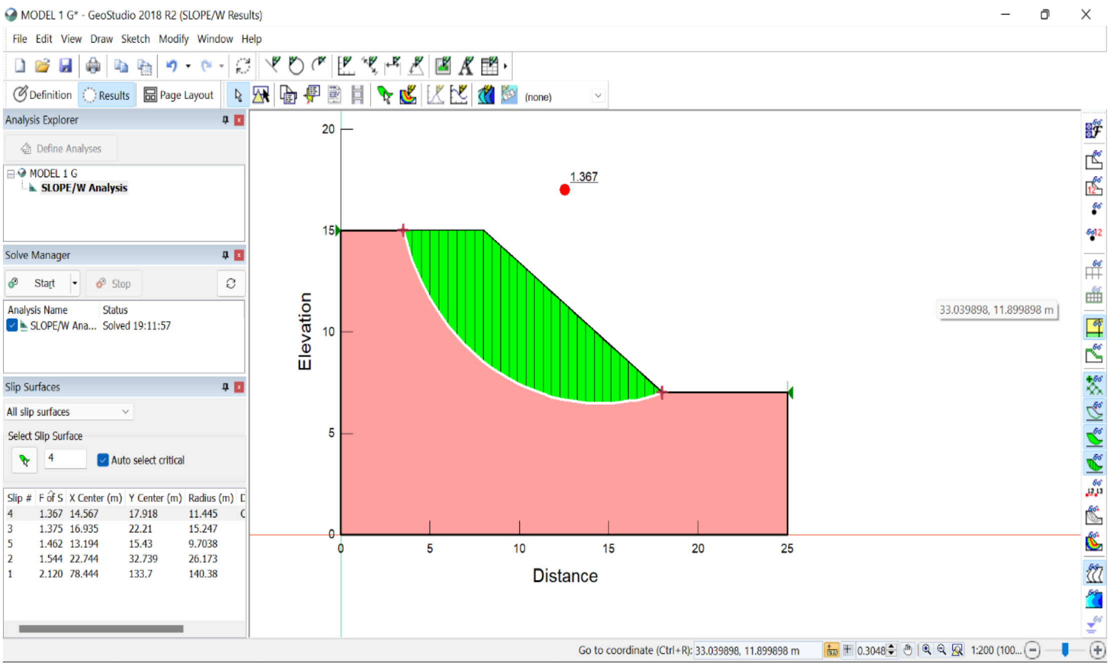

Fig. 3.3 SLOPE/W factor of safety value

3.4.2 PLAXIS 2D Software

PLAXIS is defined as a finite element FE program for geotechnical analysis. It can perform the analysis in both three dimensions and two dimensions in calculating the moment of inertia and shear forces of slope stability, deflection, displacements, and deformation observed by slopes. The version PLAXIS 2D 8.6 is used in this study. The details of soil properties are presented in Table 3.2.

Table 3.2 Soil properties required for PLAXIS 2D

Property	Symbol	Units
Unit weight	γ	kN/m³
Cohesion	c	kN/m²
Angle of internal friction	ϕ	°
Poisson's Ratio	μ	-
Elastic modulus	E	kN/m²

3.4.2.1 The Methodology of PLAXIS 2D Analysis

Figure 3.4 shows units, grid spacing, scale and geometry dimension (right, left, bottom and top) for the model. The axes can be drawn after inputting the all values.

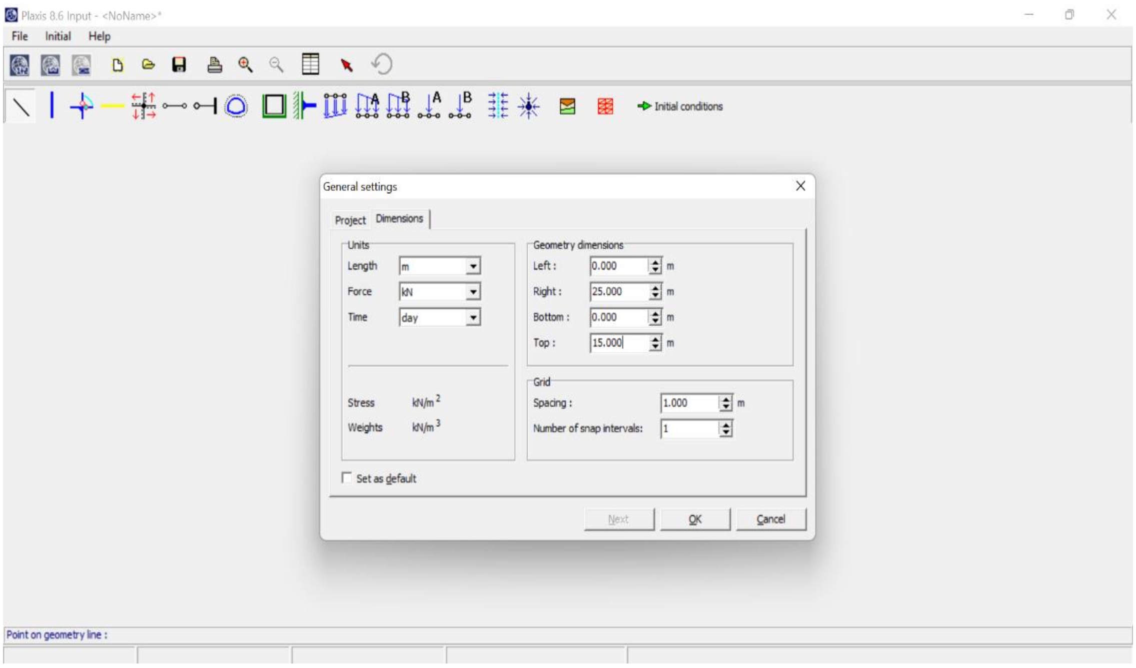

Fig. 3.4 Units in PLAXIS

By selecting the standard fixities button from the toolbar, the model should be fixed to make the slope immovable from continuous sides, as shown in Figure 3.5.

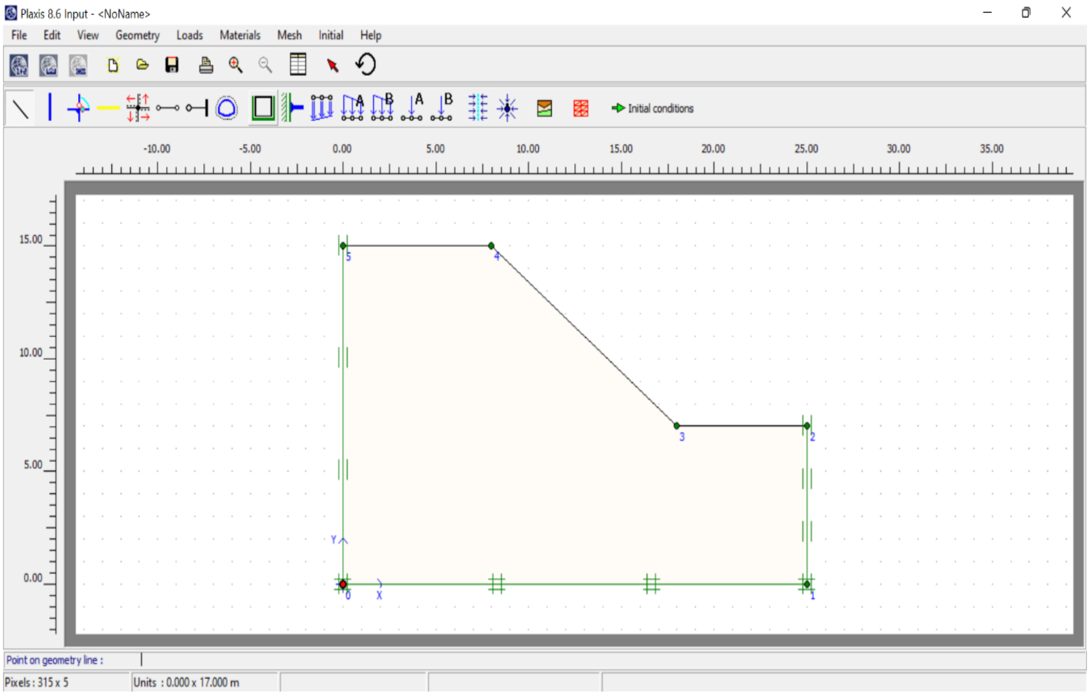

Fig. 3.5 PLAXIS standard fixities

Figure 3.6 show the properties of the soil on software, but PLAXIS also requires advanced properties, such as the elastic parameters; Young's modulus and Poisson's ratio, they have little impact on the computed factor of safety.

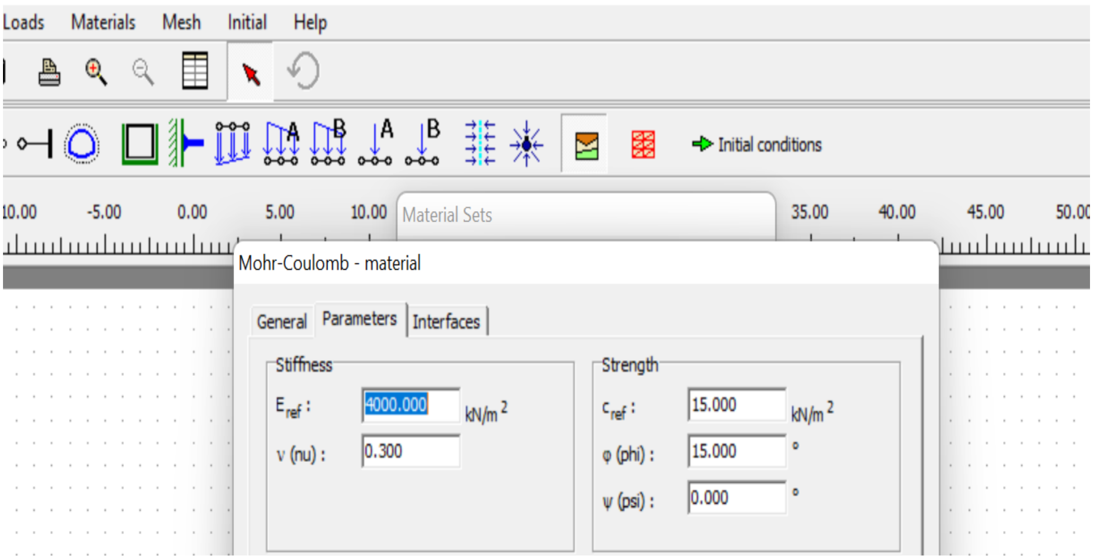

Fig. 3.6 Properties of the soil used in PLAXIS

After assigning the required property, mesh should be generated. In order to improve accuracy, a medium mesh is being used in this analysis as shown in Figure 3.7.

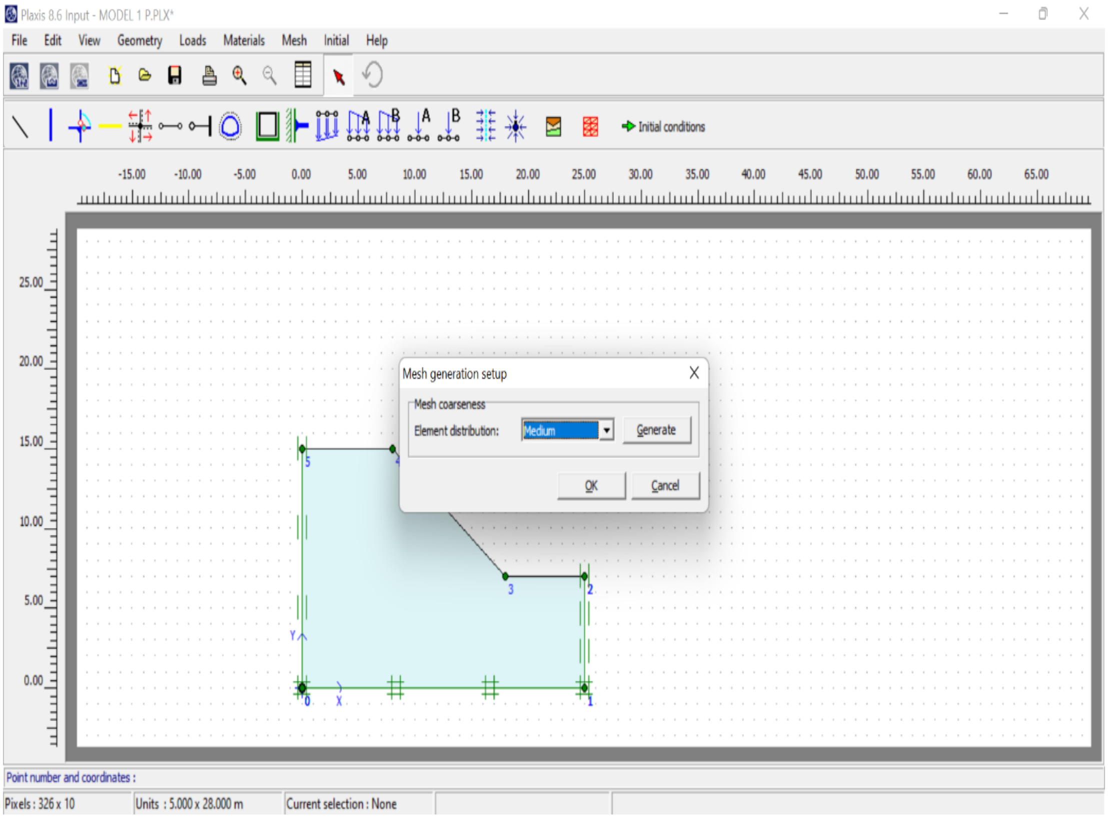

Fig. 3.7 Mesh size selection on PLAXIS

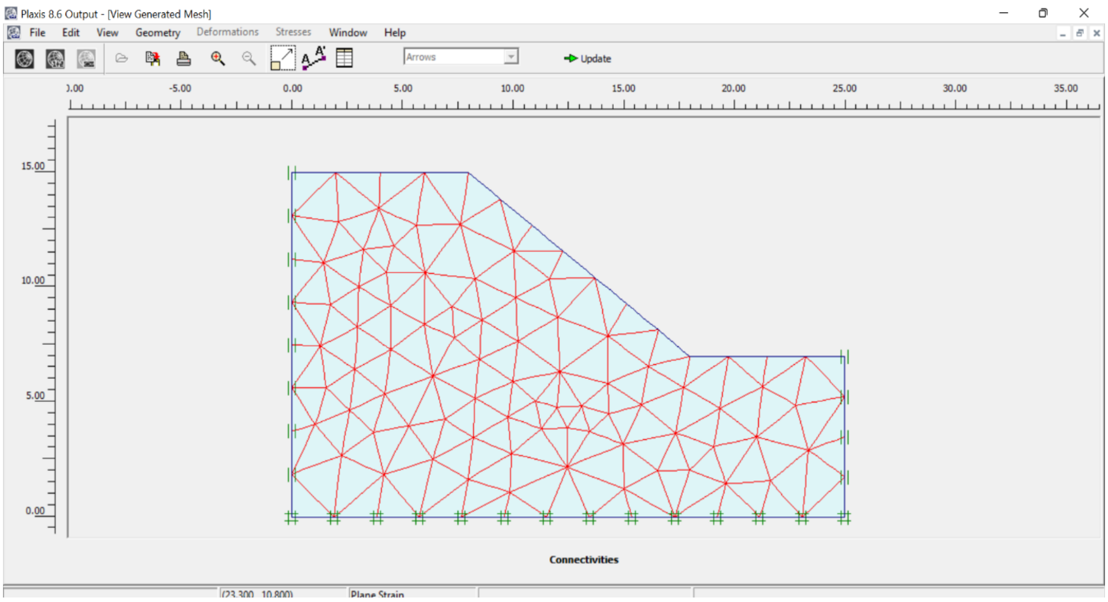

Fig. 3.8 PLAXIS before generating mesh

When click the calculate button in the toolbar, the application will ask to select certain points on the slope where the failure surface will be expected as shown in Figure 3.9 and then compute factor of safety value.

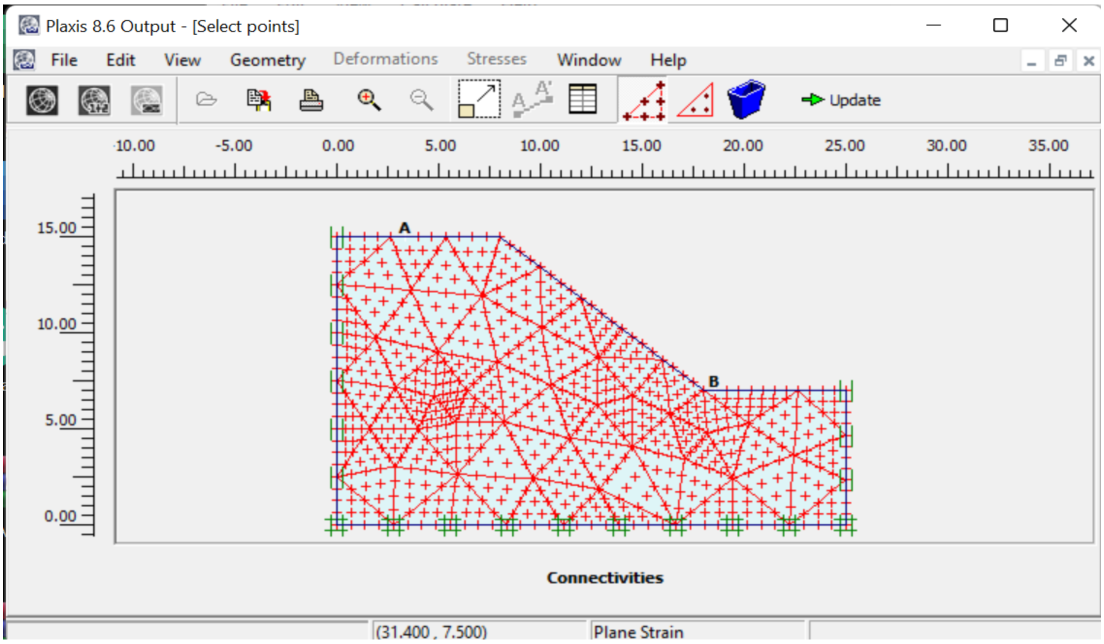

Fig. 3.9 PLAXIS after generating mesh

Figure 3.10 shows the deformed shape of the slope after press the calculate button. For the shading portion of slope failure press the total deformation button, it will gives the value of factor of safety, as shown in Figure 3.11.

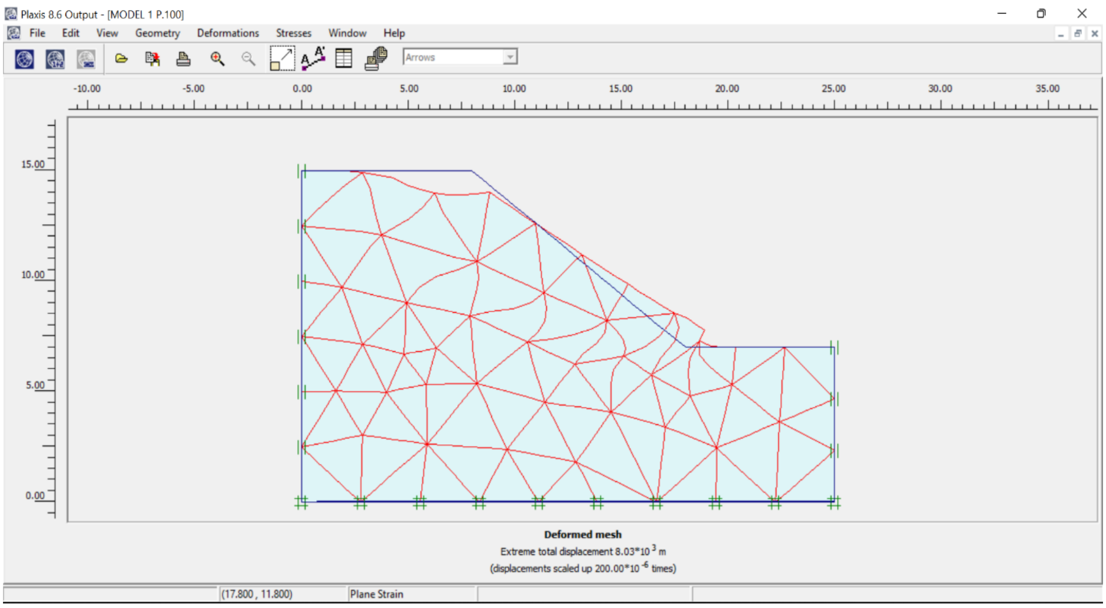

Fig. 3.10 Slope displacement on PLAXIS

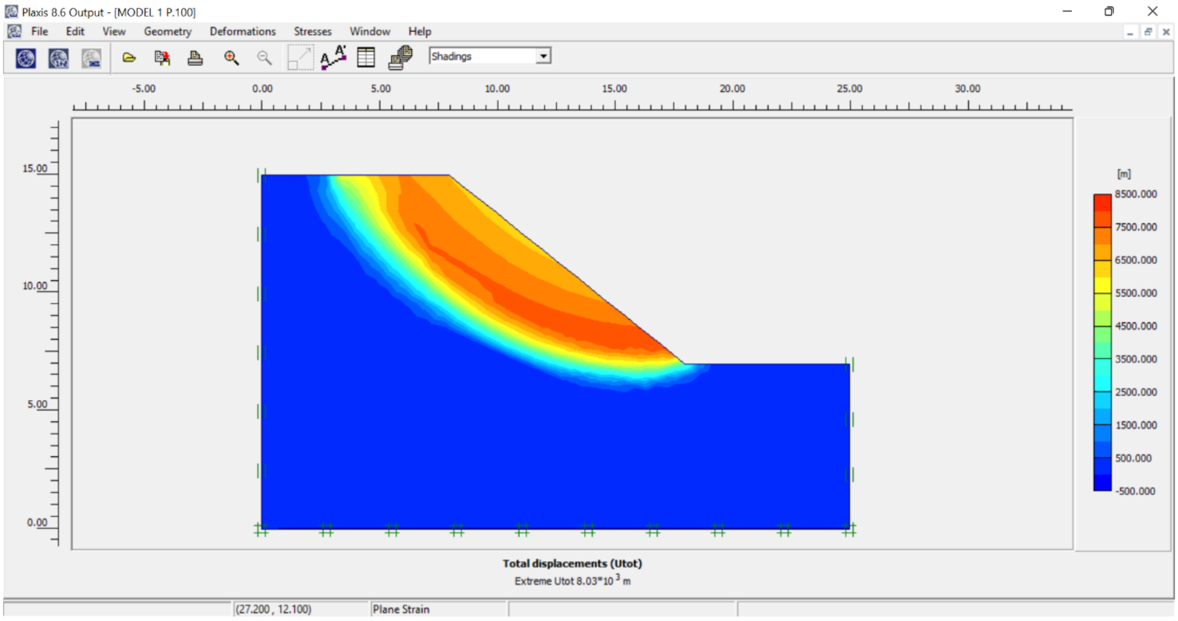

Fig. 3.11 Critical slope failure on PLAXIS

3.5 Concluding Remarks

This chapter summarizes LEM and FEM approaches for the calculation of factor of safety of slope. It also describes all the steps involved in both software (SLOPE/W and PLAXIS 2D) to determine of factor of safety. After carrying out the steps provided in the procedure, deformed mesh will be generated and then critical failure surface with minimum factor of safety will be obtained.

Results

and

Discussion

Chapter 4 RESULTS AND DISCUSSION

4.1 General

This chapter presents the effect of each parameter of soil, cohesion, unit weight and angle of internal friction (c, γ and ϕ) on the factor of safety (FOS) and failure surface. In the first part of the results, a number of models were examined to determine the variations in factor of safety and slip surface while a sufficient number of models were examined in the second part to identify the particular link between the soil parameters and the failure surface. Figures were drawn to show the influences of the variables on factor of safety and failure surface after all the models had been created and analyzed. After that values of factor of safety obtained from limit equilibrium method and finite element method are compared.

4.2 Effect of Soil Parameters on the Factor of Safety

In this section, three series of analyses were conducted in order to examine the viability of this study. These models were examined to see if there is any relationship between the position of the surfaces of failure and the soil parameters, with one of the parameters in each set of models changing while the other two parameters remained fixed in case of individual variation of soil parameters and after that two of the parameters changing while one parameter remained constant for examine the combined effect of soil parameters on factor of safety.

4.2.1 Effect of cohesion on factor of safety

In order to investigate how cohesion affects factor of safety, cohesion values varying from 15 to 30 kPa were selected, with an angle of internal friction and soil unit weight of 15° and 15 kN/m³. The calculated values of factor of safety for different cohesion values are shown in Table 4.1.

Table 4.1 Effect of cohesion on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
1	15	15	15	1.367
2	16	15	15	1.420
3	18	15	15	1.526
4	20	15	15	1.631
5	22	15	15	1.737
6	24	15	15	1.842
7	26	15	15	1.948
8	28	15	15	2.054
9	30	15	15	2.159

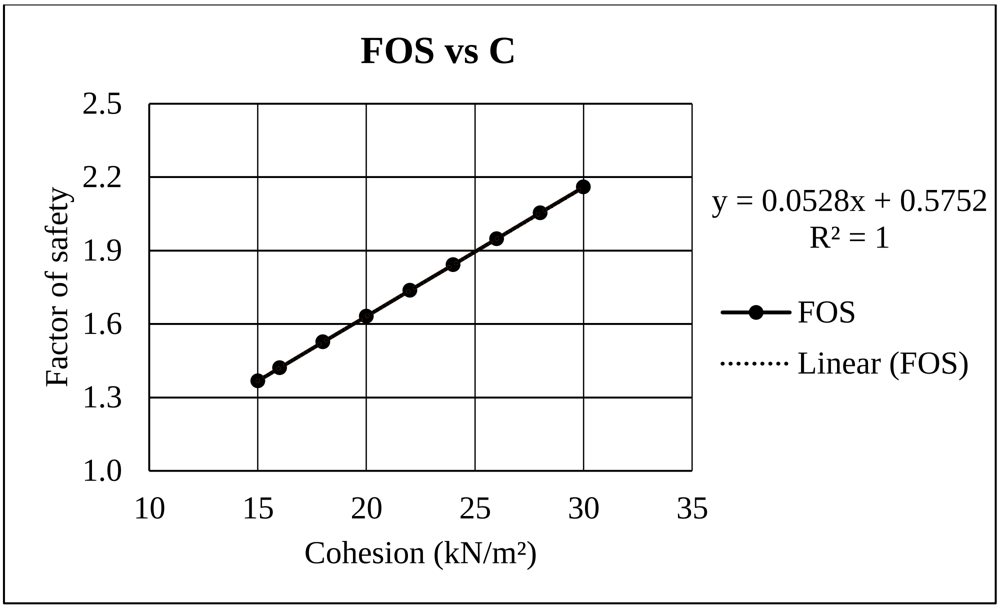

Fig 4.1 Effect of Cohesion on factor of safety

The results in Table 4.1 demonstrated that as the values of cohesion increased the value of factor of safety is also increased. Cohesion is one of the resisting factors in that the slope became more stable as the cohesion increased, enhancing the factor of safety. Figure 4.1 shows the linear correlation between cohesion and factor of safety. FOS is nearly linear with R^2 factor of 1.

4.2.2 Effect of angle of internal friction on factor of safety

In order to investigate the effect of angle of internal friction on the factor of safety of soil, several values ranging from 16 to 30 degrees were chosen, while the cohesion and unit weight of the soil was kept constant at 15 kN/m² and 15 kN/m³ respectively, as given in Table 4.2.

Table 4.2 Effect of angle of internal friction on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
10	15	16	15	1.408
11	15	18	15	1.484
12	15	20	15	1.559
13	15	22	15	1.636
14	15	24	15	1.716
15	15	26	15	1.797
16	15	28	15	1.882
17	15	30	15	1.969

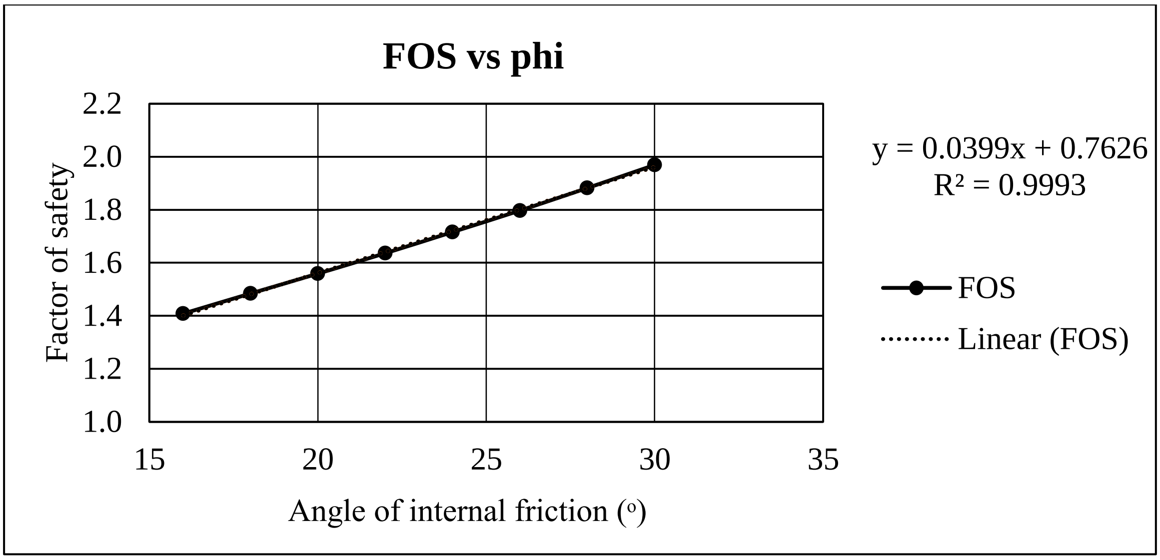

Fig 4.2 Effect of angle of internal friction on FOS

Data in Table 4.2 shows that raising the angle of internal friction value improves the factor of safety. The relationship between FOS and angle of internal friction is depicted in Figure 4.2. The angle of internal friction is one of the holding and resisting variables, as values of angle of internal friction is increased, the factor of safety is also increased. The approximately linear relationship between the angle of internal friction and factor of safety of slope *i.e.* R^2=0.9993.

4.2.3 Effect of unit weight on factor of safety

The values of unit weight have been set between 16 and 30 kN/m³, while the angle of internal friction and cohesion have been set at 15° and 15 kN/m² respectively, in order to explore the effect of unit weight on FOS. The calculated values of FOS for different unit weight values are shown in Table 4.3.

Table 4.3 Effect of unit weight on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
18	15	15	16	1.318
19	15	15	18	1.232
20	15	15	20	1.160
21	15	15	22	1.101
22	15	15	24	1.052
23	15	15	26	1.011
24	15	15	28	0.976
25	15	15	30	0.945

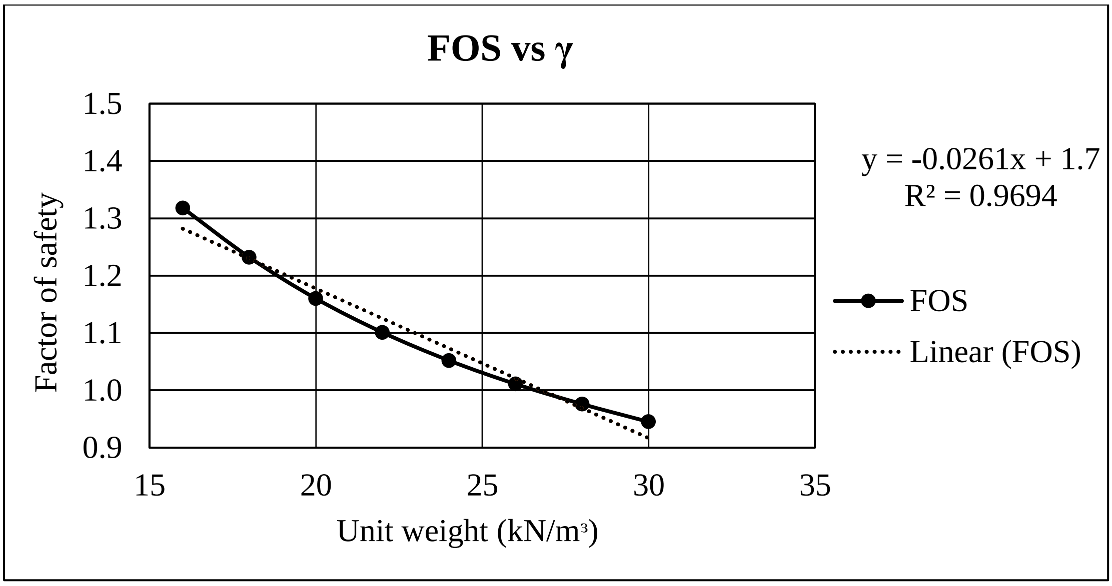

Fig 4.3 Effect of unit weight on FOS

The effect of soil unit weight on the factor of safety is depicted in Figure 4.3. As can be seen from the Figure, the major derivative factor that was unit weight of soil applied to the soil mass is inversely related to the factor of safety.

4.2.4 Effect of cohesion and angle of internal friction on factor of safety

In this section, the unit weight remained constant at 15 kN/m³, while the values for the cohesion and angle of internal friction, measured in kN/m² and ° respectively, vary from 16 to 30, as shown in Table 4.4.

Table 4.4 Effect of cohesion and angle of internal friction on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
26	16	16	15	1.461
27	18	18	15	1.648
28	20	20	15	1.838
29	22	22	15	2.029
30	24	24	15	2.223
31	26	26	15	2.420
32	28	28	15	2.620
33	30	30	15	2.824

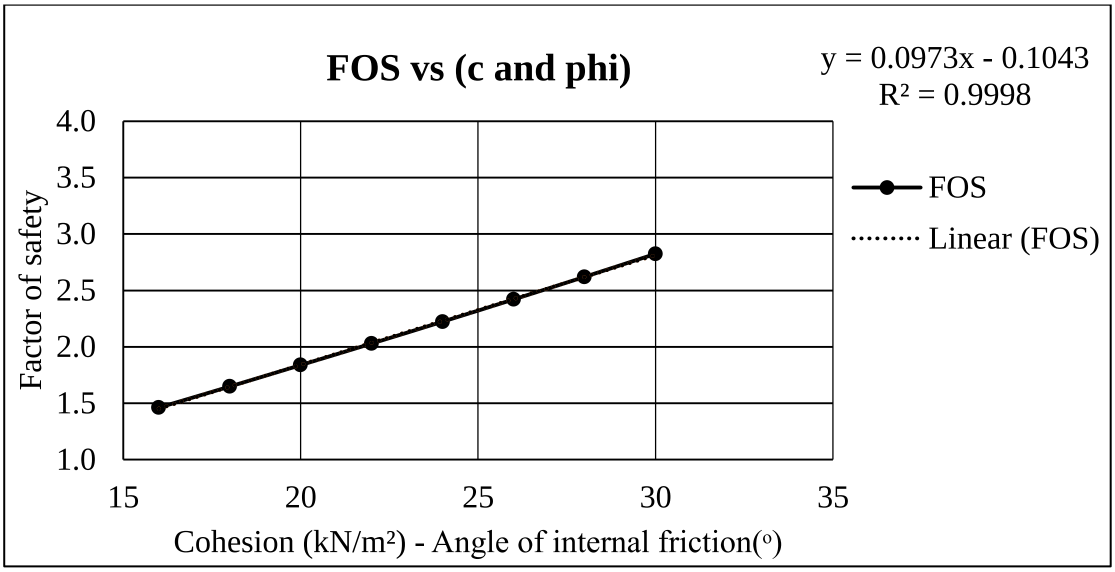

Fig 4.4 Effect of cohesion and angle of internal friction on the factor of safety

Since both C and ϕ values are anticipated to have an impact on the surface of probable failure, Figure 4.4 depicts the link between the factor of safety and C, ϕ. The value of the factor of safety rises when either of these two shear strength parameters is increased since they both operate as holding factors. With an R^2 score of 0.9998, FOS is virtually linear.

4.2.5 Effect of cohesion and unit weight on factor of safety

The angle of internal friction was kept unchanged at 15° in this part and the values varied from 16 to 30 for both parameters, cohesion and unit weight kN/m² and kN/m³ respectively, as given in Table 4.5.

Table 4.5 Effect of cohesion and unit weight on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
34	16	15	16	1.367
35	18	15	18	1.367
36	20	15	20	1.367
37	22	15	22	1.367
38	24	15	24	1.367
39	26	15	26	1.367
40	28	15	28	1.367
41	30	15	30	1.367

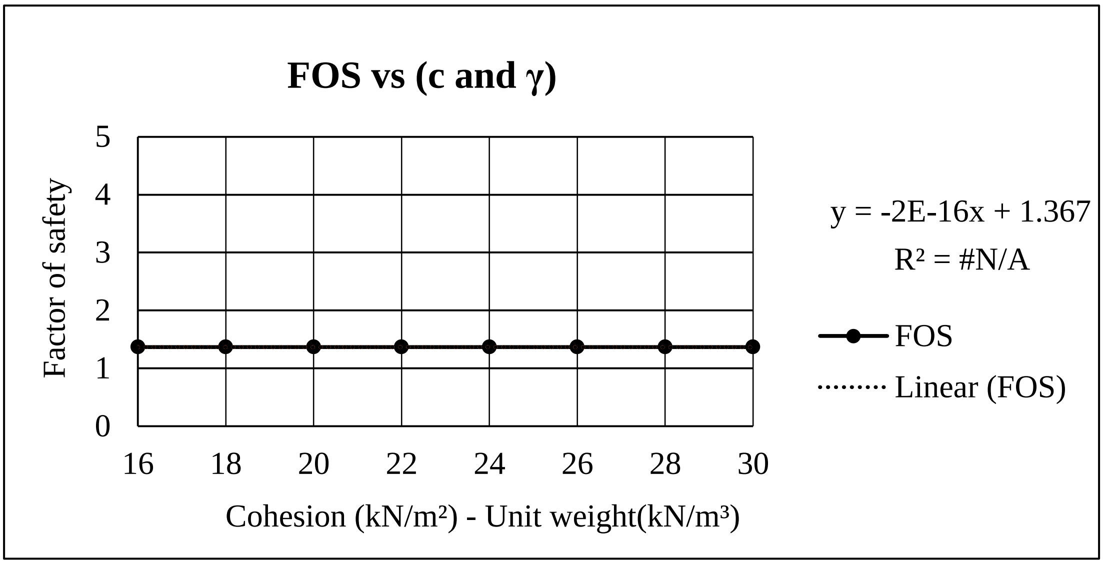

Fig 4.5 Effect of cohesion and unit weight on the factor of safety

This section looked at how cohesion and soil unit weight affected the factor of safety. Here, both cohesion and soil unit weight were increased, but the ratio remained constant. The results show that combining Phi and C has an impact on the potential surface of slip, with the function being defined as λ being equivalent to (Lin and Cao, 2011):

$$\lambda = \frac{C}{(\gamma \times h \times \tan\phi)} \tag{2.15}$$

The effect of cohesion and unit weight on FOS is depicted in Figure 4.5 while the lambda value is kept constant.

4.2.6 Effect of angle of internal friction and unit weight on factor of safety

In this part, the cohesion remained constant at 15 kN/m², but the values for the parameters angle of internal friction and unit weight (° and kN/m³ respectively) ranged from 16 to 30. The calculated values of FOS are shown in Table 4.6.

Table 4.6 Effect of angle of internal friction and unit weight on factor of safety

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (SLOPE/W)
42	15	16	16	1.357
43	15	18	18	1.260
44	15	20	20	1.162
45	15	22	22	1.080
46	15	24	24	1.024
47	15	26	26	0.951
48	15	28	28	0.910
49	15	30	30	0.910

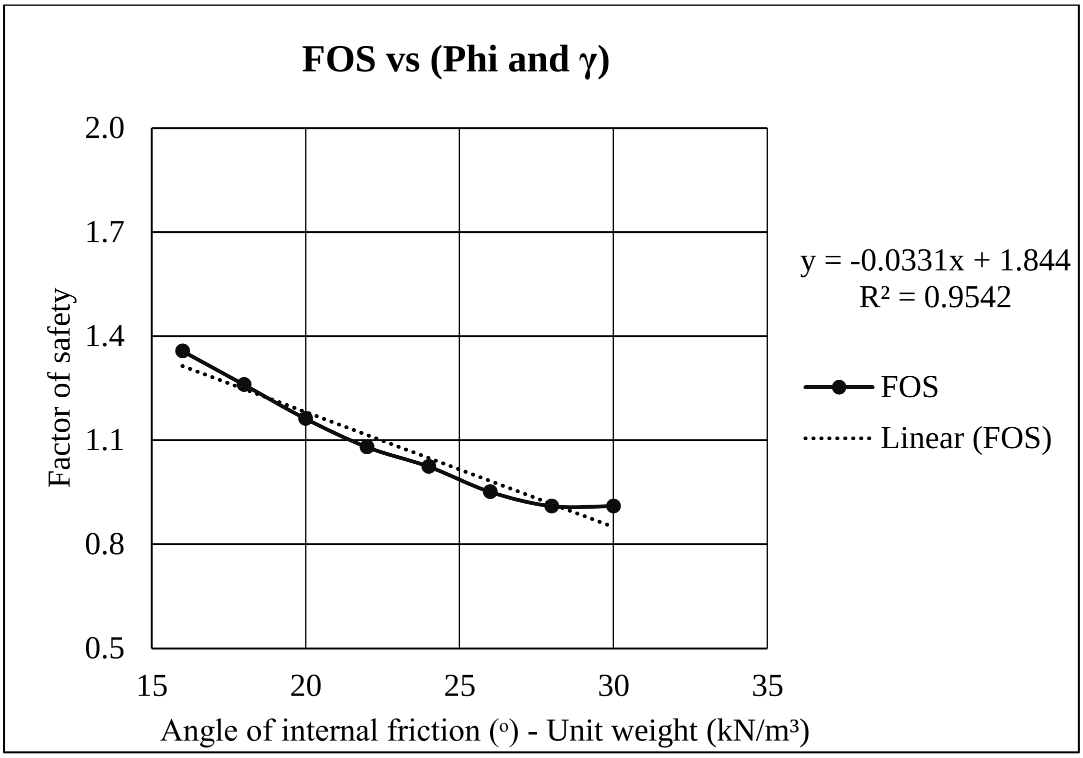

Fig 4.6 Effect of angle of internal friction and unit weight on the factor of safety

Figure 4.6 showed the factor of safety in relation to the angle of internal friction and unit weight. By raising the values of angle of internal friction and unit weight respectively, leads to a drop in the value of FOS, as seen in Figure. This is a result of the failure surface shifting to the upper side which shortens the arc length and reduces the effect of holding and resisting forces.

Figures 4.7 to 4.12 show the failure surface of the slope with a minimum factor of safety value in SLOPE/W software for all cases which are discussed above.

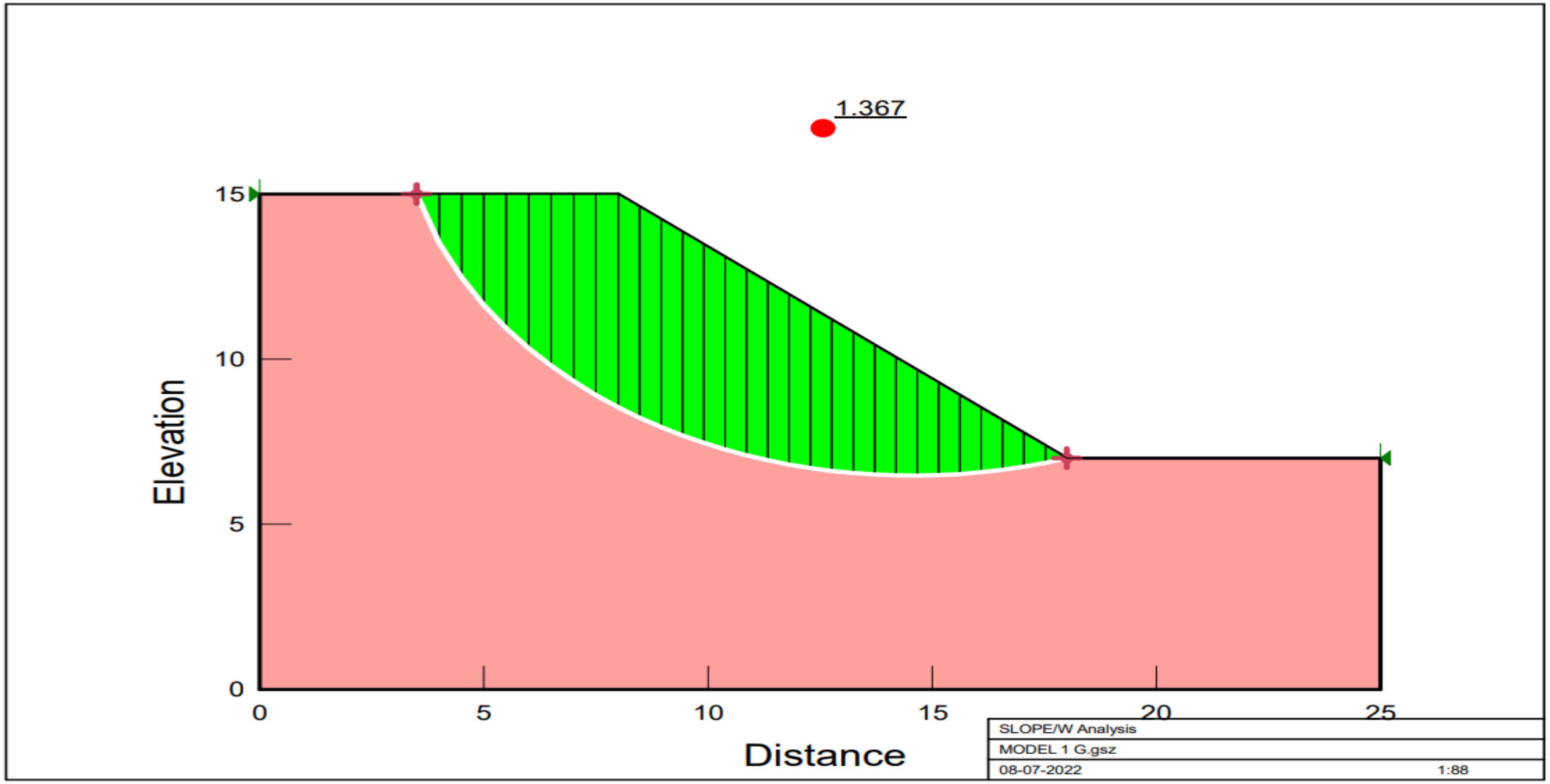

Fig. 4.7 Failure slope due to effect of cohesion using SLOPE/W

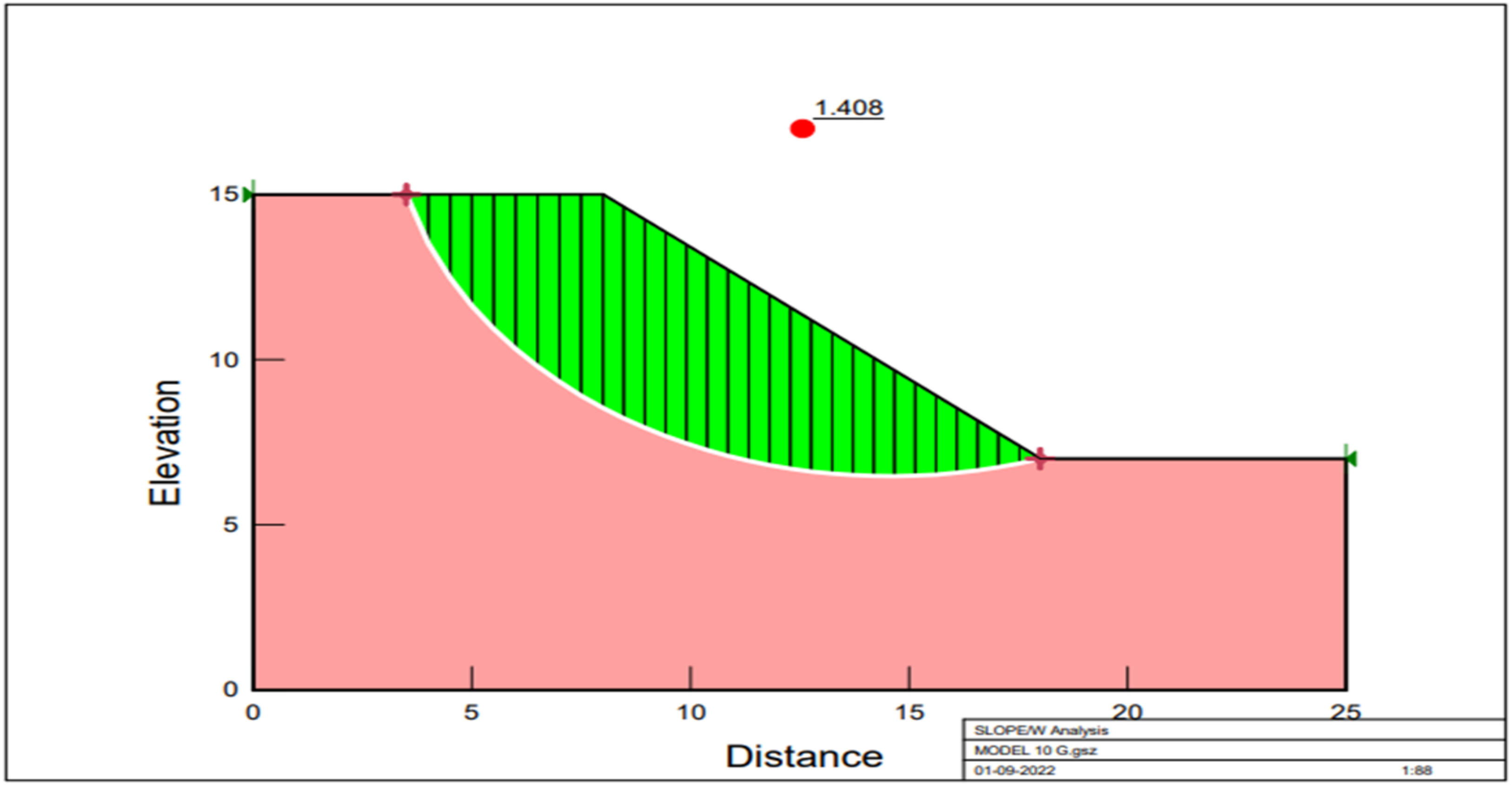

Fig. 4.8 Failure slope due to effect of angle of internal friction using SLOPE/W

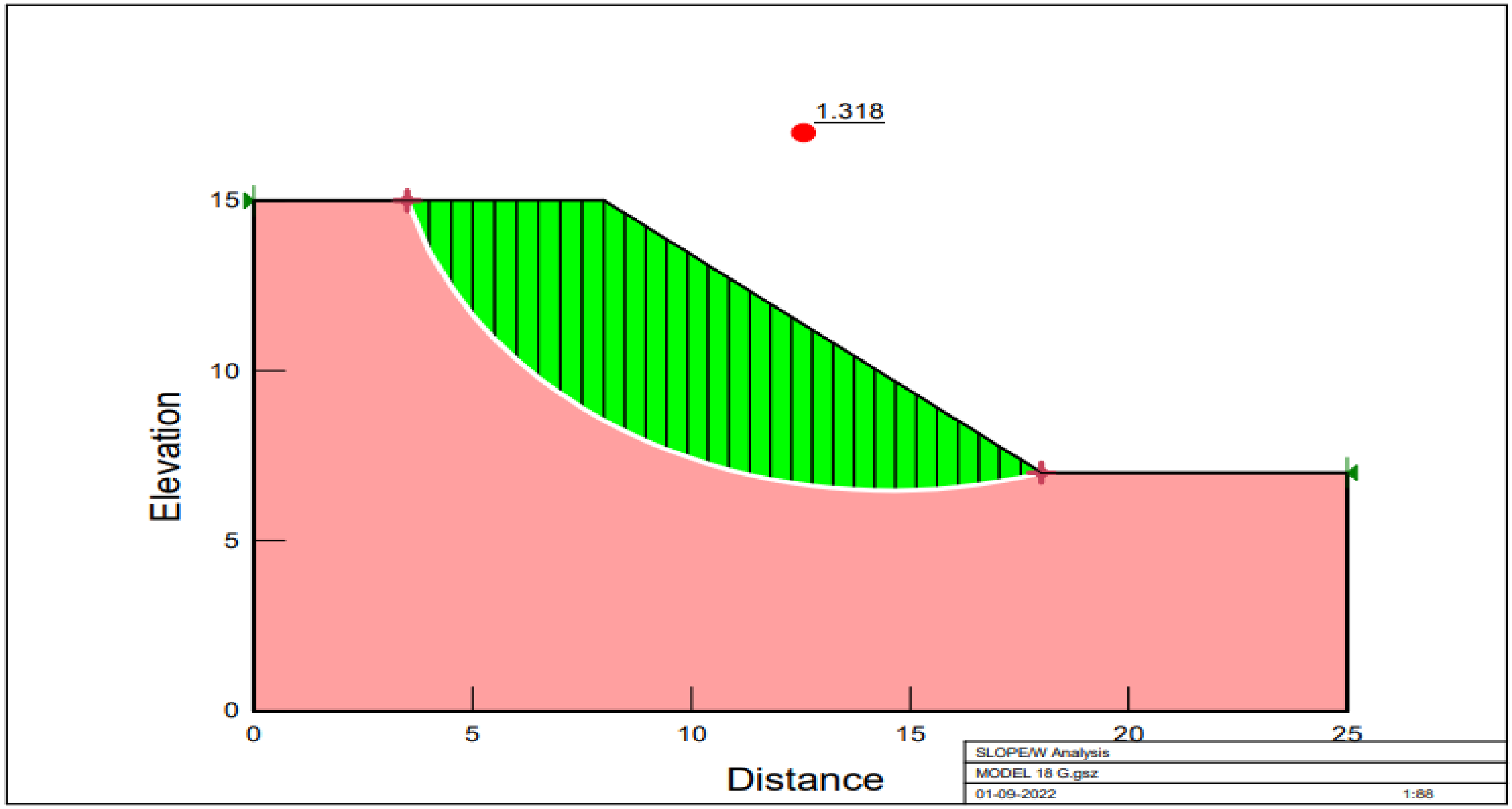

Fig. 4.9 Failure slope due to effect of unit weight using SLOPE/W

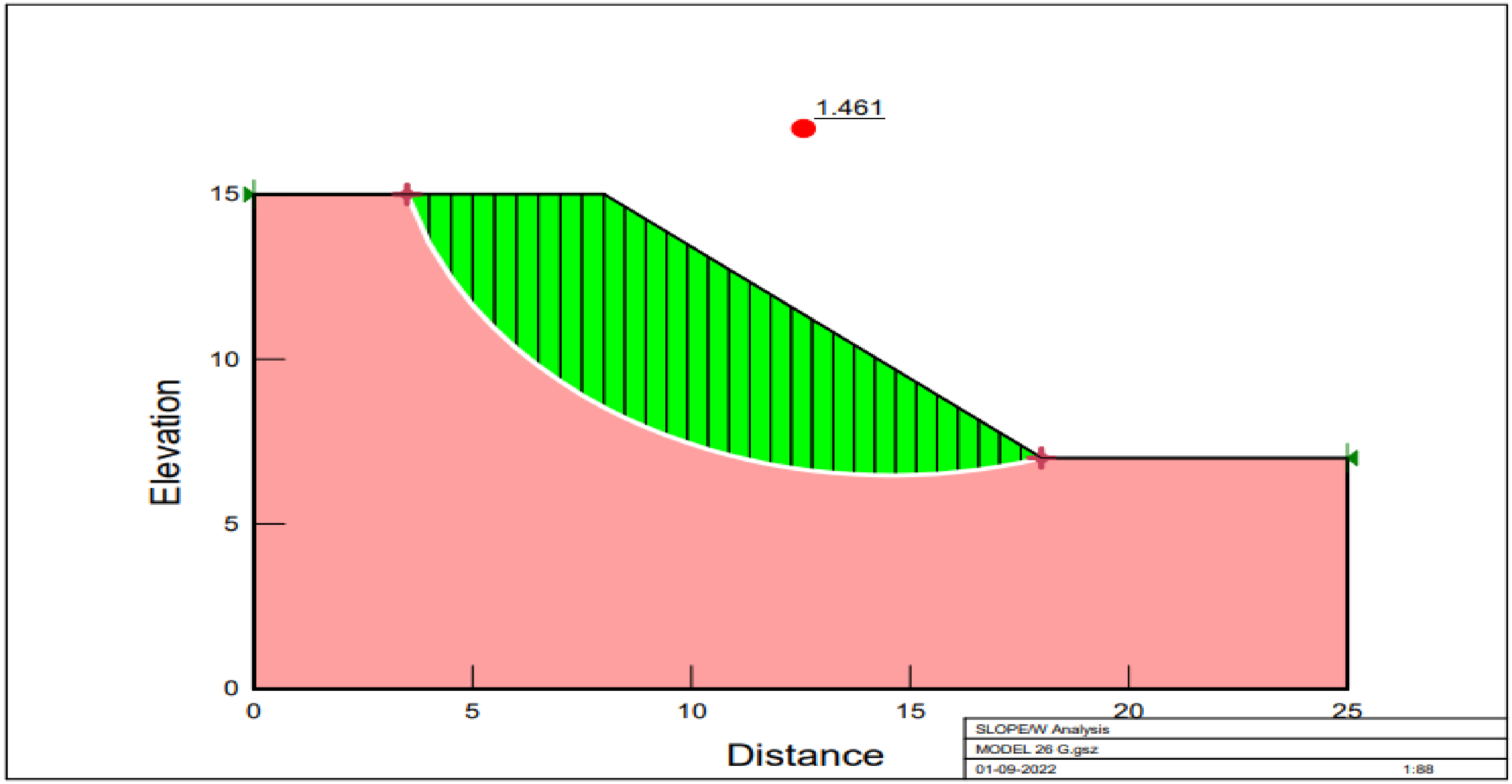

Fig. 4.10 Failure slope due to combined effect of cohesion and angle of internal friction using SLOPE/W

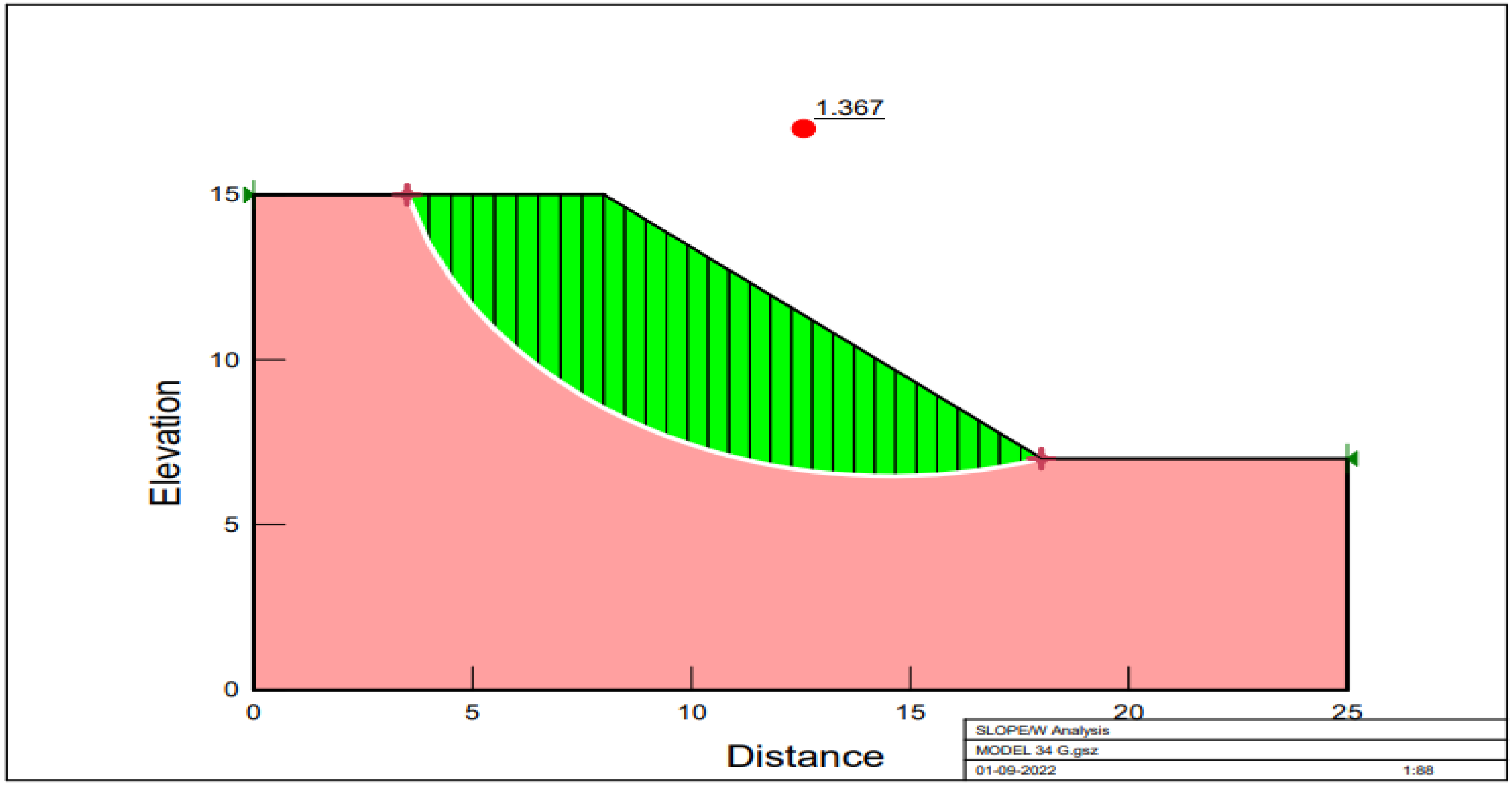

Fig. 4.11 Failure slope due to combined effect of cohesion and unit weight using SLOPE/W

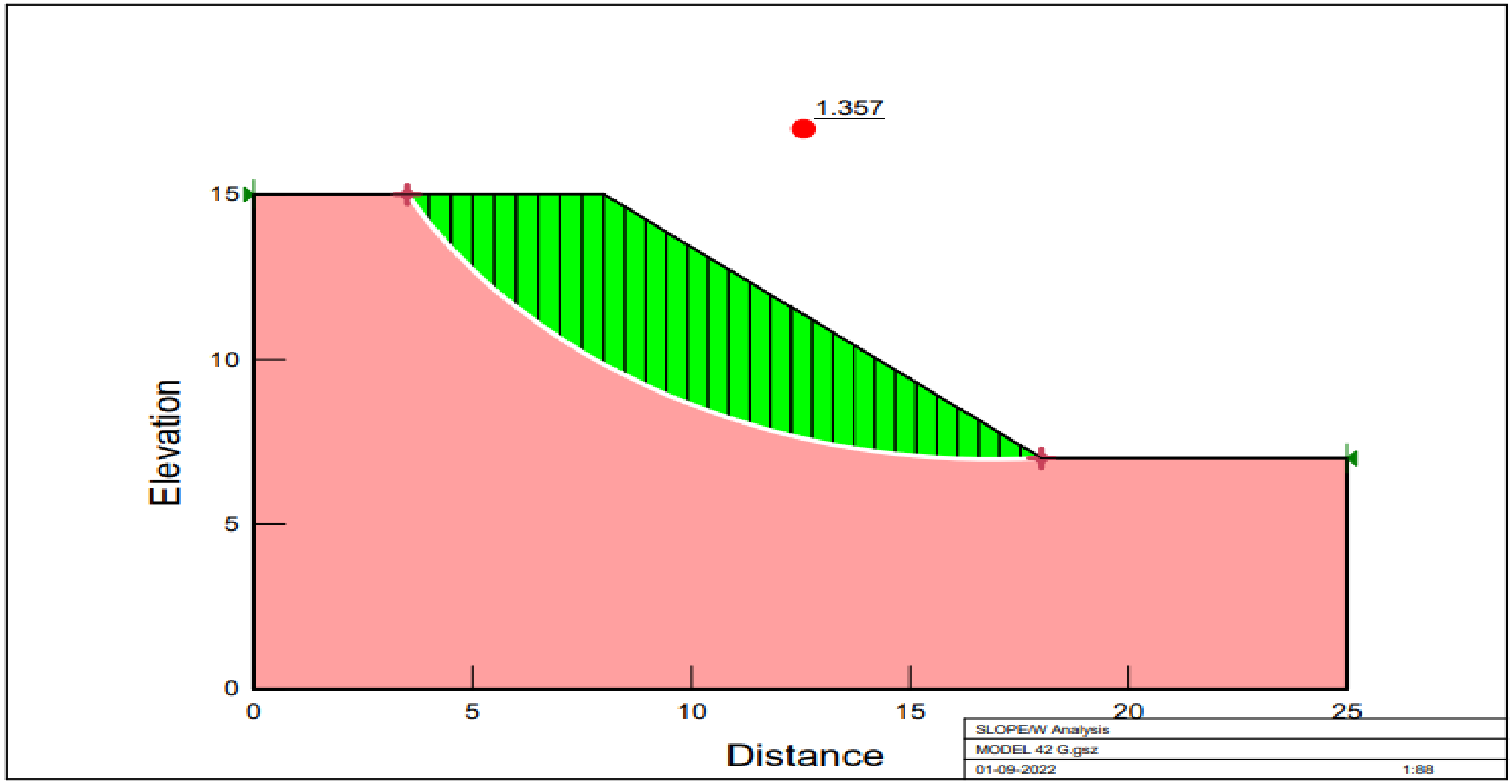

Fig. 4.12 Failure slope due to combined effect of angle of internal friction and unit weight using SLOPE/W

4.3 Effect of Soil Parameters on the Slip Surface

This step involved generating many models using the SLOPE/W programme. The circular failure surface radius, the factor of safety and the coordinates for the centre of the slip circle will all be produced in this aspect.

4.3.1 Effect of cohesion on slip surface

In this section the angle of internal friction and unit weight of the soil are kept constant at 15° and 15 kN/m³ respectively and the cohesion is varied from 15 to 30 kN/m² as shown in Table 4.7.

Table 4.7 Effect of Cohesion on the slip surface

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
1	15	15	15	4.57,15	18.31,7	11.218	17.621	1.356
2	16	15	15	4.57,15	18.31,7	11.218	17.621	1.411
3	18	15	15	4.00,15	18.35,7	11.404	17.913	1.522
4	20	15	15	4.00,15	18.35,7	11.404	17.913	1.631
5	22	15	15	4.00,15	18.35,7	11.404	17.913	1.740
6	24	15	15	4.00,15	18.35,7	11.404	17.913	1.848
7	26	15	15	3.50,15	18.32,7	11.599	18.62	1.955
8	28	15	15	3.50,15	18.32,7	11.599	18.62	2.061
9	30	15	15	3.50,15	18.32,7	11.599	18.62	2.167

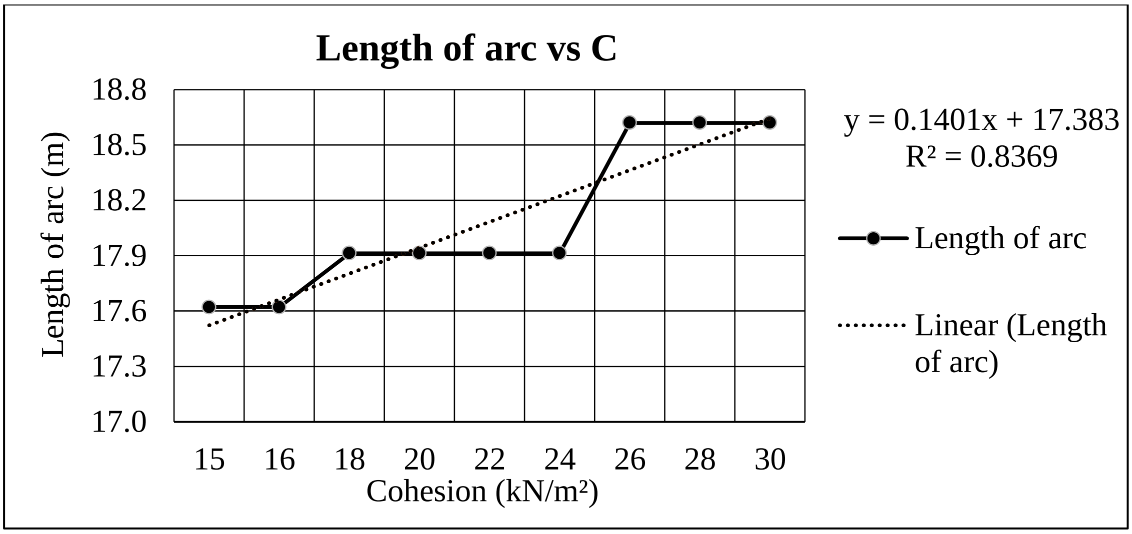

Fig 4.13 Effect of cohesion on length of failure arc

Figure 4.13 shows that when cohesion increases, the length of the failure surface also increases. As the cohesive force increases, the holding force also increases, which also applies to the FOS. In order to find the minimum value of FOS (which is the main purpose for slope stability analysis), the driving force must increase, which might be performed by increasing the area of slope failure. As a result, the greater value of arc failure length and so FOS is also increased.

4.3.2 Effect of angle of internal friction on slip surface

The values of cohesion and unit weight of the soil are kept constant at 15 kN/m³ and 15 kN/m² respectively, while the angle of internal friction varied from 16° to 30°, as shown in Table 4.8.

Table 4.8 Effect of Angle of internal friction on slip surface

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
10	15	16	15	4.60,15	18.31,7	11.218	17.621	1.392
11	15	18	15	5.15,15	18.30,7	11.042	17.34	1.465
12	15	20	15	5.15,15	18.30,7	11.042	17.34	1.537
13	15	22	15	5.15,15	18.30,7	11.042	17.34	1.610
14	15	24	15	5.15,15	18.30,7	11.042	17.34	1.685
15	15	26	15	5.75,15	18.35,7	10.877	17.085	1.761
16	15	28	15	5.75,15	18.35,7	10.877	17.085	1.837
17	15	30	15	5.75,15	18.35,7	10.877	17.085	1.916

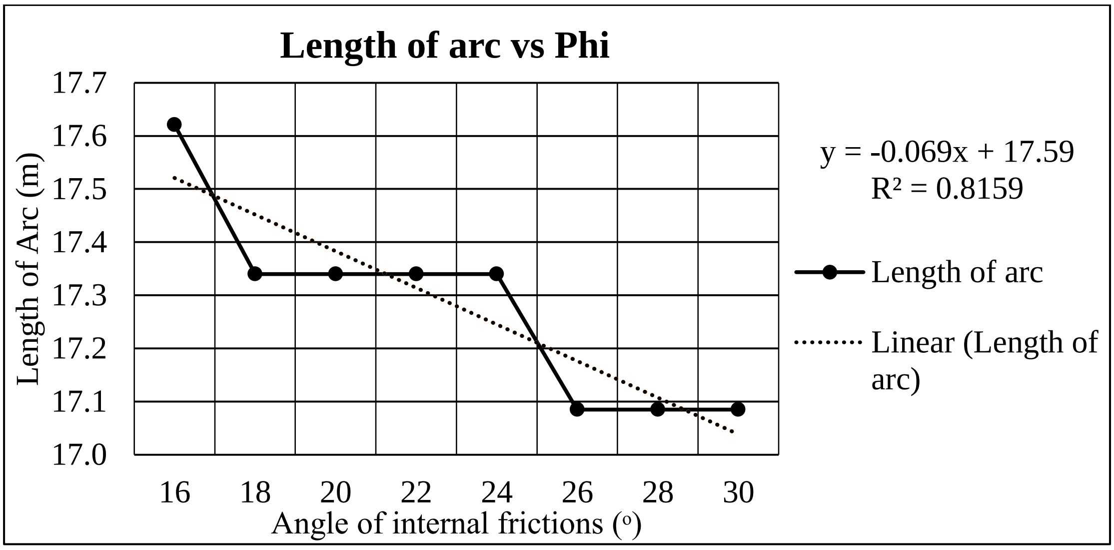

Fig 4.14 Effect of angle of internal friction on length of failure arc

The length of arc and ϕ are inversely connected, as can be seen in Figure 4.14, which states that when the distribution of geometry of the slope, unit weight in a homogeneous soil slope is given, the critical slip surface location for the slicing technique specifically is only related to the ratio C/tan(ϕ) of the slope (Jiang and Yamagami, 2008). This study shows that the length of the arc and the slip surface position have an inverse relationship to the angle of friction.

4.3.3 Effect of unit weight on slip surface

In order to investigate the effect of unit weight on slip surface, the angle of friction and cohesion of soil are kept constant at 15° and 15 kN/m², but the unit weight varied from 16 kN/m³ to 30 kN/m³, as given in Table 4.9.

Table 4.9 Effect of Unit weight on slip surface

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
18	15	15	16	4.59,15	18.30,7	11.218	17.621	1.303
19	15	15	18	4.59,15	18.30,7	11.218	17.621	1.216
20	15	15	20	5.16,15	18.31,7	11.042	17.340	1.143
21	15	15	22	5.16,15	18.31,7	11.042	17.340	1.084
22	15	15	24	5.16,15	18.31,7	11.042	17.340	1.035
23	15	15	26	5.73,15	18,35,7	10.877	17.085	0.992
24	15	15	28	5.73,15	18,35,7	10.877	17.085	0.955
25	15	15	30	5.73,15	18,35,7	10.877	17.085	0.922

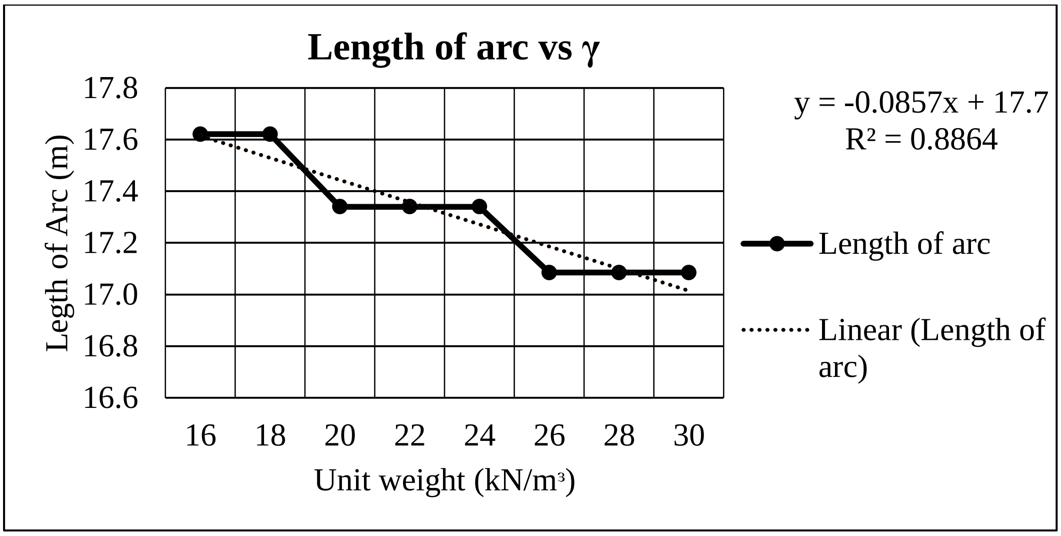

Fig 4.15 Effect of unit weight on length of failure arc

By increasing soil unit weight, the weight of the fallen area increases, resulting in a smaller value of factor of safety as shown in Figure 4.15. To put it another way, when lambda is taken into account, the surface of the failure slip moves towards the slope's face, however, when the length of arc is decreased, the effect of the angle of internal friction and cohesion as the forces of resistance decrease, resulting in a smaller factor of safety.

4.3.4 Effect of cohesion and angle of internal friction on slip surface

In this part, the angle of internal friction and cohesion changed from 16 to 30, while the unit weight remained at 15 kN/m³, as presented in Table 4.10.

Table 4.10 Effect of cohesion and angle of internal friction on slip surface

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
26	16	16	15	4.59,15	18.3,7	11.218	17.620	1.448
27	18	18	15	4.59,15	18.3,7	11.218	17.620	1.633
28	20	20	15	4.59,15	18.3,7	11.218	17.620	1.820
29	22	22	15	4.59,15	18.3,7	11.218	17.620	2.009
30	24	24	15	4.59,15	18.3,7	11.218	17.620	2.201
31	26	26	15	4.59,15	18.3,7	11.218	17.620	2.394
32	28	28	15	4.59,15	18.3,7	11.218	17.620	2.591
33	30	30	15	4.59,15	18.3,7	11.218	17.620	2.791

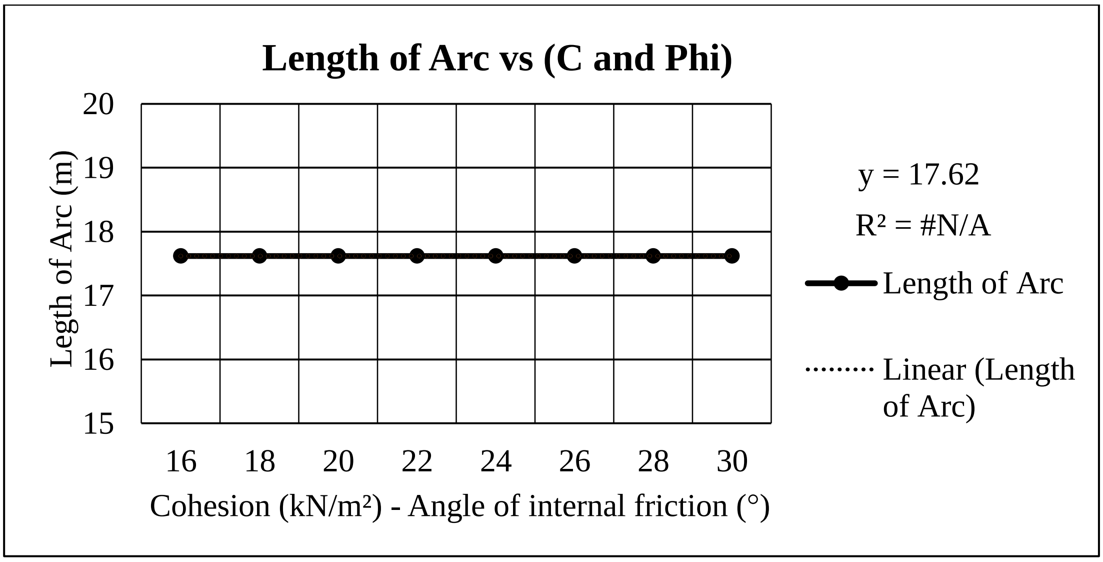

Fig 4.16 Effect of cohesion and angle of internal friction on length of failure arc

The combined effects of varying angle of internal friction and cohesion are depicted in Figure 4.16, which shows how they affect the length of the failure arc. When the factors cohesion and angle of internal friction are held constant between the values (16-30), it can be observed that the Length of arc will remain largely unchanged at the value (17.62 m). The length of the arc also stays constant since a constant lambda indicates a constant surface of failure and a constant lambda is produced by a constant C and tan(ϕ).

4.3.4 Effect of cohesion and unit weight on slip surface

The values of cohesion and unit weight of the soil varied from 16 to 30 respectively, but the angle of internal friction is kept constant at 15°, as presented in Table 4.11.

Table 4.11 Effect of cohesion and unit weight on slip surface

Model number	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
34	16	15	16	4.59,15	18.3,7	11.218	17.620	1.356
35	18	15	18	4.59,15	18.3,7	11.218	17.620	1.356
36	20	15	20	4.59,15	18.3,7	11.218	17.620	1.356
37	22	15	22	4.59,15	18.3,7	11.218	17.620	1.356
38	24	15	24	4.59,15	18.3,7	11.218	17.620	1.356
39	26	15	26	4.59,15	18.3,7	11.218	17.620	1.356
40	28	15	28	4.59,15	18.3,7	11.218	17.620	1.356
41	30	15	30	4.59,15	18.3,7	11.218	17.620	1.356

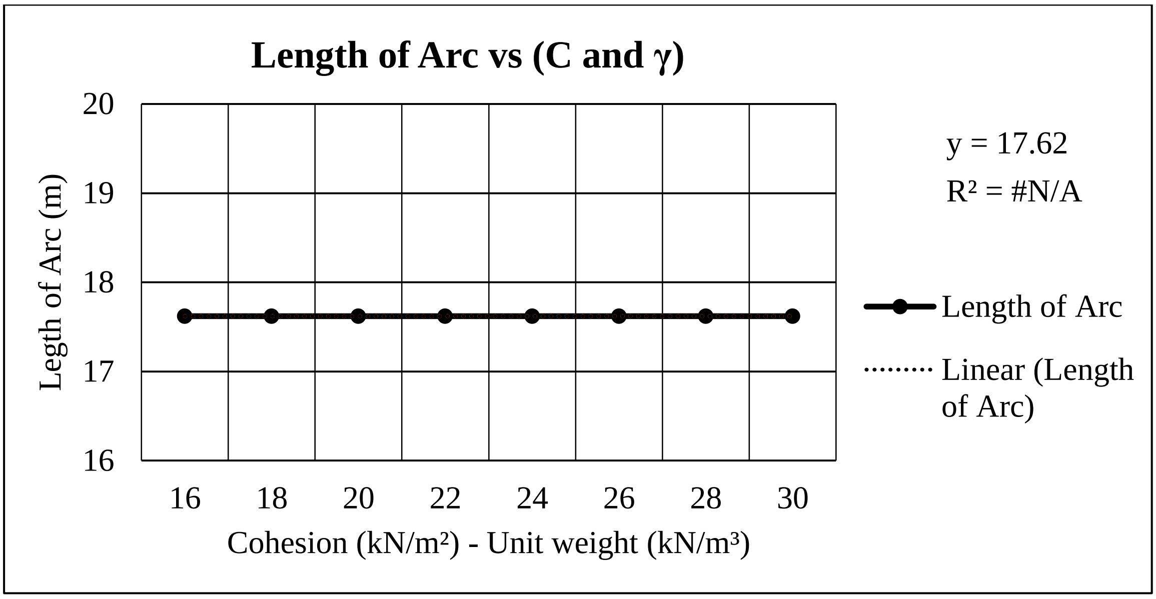

Fig 4.17 Effect of cohesion and unit weight on length of failure arc

In this part, unit weight and cohesion increased altogether in a way the ratio remain unchanged. The outcomes are shown in Figure 4.17.

Constant cohesion over unit weight ratio, which gives in a constant λ from equation 2.15. This indicates the same shape of failure and thus, an unchanging value of length of arc, as stated in the study by (Lin & Cao, 2011).

4.3.6 Effect of unit weight and angle of internal friction on slip surface

While the angle of internal friction and unit weight of soil, varied between 16 to 30, the cohesion factor remained constant at 15 kN/m², as given in Table 4.12.

Table 4.12 Effect of Internal angle friction and Unit weight on slip surface

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	Entry point (X,Y) (m)	Exit point (X,Y) (m)	Radius (m)	Arc length (m)	FOS
42	15	16	16	4.59,15	18.3,7	11.218	17.62	1.339
43	15	18	18	5.17,15	18.31,7	11.042	17.34	1.320
44	15	20	20	5.70,15	18.29,7	10.877	17.08	1.317
45	15	22	22	5.70,15	18.29,7	10.877	17.08	1.305
46	15	24	24	6.30,15	18.30,7	10.725	16.84	1.287
47	15	26	26	6.30,15	18.30,7	10.725	16.84	1.256
48	15	28	28	5.73,15	17.90,7	10.470	16.44	1.190
49	15	30	30	5.73,15	17.90,7	10.470	16.44	1.280

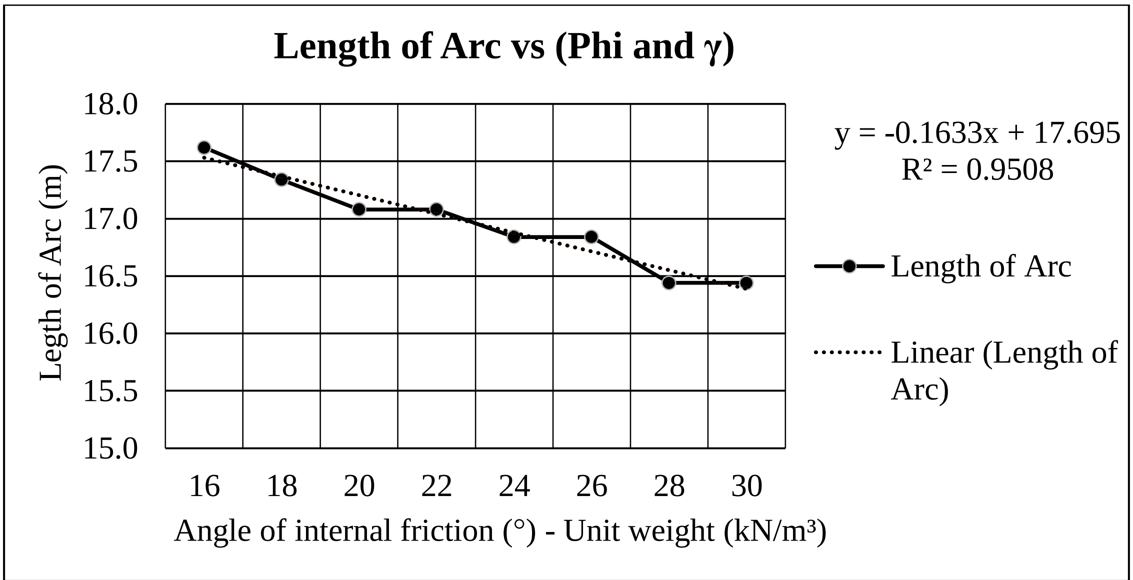

Fig 4.18 Effect of angle of internal friction and unit weight on length of arc

In this section, unit weight and angle of internal friction both are increased. The outcomes are depicted in Figure 4.18. By raising the value of γ and tanϕ, it is seen that the length of the surface failure will be reduced. A smaller λ value indicates that the failure surface is closer to the surface of slope and consequently, the length of arc is less.

Figures 4.19 to 4.24 show the critical failure surface of the slope with a minimum factor of safety value in SLOPE/W for all cases which are discussed above.

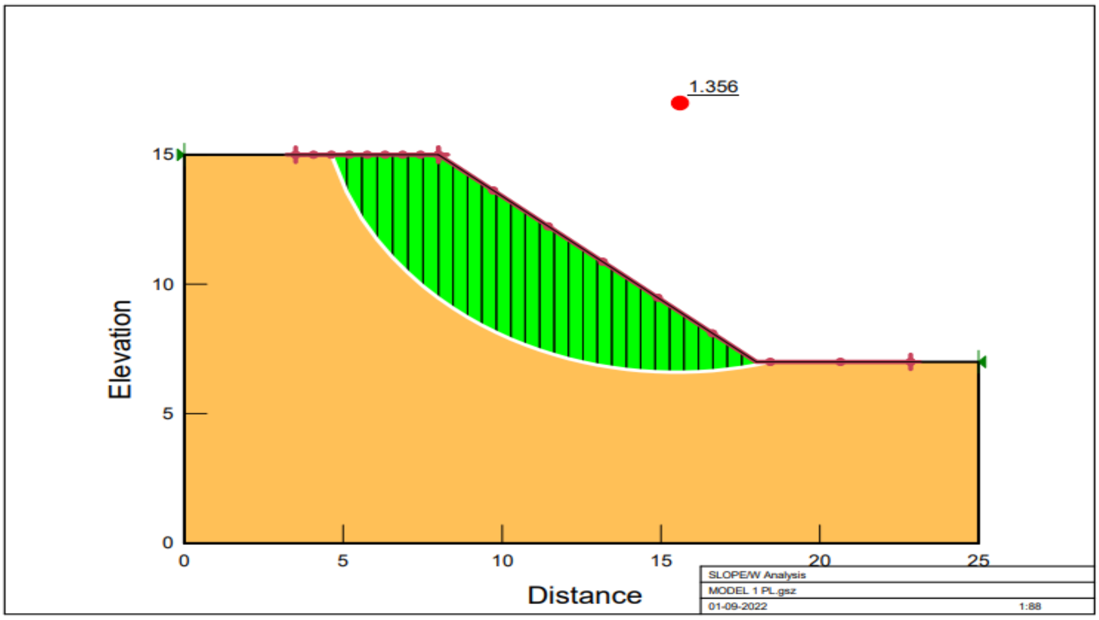

Fig. 4.19 Critical slope failure due to effect of cohesion using SLOPE/W

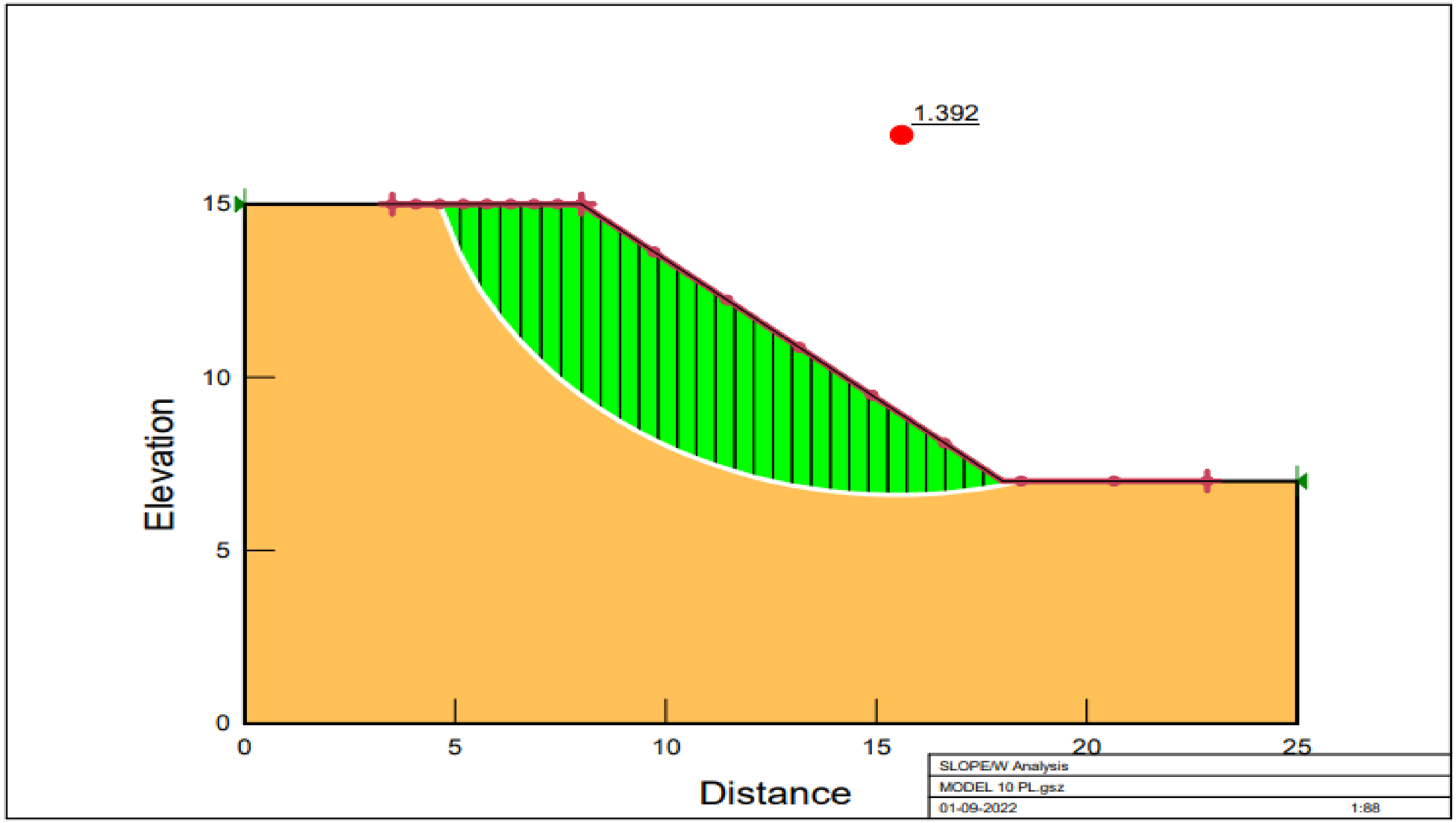

Fig. 4.20 Critical slope failure due to effect of angle of internal friction using SLOPE/W

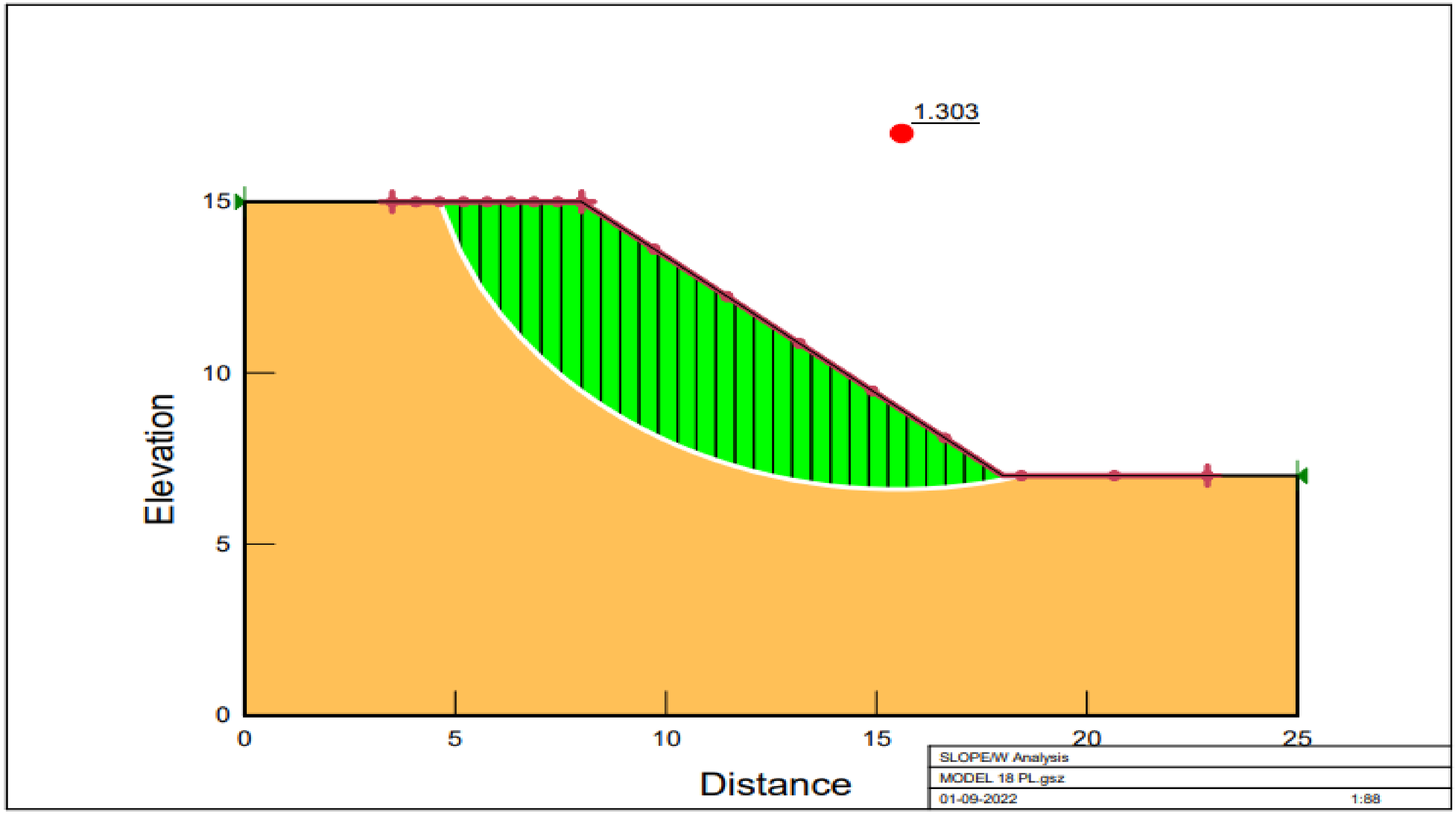

Fig. 4.21 Critical slope failure due to effect of unit weight using SLOPE/W

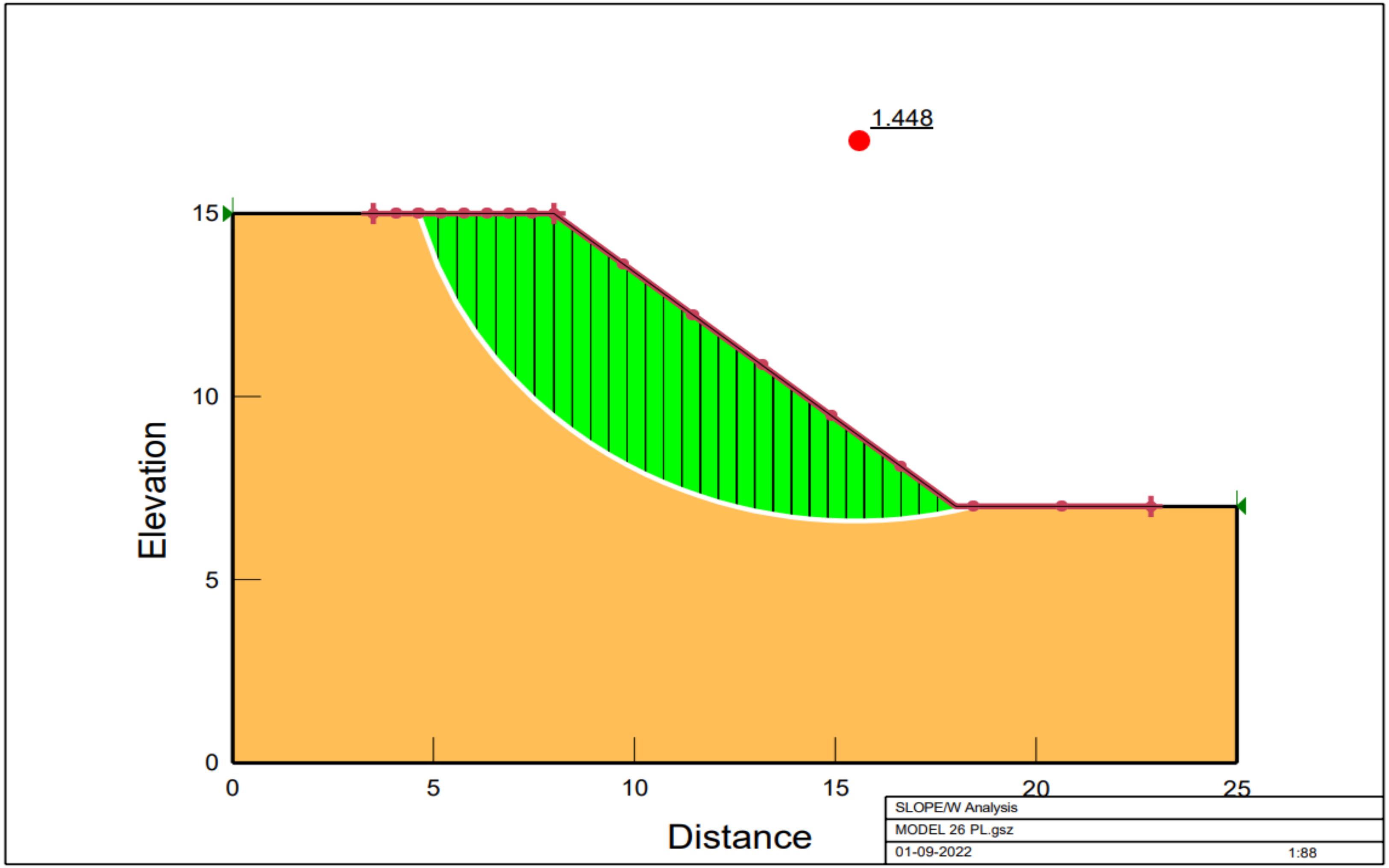

Fig. 4.22 Critical slope failure due to combined effect of cohesion and angle of internal friction using SLOPE/W

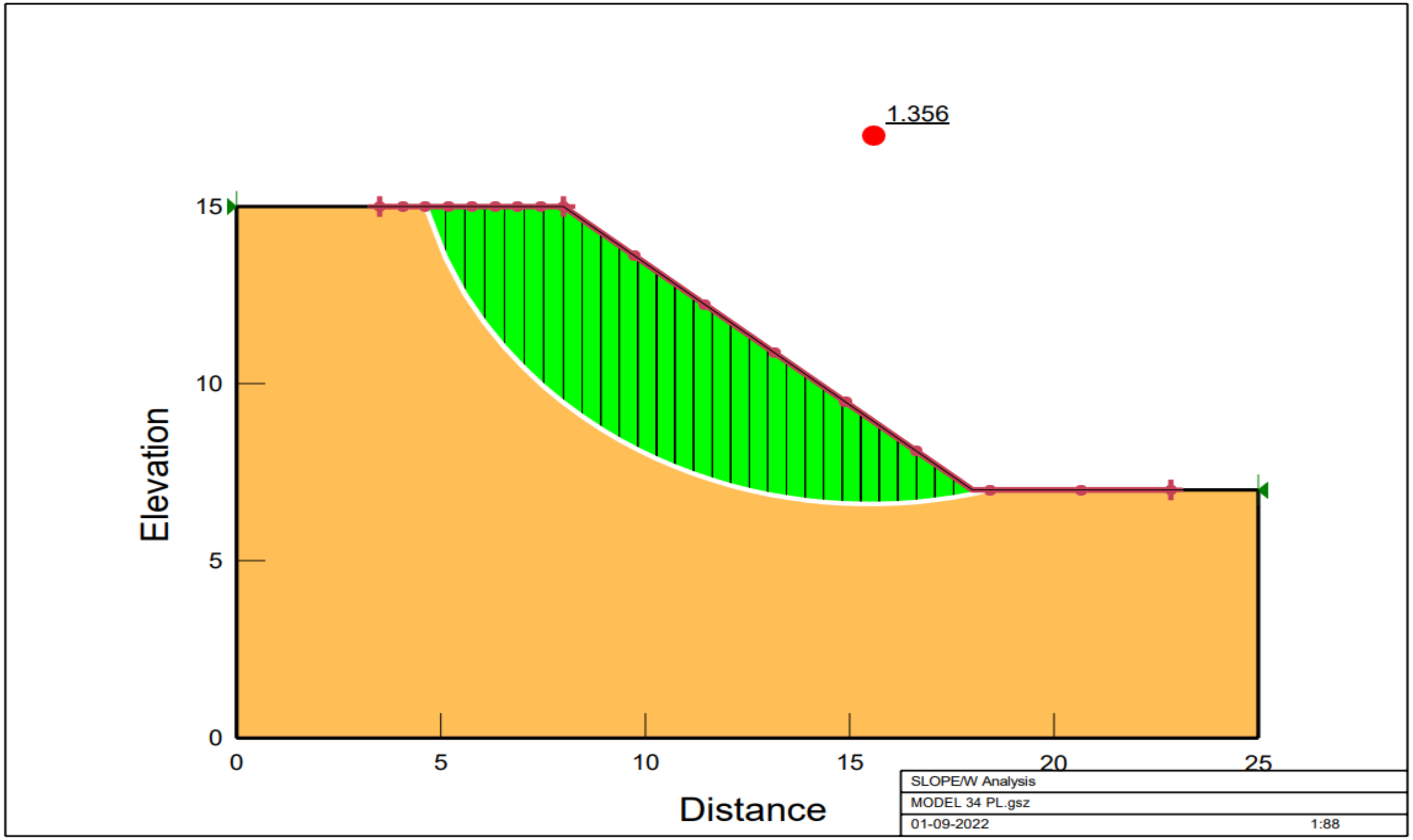

Fig. 4.23 Critical slope failure due to combined effect of cohesion and unit weight using SLOPE/W

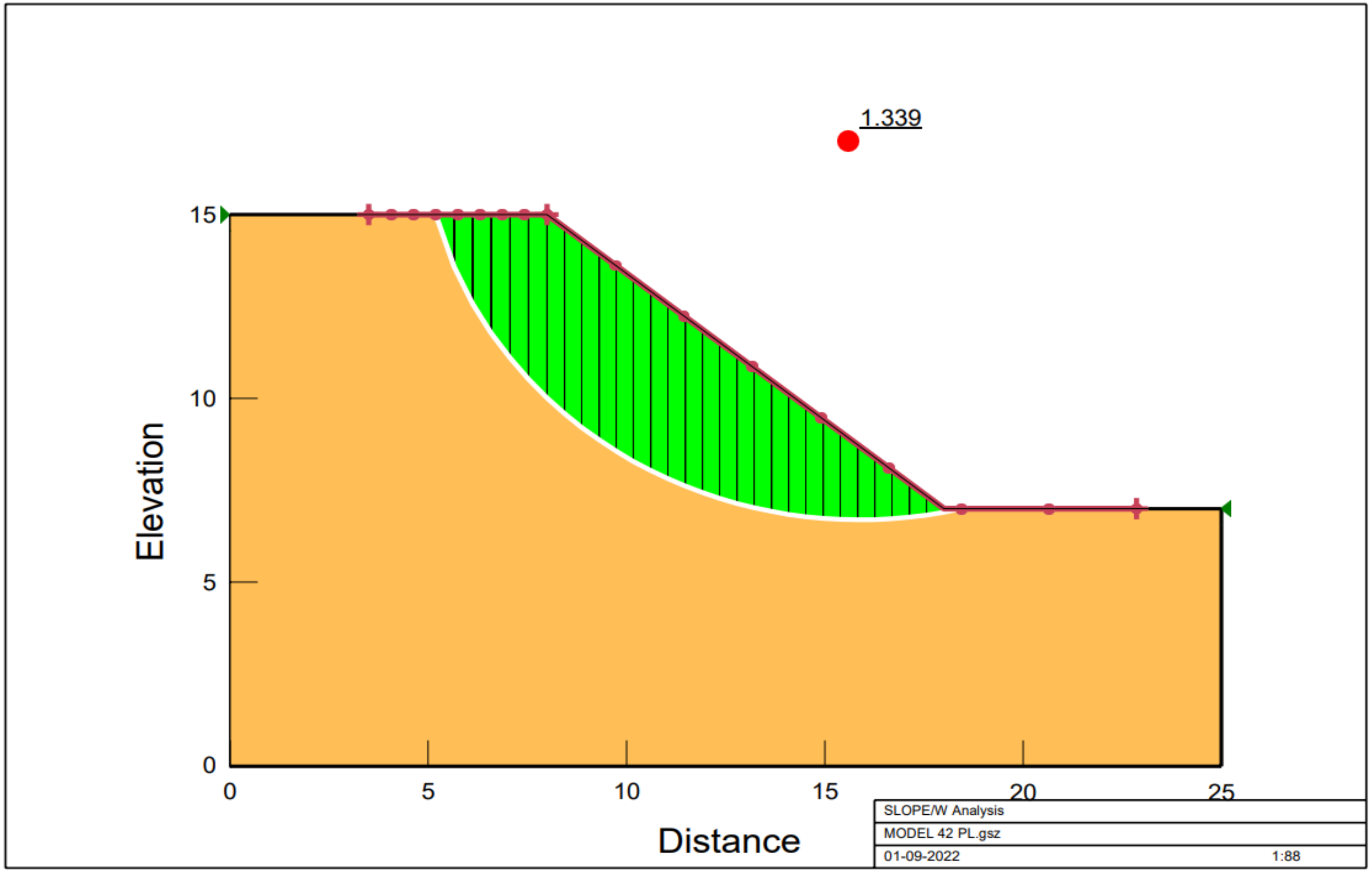

Fig. 4.24 Critical slope failure due to combined effect of angle of internal friction and unit weight using SLOPE/W

4.4 Effect of Slope Geometry on Factor of Safety

In order to track the effect of the slope shape on the factor of safety, different slope models were analyzed with constant soil parameters c = 15 kN/m², γ = 15 kN/m³ and ϕ= 15°.

In this part different types of sequence modelling were conducted. Every sequence of the model was to investigated for the slope stability analysis purpose with varying slope heights and slope angles were taken into account. Here are 3 different slope heights 4m, 7m and 10m and slope angles 30°, 40°, 50° and 60° were taken, as shown in Table 4.13.

Table 4.13 Effect of slope geometry on Factor of safety

Model number	Slope height (m)	Slope angle (°)	FOS
1	4	30	2.401
		40	2.160
		50	1.903
		60	1.726
2	7	30	1.659
		40	1.447
		50	1.271
		60	1.059
3	10	30	1.358
		40	1.159
		50	1.050
		60	0.894

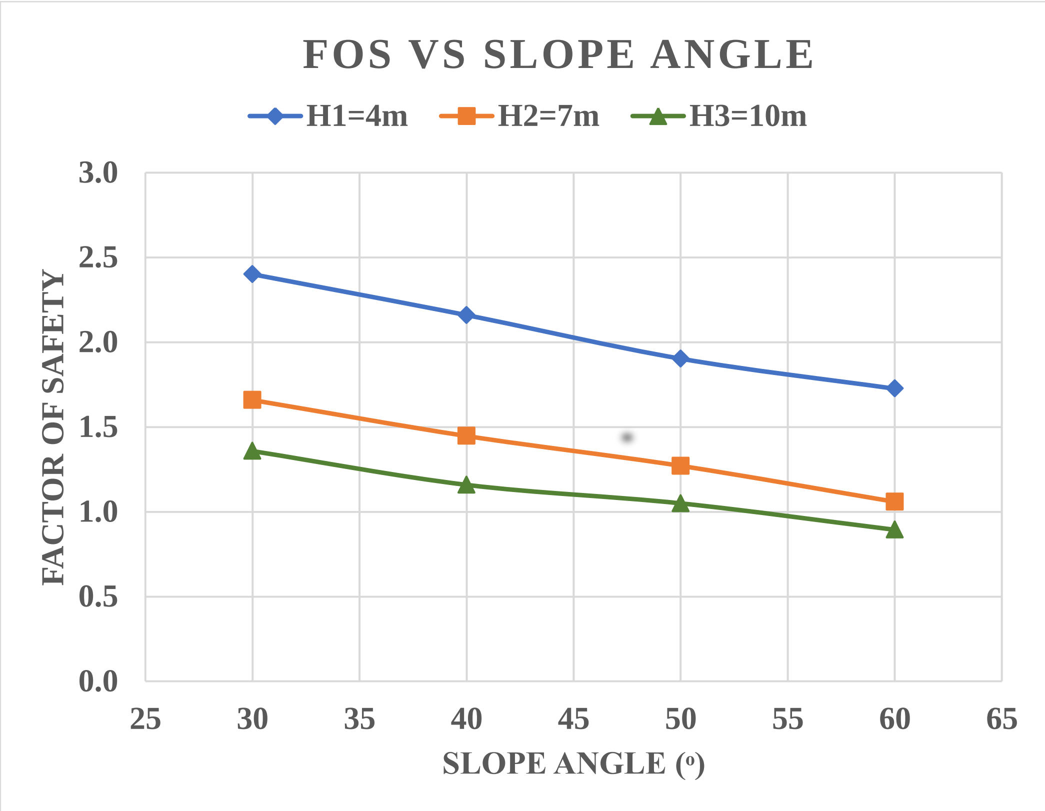

Fig. 4.25 Effect of slope angle and slope height on FOS

The factor of safety for the estimated slope surface is higher at the beginning and decreases as the slope angle and slope height increase. These decrease because of the increase in the angle as if adding an additional overhead load on the surface of the slope. As the angle is increased, the derivative force increases which cause the value of the factor of safety to fall.

Figures 4.26 to 4.28 show the failure surface of the slope with a minimum factor of safety value in SLOPE/W software for 3 different heights (4, 7 and 10m) with slope angle 30°, which are discussed above.

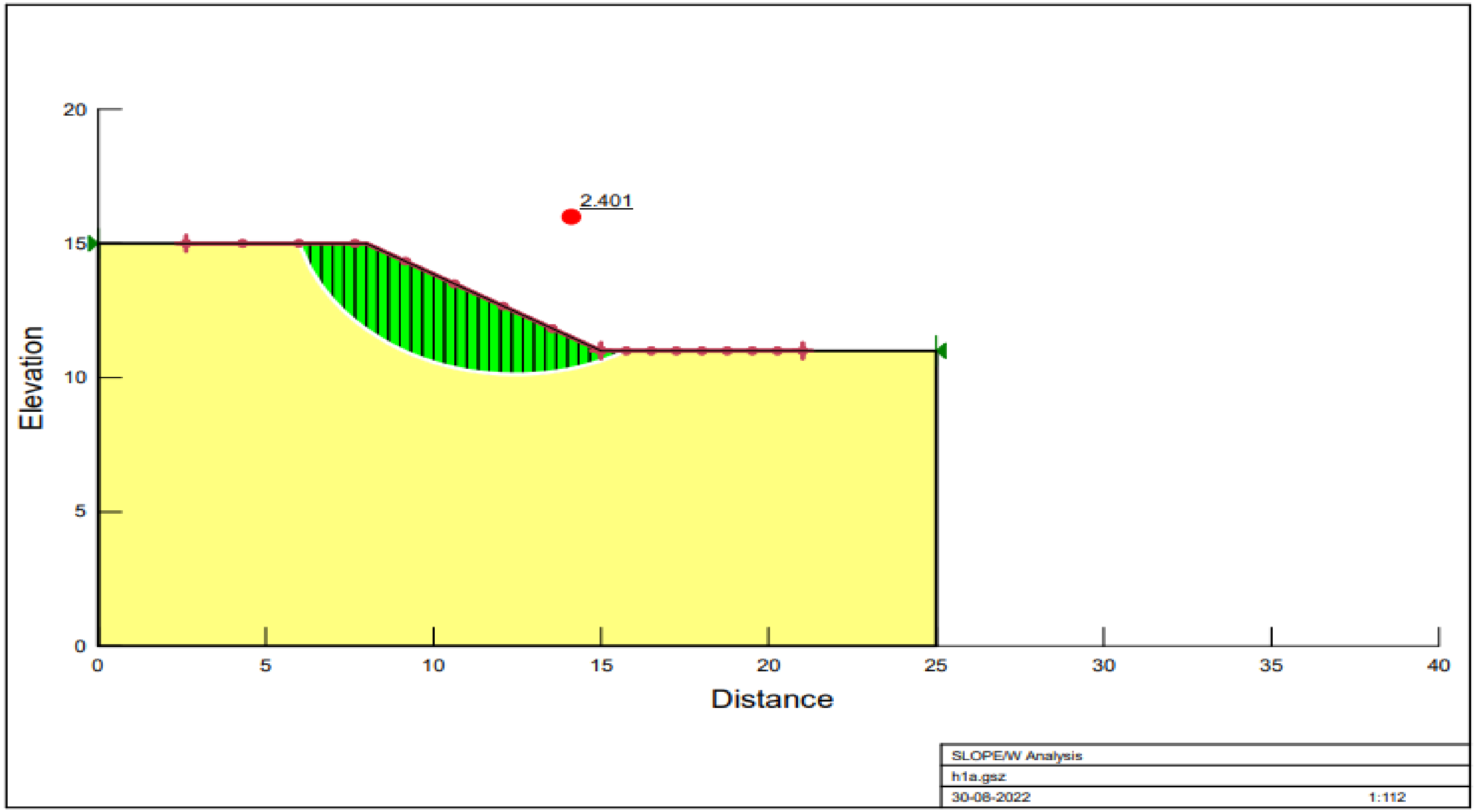

Fig. 4.26 Factor of safety of soil slope 30 degree with slope height of 4m using SLOPE/W

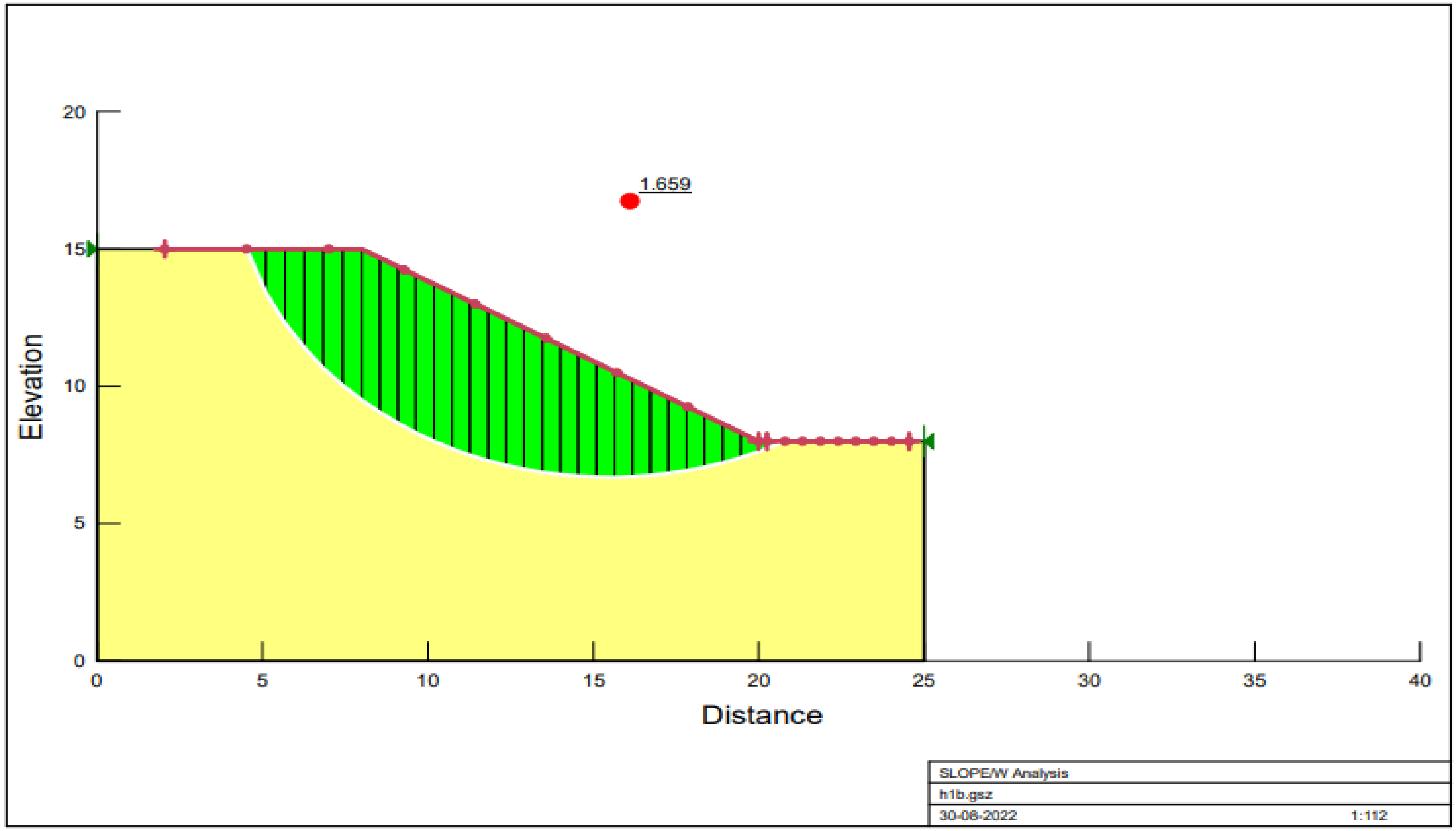

Fig. 4.27 Factor of safety of soil slope 30 degree with slope height of 7m using SLOPE/W

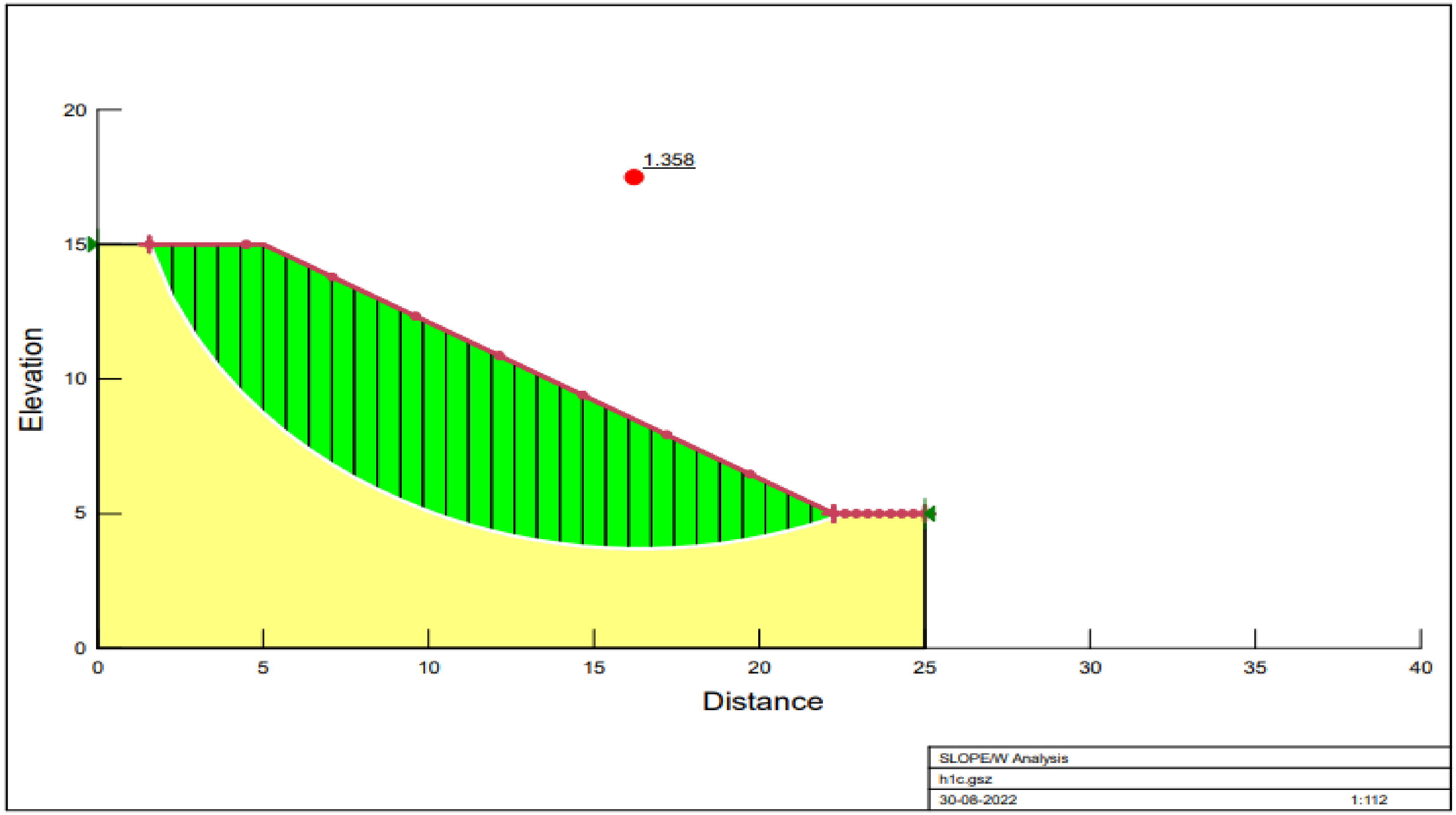

Fig. 4.28 Factor of safety of soil slope 30 degree with slope height of 10m using SLOPE/W

4.5 Reanalyzing Models by PLAXIS 2D and Comparison of Results

To ensure the accuracy of the results of the SLOPE/W programme obtained in section 4.2, the investigated models were analysed using the PLAXIS software. Tables 4.14 to 4.19 show the results obtained by PLAXIS 2D. Figures 4.29 to 4.34 show the critical failure surface of the slope with a minimum factor of safety value in PLAXIS 2D for all cases which are discussed above.

Table 4.14 Models of cohesion values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
1	15	15	15	1.360
2	16	15	15	1.415
3	18	15	15	1.525
4	20	15	15	1.627
5	22	15	15	1.735
6	24	15	15	1.847
7	26	15	15	1.946
8	28	15	15	2.051
9	30	15	15	2.151

Table 4.15 Models of angle of internal friction values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
10	15	16	15	1.398
11	15	18	15	1.481
12	15	20	15	1.542
13	15	22	15	1.580
14	15	24	15	1.701
15	15	26	15	1.768
16	15	28	15	1.854
17	15	30	15	1.931

Table 4.16 Models of unit weight values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
18	15	15	16	1.313
19	15	15	18	1.230
20	15	15	20	1.158
21	15	15	22	1.108
22	15	15	24	1.045
23	15	15	26	0.997
24	15	15	28	0.971
25	15	15	30	0.940

Table 4.17 Models of cohesion and angle of internal friction values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
26	16	16	15	1.455
27	18	18	15	1.644
28	20	20	15	1.832
29	22	22	15	2.026
30	24	24	15	2.212
31	26	26	15	2.416
32	28	28	15	2.612
33	30	30	15	2.818

Table 4.18 Models of cohesion and unit weight values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
34	16	15	16	1.360
35	18	15	18	1.360
36	20	15	20	1.360
37	22	15	22	1.360
38	24	15	24	1.360
39	26	15	26	1.360
40	28	15	28	1.360
41	30	15	30	1.360

Table 4.19 Models of angle of internal friction and unit weight values for the factor of safety analysis in PLAXIS 2D

Model number	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (PLAXIS 2D)
42	15	16	16	1.352
43	15	18	18	1.231
44	15	20	20	1.149
45	15	22	22	1.025
46	15	24	24	0.981
47	15	26	26	0.928
48	15	28	28	0.864
49	15	30	30	0.862

Table 4.20 analysis the outcomes using the following formula and explains the differences between the FOS obtained from the two softwares (PLAXIS and SLOPE/W).

$$Percentage\ Difference = \frac{FOS(SLOPEW) - FOS(PLAXIS)}{FOS(PLAXIS)} \times 100 \qquad (4.1)$$

Table 4.20 Difference of FOS between PLAXIS and SLOPE/W

Model number	FOS (SLOPE/W)	FOS (PLAXIS)	Difference, %
1	1.367	1.360	0.514
2	1.420	1.415	0.353
3	1.526	1.525	0.065
4	1.631	1.627	0.245
5	1.737	1.735	0.115
6	1.842	1.847	-0.270
7	1.948	1.946	0.102
8	2.054	2.051	0.146
9	2.159	2.151	0.371
10	1.408	1.398	0.715
11	1.484	1.481	0.202
12	1.559	1.542	1.102
13	1.636	1.580	3.544
14	1.716	1.701	0.881
15	1.797	1.768	1.640
16	1.882	1.854	1.510
17	1.969	1.931	1.967
18	1.318	1.313	0.380
19	1.232	1.230	0.162
20	1.160	1.158	0.172
21	1.101	1.108	-0.631
22	1.052	1.045	0.669
23	1.011	0.997	1.404
24	0.976	0.971	0.514

25	0.945	0.940	0.531
26	1.461	1.455	0.412
27	1.648	1.644	0.243
28	1.838	1.832	0.327
29	2.029	2.026	0.148
30	2.223	2.212	0.497
31	2.420	2.416	0.165
32	2.620	2.612	0.306
33	2.824	2.818	0.212
34	1.367	1.360	0.514
35	1.367	1.360	0.514
36	1.367	1.360	0.514
37	1.367	1.360	0.514
38	1.367	1.360	0.514
39	1.367	1.360	0.514
40	1.367	1.360	0.514
41	1.367	1.360	0.514
42	1.357	1.352	0.369
43	1.260	1.231	2.355
44	1.162	1.149	1.131
45	1.080	1.025	5.365
46	1.024	0.981	4.383
47	0.951	0.928	2.478
48	0.910	0.864	5.324
49	0.910	0.862	5.568

Table 4.20 demonstrates that PLAXIS is a more conservative design program. Apart from a few models, PLAXIS typically provides FOS that is less than 6% lower than that of SLOPE/W software. This makes PLAXIS more conservative and hence, safer to design and analyze slopes with larger significance. In comparison, higher the FOS of SLOPE/W makes it more advantageous to study and develop less significant slopes.

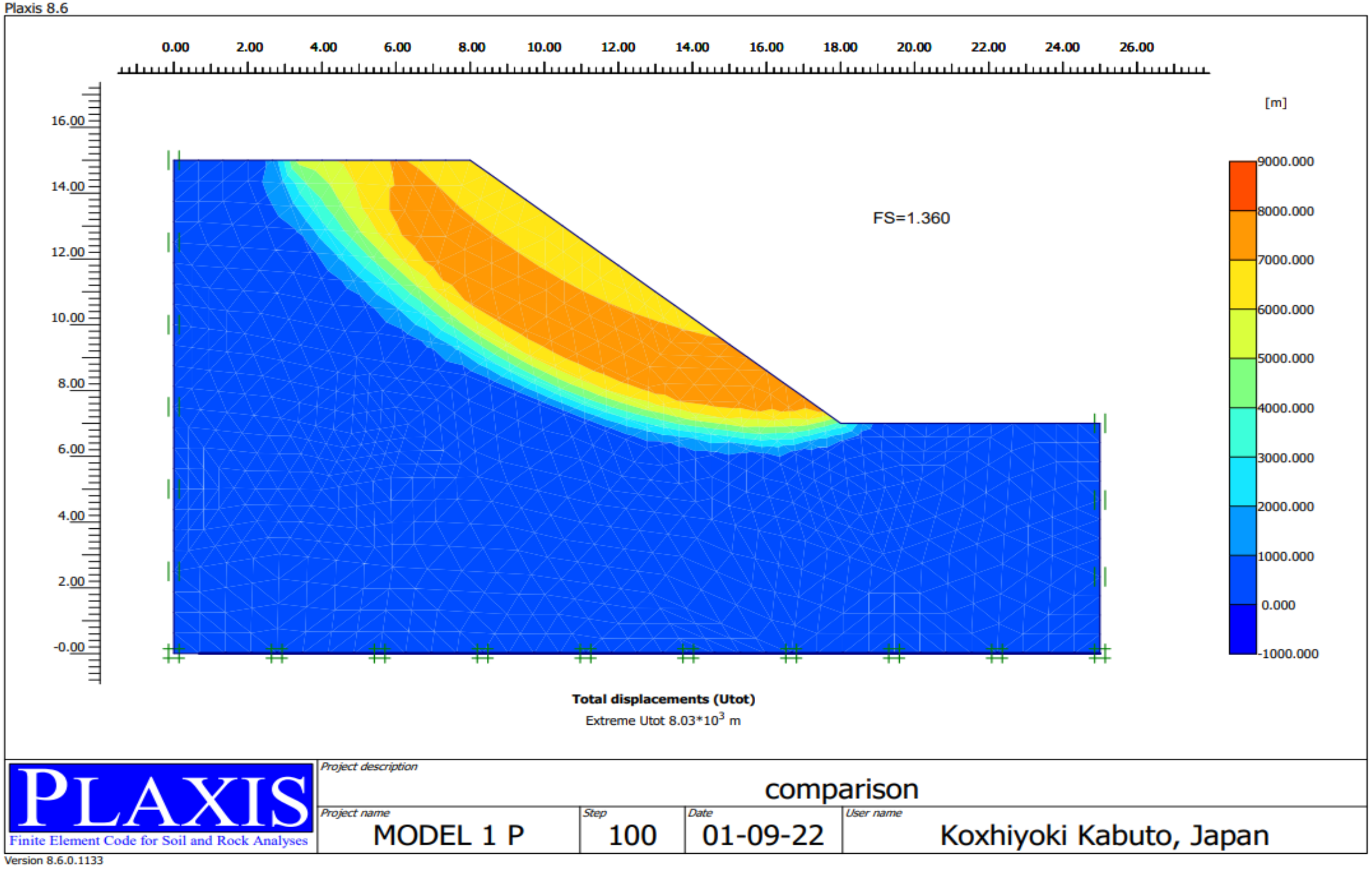

Fig. 4.29 Failure slope due to effect of cohesion using PLAXIS 2D

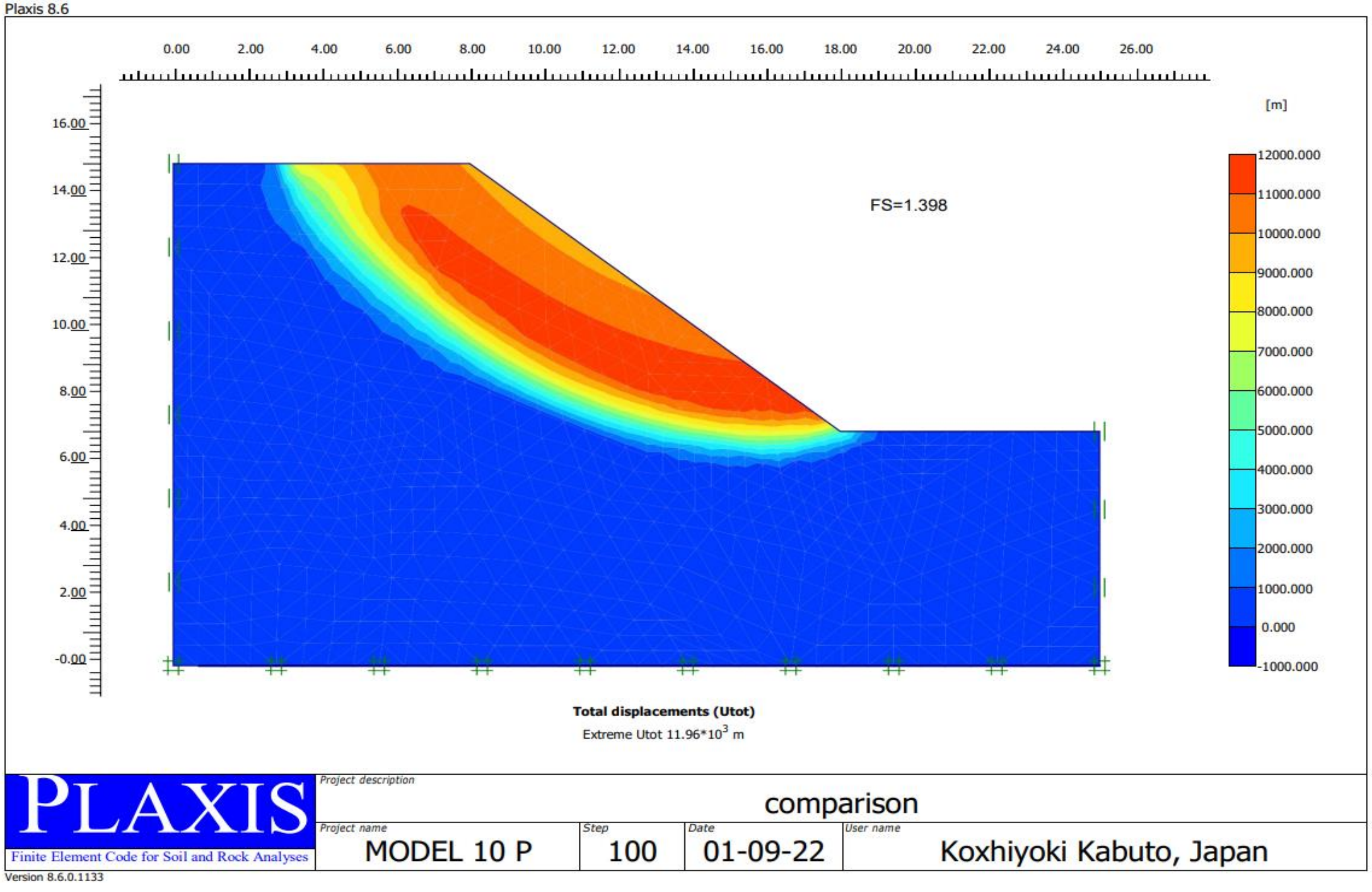

Fig. 4.30 Failure slope due to effect of angle of internal friction using PLAXIS 2D

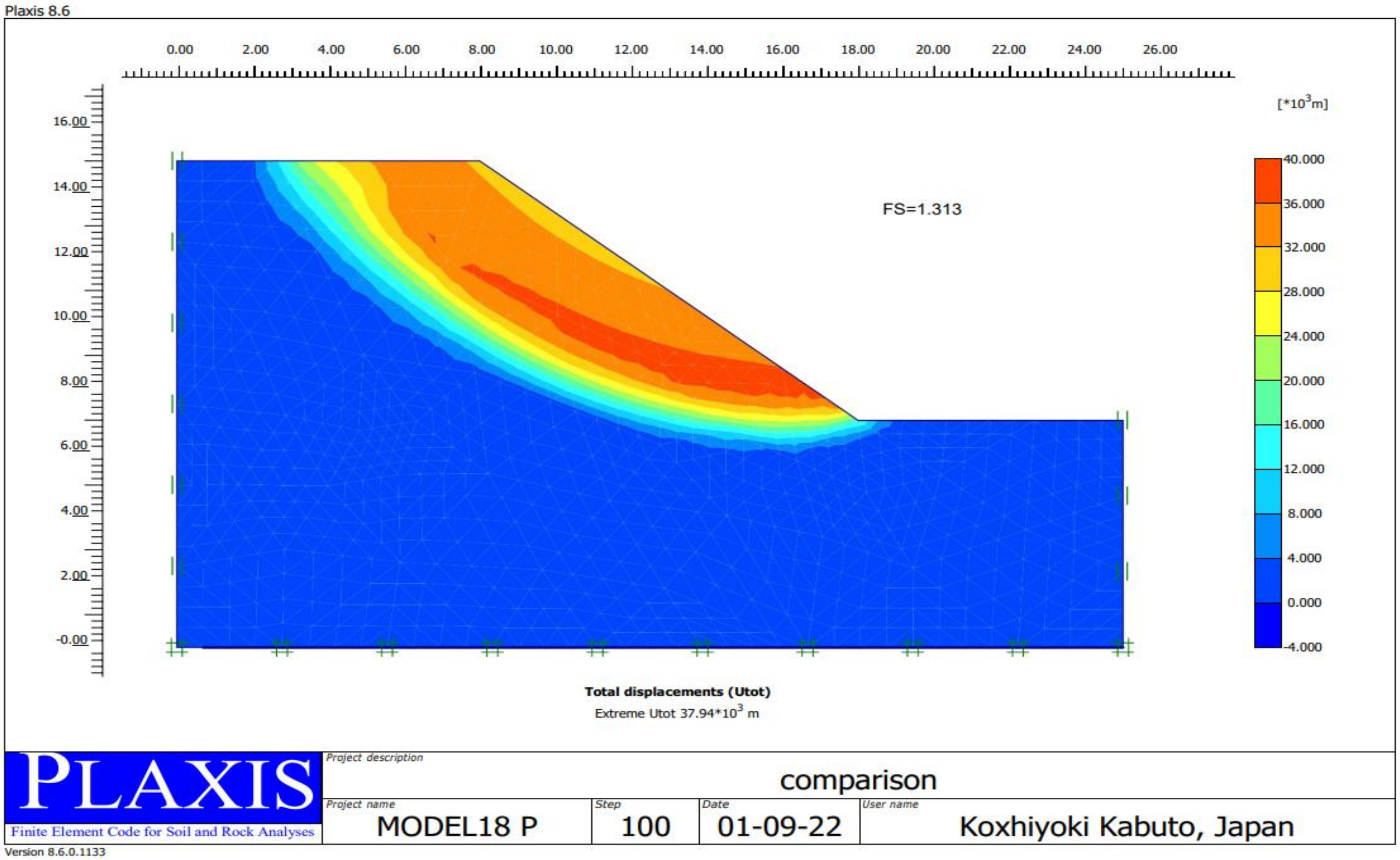

Fig. 4.31 Failure slope due to effect of unit weight using PLAXIS 2D

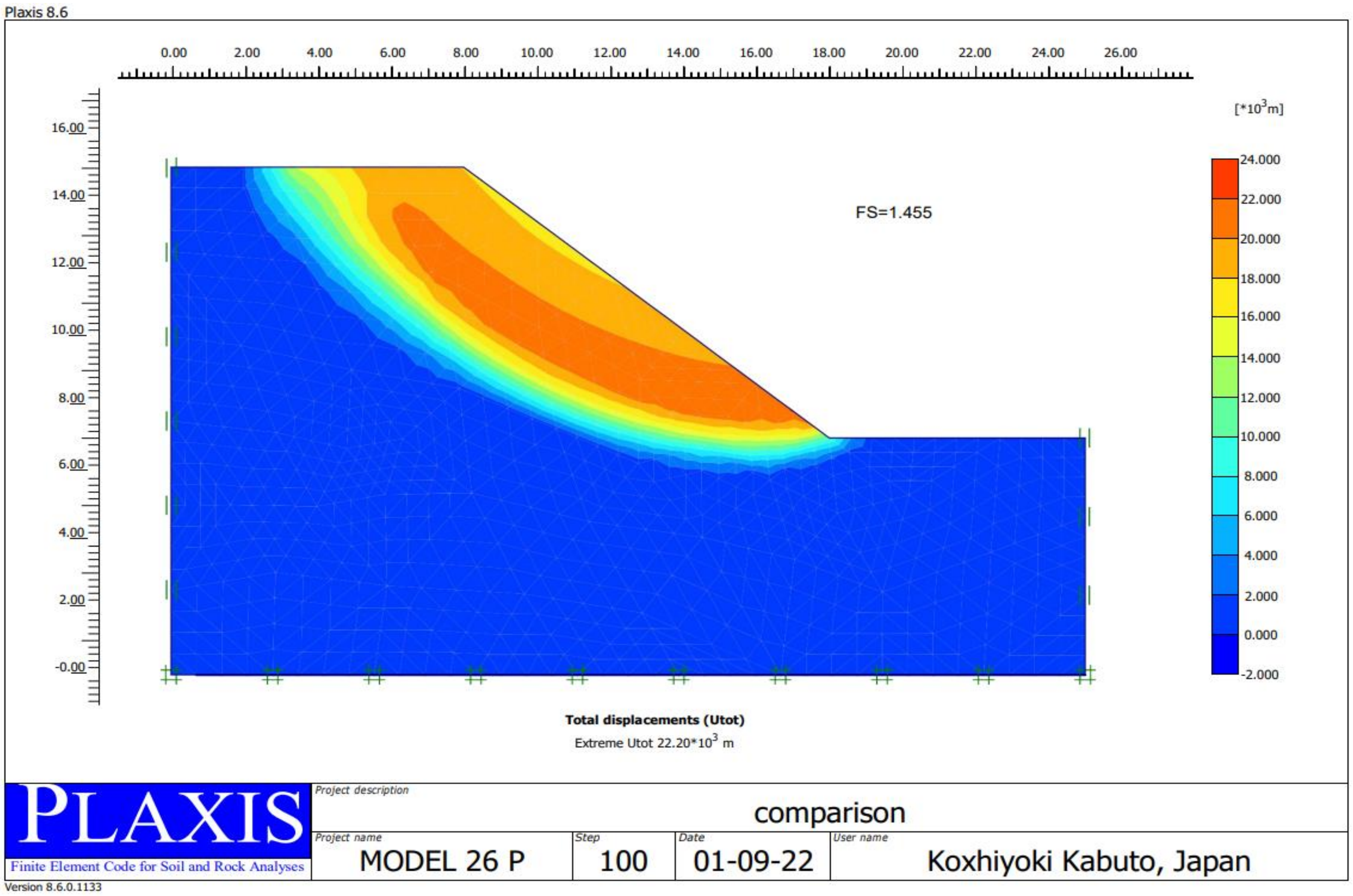

Fig. 4.32 Failure slope due to combined effect of cohesion and angle of internal friction using PLAXIS 2D

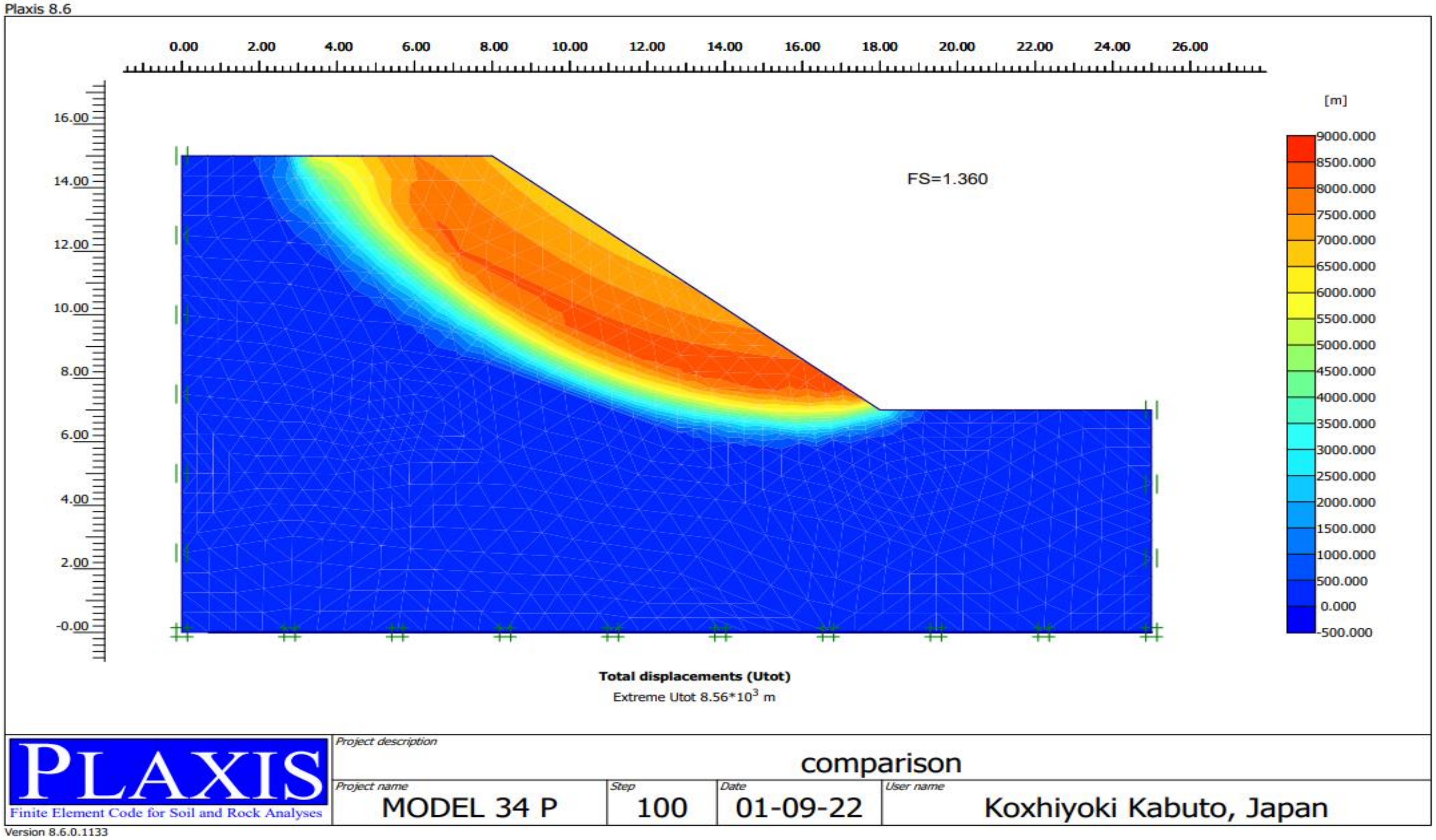

Fig. 4.33 Failure slope due to combined effect of cohesion and unit weight using PLAXIS 2D

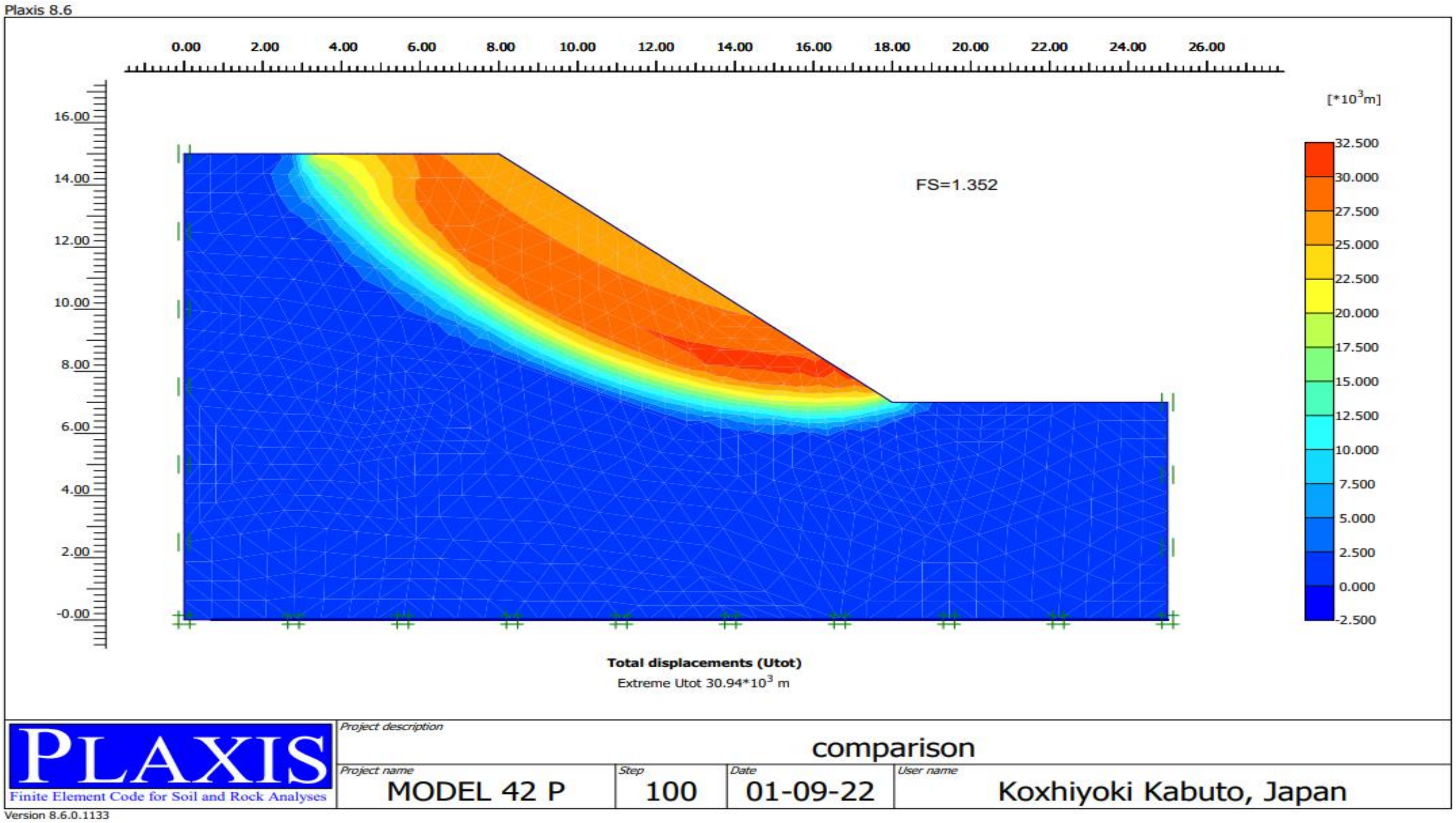

Fig. 4.34 Failure slope due to combined effect of angle of internal friction and unit weight using PLAXIS 2D

4.6 Reanalyzing Models by Swedish circle method

In order to examine the results of PLAXIS 2D and SLOPE/W, sample of the models were selected based on their properties. Then these models were reanalyzed by Swedish circle method. In Swedish circle approach number of trials had been done. In this part three number of trials have been taken for all individual models. Trials performed for the model number 1 are shown in Tables 4.21, 4.22 and 4.23 respectively.

Table 4.21 Analysis of model number 1 as per Swedish circle method (Trial 1)

Slice No.	Angle in radians (α)	Slice height (m)	Weight of slice (KN)	T=W (sinα)	N=W(cosα)	CL	FOS
1	0.174	2.4	93.6	-16.204	92.186	39.597	1.388
2	0.008	3.8	148.2	1.1850	148.195	39.001	
3	0.209	5.6	218.4	45.314	213.647	39.867	
4	0.523	6.6	257.4	128.566	222.991	45.017	
5	0.698	5.6	218.4	140.362	167.322	50.905	
6	1.047	2.6	78.0	67.542	39.013	59.979	
Total				366.766	883.357	274.369	

Table 4.22 Analysis of model number 1 as per Swedish circle method (Trial 2)

Slice No.	Angle in radians (α)	Slice height (m)	Weight of slice (KN)	T=W (sinα)	N=W(cosα)	CL	FOS
1	0.261	2.4	86.4	-22.295	83.473	37.261	1.435
2	0.034	3.6	129.6	-4.405	129.525	36.020	
3	0.174	5.2	187.2	32.408	184.373	36.551	
4	0.349	6.6	237.6	81.249	223.276	38.309	
5	0.698	6.4	230.4	148.075	176.516	46.989	
6	1.047	3.2	144.0	124.693	72.024	89.969	
Total				359.725	869.189	285.102	

Table 4.23 Analysis of model number 1 as per Swedish circle method (Trial 3)

Slice No.	Angle in radians (α)	Slice height (m)	Weight of slice (kN)	T=W (sinα)	N=W(cosα)	CL	FOS
1	0.261	2.4	86.4	-22.295	83.473	37.261	1.439
2	0.034	3.6	129.6	-4.405	129.525	36.020	
3	0.174	5.2	187.2	32.408	184.373	36.551	
4	0.523	6.6	257.4	128.566	222.991	45.017	
5	0.698	6.0	234.0	150.388	179.274	50.905	
6	1.047	2.0	78.0	67.542	39.013	77.973	
Total				352.205	838.651	283.731	

Similarly, all the models were analyzed by preforming three trials for obtaining factor of safety. Among these trials, the minimum value was adopted as factor of safety for that particular model. These trials were performed on excel spreadsheet which make manual calculation easier. FOS for all the models for which trials had been done by Swedish circle method is shown in the Tables 4.24 to 4.29.

Table 4.24 Models of cohesion values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m²)	Angle of internal friction (°)	Unit weight (kN/m³)	FOS (Swedish circle method)
1	15	15	15	1.388
2	16	15	15	1.438
3	18	15	15	1.538
4	20	15	15	1.638
5	22	15	15	1.737
6	24	15	15	1.837
7	26	15	15	1.937
8	28	15	15	2.037
9	30	15	15	2.136

Table 4.25 Models of phi values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	FOS (Swedish circle method)
10	15	16	15	1.438
11	15	18	15	1.530
12	15	20	15	1.624
13	15	22	15	1.718
14	15	24	15	1.817
15	15	26	15	1.920
16	15	28	15	2.026
17	15	30	15	2.136

Table 4.26 Models of unit weight values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	FOS (Swedish circle method)
18	15	15	16	1.342
19	15	15	18	1.264
20	15	15	20	1.201
21	15	15	22	1.150
22	15	15	24	1.108
23	15	15	26	1.072
24	15	15	28	1.041
25	15	15	30	1.014

Table 4.27 Models of cohesion and angle of internal friction values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	FOS (Swedish circle method)
26	16	16	15	1.487
27	18	18	15	1.679
28	20	20	15	1.873
29	22	22	15	2.067
30	24	24	15	2.266
31	26	26	15	2.469
32	28	28	15	2.674
33	30	30	15	2.884

Table 4.28 Models of cohesion and unit weight values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	FOS (Swedish circle method)
34	16	15	16	1.388
35	18	15	18	1.388
36	20	15	20	1.388
37	22	15	22	1.388
38	24	15	24	1.388
39	26	15	26	1.388
40	28	15	28	1.388
41	30	15	30	1.388

Table 4.29 Models of phi and unit weight values for the factor of safety analysis for the Swedish circle method

Model no.	Cohesion (kN/m^2)	Angle of internal friction (°)	Unit weight (kN/m^3)	FOS (Swedish circle method)
42	15	16	16	1.391
43	15	18	18	1.303
44	15	20	20	1.214
45	15	22	22	1.108
46	15	24	24	1.065
47	15	26	26	0.997
48	15	28	28	0.961
49	15	30	30	0.937

4.7 Comparison of FOS Obtained from SLOPE/W, PLAXIS 2D and Swedish Circle Method

The factor of safety obtained from SLOPE/W, PLAXIS 2D and Swedish circle method for all the models are represented in the tabulable form, as shown in Tables 4.30 and percentage difference between Swedish circle method and the others two softwares programs have been determine.

Table 4.30 Percentage difference in FOS between SLOPE/W, PLAXIS 2D and Swedish circle method

Model number	Factor of safety			% Difference b/w Swedish circle method and	
	SLOPE/W	PLAXIS 2D	CONVENTIONAL	SLOPE/W (%)	PLAXIS 2D (%)
1	1.367	1.360	1.388	1.512	2.017
2	1.420	1.415	1.438	1.251	1.599
3	1.526	1.525	1.538	0.780	0.845
4	1.631	1.627	1.638	0.427	0.671
5	1.737	1.735	1.737	0.000	0.115
6	1.842	1.847	1.837	-0.272	-0.544
7	1.948	1.946	1.937	-0.567	-0.464
8	2.054	2.051	2.037	-0.834	-0.687
9	2.159	2.151	2.136	-1.076	-0.702
10	1.408	1.398	1.438	2.086	2.781
11	1.484	1.481	1.530	3.006	3.202
12	1.559	1.542	1.624	4.002	5.049
13	1.636	1.580	1.718	4.772	8.032
14	1.716	1.701	1.817	5.558	6.384
15	1.797	1.768	1.920	6.406	7.916
16	1.882	1.854	2.026	7.107	8.489
17	1.969	1.931	2.136	7.818	9.597
18	1.318	1.313	1.342	1.788	2.160
19	1.232	1.230	1.264	2.531	2.689
20	1.16	1.158	1.201	3.413	3.580
21	1.101	1.108	1.150	4.260	3.652
22	1.052	1.045	1.108	5.054	5.685

23	1.011	0.997	1.072	5.690	6.996
24	0.976	0.971	1.041	6.243	6.724
25	0.945	0.94	1.014	6.804	7.297
26	1.461	1.455	1.487	1.748	2.151
27	1.648	1.644	1.679	1.846	2.084
28	1.838	1.832	1.873	1.868	2.189
29	2.029	2.026	2.067	1.838	1.983
30	2.223	2.212	2.266	1.897	2.383
31	2.420	2.416	2.469	1.984	2.146
32	2.620	2.612	2.674	2.019	2.318
33	2.824	2.818	2.884	2.080	2.288
34	1.367	1.360	1.388	1.512	2.017
35	1.367	1.360	1.388	1.512	2.017
36	1.367	1.360	1.388	1.512	2.017
37	1.367	1.360	1.388	1.512	2.017
38	1.367	1.360	1.388	1.512	2.017
39	1.367	1.360	1.388	1.512	2.017
40	1.367	1.360	1.388	1.512	2.017
41	1.367	1.360	1.388	1.512	2.017
42	1.357	1.352	1.391	2.444	2.803
43	1.260	1.231	1.303	3.300	5.525
44	1.162	1.149	1.214	4.283	5.354
45	1.080	1.025	1.108	2.527	7.490
46	1.024	0.981	1.065	3.849	7.887
47	0.951	0.928	0.997	4.613	6.920
48	0.910	0.864	0.961	5.306	10.093
49	0.910	0.862	0.937	2.881	8.004

4.8 Conclusions Based on Results

- For all models the FOS values obtained through PLAXIS 2D are less than the those obtained by SLOPE/W, apart from a few models.
- The FOS calculated by Swedish circle method gave highest value than the SLOPE/W and PLAXIS 2D softwares because of the higher number of slips and trials evaluated using softwares, which gave the higher accuracy.
- Cohesion and angle of internal friction have a linear relation to the factor of safety, whereas unit weight has a non-linear relation to the safety factor.
- The results indicated that a greater cohesion value corresponds to a higher value of the length of failure arc. On the other hand, by increasing the angle of internal friction and soil unit weight, decreasing the value of length of the failure arc.
- As increasing the height and angle of the slope, factor of safety is decreasing simultaneously and the slope becomes more unstable.

4.9 Concluding Remarks

By using LEM based software such as SLOPE/W, FEM based software such as PLAXIS 2D and LEM based Swedish circle method, their respective FOS has been studied and found that PLAXIS 2D are more conservative method for calculating FOS than the others. Variation on FOS is similar for SLOPE/W, PLAXIS 2D and Swedish circle method only values of FOS are different.

Summary and Conclusions

Chapter 5 SUMMARY AND CONCLUSION

5.1 General

In the field of Geotechnical engineering, they mainly focused on soil slope analysis and design. On the basis of different ways of assumption and assessment, many techniques have been designed and developed to examine two and three-dimensional slopes. When comparing the factor of safety of several trial slip surfaces, it is possible to identify the critical failure surface for a given slope. The critical failure surface for the specified slope must be obtained in order to determine the minimum factor of safety. In the past, several research and optimization techniques that were difficult to utilize for calculations by hand have been applied. Throughout this study, limit equilibrium and finite element methods have been used to analyze the slope stability of soil and to identify the critical slip surface of failure by using PLAXIS 2D, SLOPE/W software programs and Swedish circle method respectively. The efficiency of these techniques was examined using various soil parameter values. The effects of various unit weight, cohesion and angle of internal friction values on the factor of safety were explored and then the outcomes of several slope stability analysis techniques were compared.

5.2 Summary of Results

The value of FOS obtained by both the software is less than the Swedish circle method because number of slices evaluated by both the softwares was more, which leads to higher accuracy. In the Table 4.30 noticeable that FOSs obtained from PLAXIS 2D is lower than the other two techniques in 75% of the models. The Swedish circle method is lengthy and time-consuming because this method required lots of trials to be done manually, as this method is complex, so softwares are more preferred now-a-days. This study discloses that almost all the models are stable and factor of safety is more than unity.

5.3 Conclusions

- Comparing PLAXIS to SLOPE/W, which provides a value for the factor of safety that is approximately 6% lower, one can see that PLAXIS 2D is a more conservative software for slope stability investigations because the results obtain from PLAXIS 2D in a controlled manner and give more precise value by selection size of mesh.

- For large projects work like embankment dams, tunnels, deep excavations, *etc.* which required more precision work for the stability analysis, PLAXIS 2D software can be used.
- The Swedish circle method is the most complex technique to deal with and usually gave out the highest value for the factor of safety in comparison with PLAXIS 2D and SLOPE/W. This is because of the fact that higher number of iterations and higher number of slices are evaluated using PLAXIS 2D and SLOPE/W softwares.

5.4 Scope of Future Study

- Analysis and modeling of a larger variety of soil characteristics could be studied.
- The behaviour of stability of soil subjected to loading could be investigated.
- Including larger slope geometry variables such as the angle of the slope itself and the length of the slope.
- Carrying out a large-scale investigation to confirm the accuracy of the equations taken to identify the critical failure surface.
- Study related to the stability of slope on stabilized soil of the soil deposit slopes.

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ABSTRACT

The stability analysis of slope is one of the most significant topic in soil mechanics, which has particular significance in geotechnical engineering. Slope stability analysis is typically used to aid in the safe and cost-effective design of excavations, embankments, earth dams and landfills. The purpose of any stability analysis of slope is to determine the critical failure surface with the minimum value of factor of safety. The factor of safety is defined as the ratio of available shear strength of soil to the strength needed to maintain equilibrium. By comparing the factor of safety of various trial slip surfaces, the critical failure surface for a given slope can be identified. For calculations of slope stability, finite element techniques have recently been developed, but limiting equilibrium techniques are still commonly utilised. In the present study, the failure surface and factor of safety of slope were examined in relation to the soil parameters cohesion (c), angle of internal friction (ϕ) and unit weight (γ). software programs (SLOPE/W and PLAXIS 2D) and Swedish circle method were used to calculate the factor of safety and determine the critical failure surface. The outcomes obtained from SLOPE/W software, PLAXIS 2D software and Swedish circle method were compared.

The conclusions showed that compared to SLOPE/W, PLAXIS 2D is easier to use as slope stability assessment software. It gives about 6 % lower factor of safety value than SLOPE/W. On the other hand, Swedish circle method is the most complicated and usually gives the highest value for the factor of safety than SLOPE/W and PLAXIS 2D. The Swedish circle method is time-consuming because this method required lots of trials to be done manually, as this method is complex, so softwares are more preferred now-a-days.

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<u>सारांश</u>

ढलान का स्थिरता विश्लेषण मृदा यांत्रिकी में सबसे महत्वपूर्ण विषयों में से एक है, जिसका भू-तकनीकी इंजीनियरिंग में विशेष महत्व है। ढलान स्थिरता विश्लेषण का उपयोग आमतौर पर खुदाई, तटबंधों, मिट्टी के बांधों और लैंडफिल के सुरक्षित और लागत प्रभावी डिजाइन में सहायता के लिए किया जाता है। ढलान के किसी भी स्थिरता विश्लेषण का उद्देश्य सुरक्षा के कारक के न्यूनतम मूल्य के साथ महत्वपूर्ण विफलता सतह का निर्धारण करना है। सुरक्षा के कारक को मिट्टी की उपलब्ध कतरनी ताकत के अनुपात के रूप में परिभाषित किया जाता है ताकि संतुलन बनाए रखने के लिए आवश्यक ताकत हो। विभिन्न परीक्षण पर्ची सतहों की सुरक्षा के कारक की तुलना करके, किसी दिए गए ढलान के लिए महत्वपूर्ण विफलता सतह की पहचान की जा सकती है। ढलान स्थिरता की गणना के लिए, परिमित तत्व तकनीकों को हाल ही में विकसित किया गया है, लेकिन सीमित संतुलन तकनीकों का अभी भी आमतौर पर उपयोग किया जाता है। वर्तमान अध्ययन में, मिट्टी के मापदंडों सामंजस्य (सी), आंतरिक घर्षण के कोण (φ) और इकाई वजन (γ) के संबंध में विफलता सतह और ढलान की सुरक्षा के कारक की जांच की गई थी। सॉफ्टवेयर प्रोग्राम (स्लोप/डब्ल्यू और प्लैक्सिस 2डी) और स्वीडिश सर्कल विधि का उपयोग सुरक्षा के कारक की गणना करने और महत्वपूर्ण विफलता सतह को निर्धारित करने के लिए किया गया था। स्लोप/डब्ल्यू सॉफ़्टवेयर, प्लैक्सिस 2डी सॉफ़्टवेयर और स्वीडिश सर्कल विधि से प्राप्त परिणामों की तुलना की गई।

निष्कर्षों से पता चला है कि, स्लोप/डब्ल्यू की तुलना में, प्लैक्सिस 2डी को स्लोप स्टेबिलिटी असेसमेंट सॉफ्टवेयर के रूप में उपयोग करना आसान है। यह स्लोप/डब्ल्यू की तुलना में सुरक्षा मान का लगभग 6% कम कारक देता है। दूसरी ओर, स्वीडिश सर्कल विधि सबसे जटिल है और आमतौर पर स्लोप/डब्ल्यू और प्लैक्सिस 2डी की तुलना में सुरक्षा के कारक के लिए उच्चतम मूल्य देती है। पारंपरिक विधि समय लेने वाली है क्योंकि इस पद्धति को मैन्युअल रूप से करने के लिए बहुत सारे परीक्षणों की आवश्यकता होती है, क्योंकि यह विधि जटिल है, इसलिए सॉफ्टवेयर आजकल अधिक पसंद किए जाते हैं।

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