An Analysis of Slope Failure Using Numerical Modelling

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***ABSTRACT*:**
In the mining industry, slopes are formed after the extraction of minerals from the deposits using opencast mining. But often, these slopes fail to cause damage to machinery and sometimes even lead to fatal incidents. To avoid such accidents caused by slope failure, the slopes need to be designed with optimal geometry. The purpose of this paper is to analyze the effects of bench height and bench angle on the factor of safety of the slope and observe how the stability of the slope is affected by the varying geometry of the slope.

Keywords: Slope Failure - Bench Height – Bench Angle- FOS - Slide2- Rocscience

1. INTRODUCTION

Failure of a slope was usually attributed to divine intervention. Particularly when the harm includes the loss of life or property, attorneys nowadays can always find someone to place the blame on and someone to pay for the damage. Any slope, whether man-made or naturally occurring, whether it is made of rocks, dirt, or garbage dump, whether it has numerous layers with discontinuities or is simply geometric, can at some point present a threat to the property or to living things. Therefore, it is crucial to have a thorough understanding of a slope's behaviour and condition before working on it and a thorough understanding of the properties of the material constituting the slope before designing it. This will help to reduce the severity of the damage or the number of casualties as a result.

There are many ways to calculate the safety factor of a slope, but the limit equilibrium method (LEM), strength reduction method (SRM), or shear strength reduction method (SSRM), are now the most used methods. Although each method has its own drawbacks, the strength reduction methodology has demonstrated to be significantly more effective in determining safety factor than limit equilibrium methods since it does not require making any assumptions about where the sliding surface of a slope is located.

The rock mass material model employed in the majority of analyses by SRM, whether using Finite Element code (FEM) or Finite Difference code (FDM), is a linear elastic - completely plastic model, with the shear strength being constrained by the Mohr-Coulomb criterion. A ubiquitous joint model is used to add strength anisotropy, which restricts shear strength in accordance with the Mohr-Coulomb criterion in a specific direction that corresponds to the orientation of the discontinuity. Speaking about shear strength, slope geometry parameters and the shear strength properties of cohesion (C) and friction angle () have a major impact on the predicted value of factor of safety.

1.1 Some of the Studies on Slope Stability

i. A Finite Element Approach of Stability Analysis of Internal Dump Slope in Wardha Valley Coal Field, India, Maharashtra.

According to Dhananjai Verma (2013), a computational analysis using the finite element method was conducted to determine the stability of internal dump slopes from an opencast coal mine in Wardha Valley Coal Field, Maharashtra, India, that are 80 meters high (FEM). In order to comprehend the failure mechanism and the variations in factor of safety with variation in bench height and the number of benches, many scenarios according to the dump heights have been accounted for and simulated using Plaxis2D-8. It has been discovered that when the height of the dump slope increases, the FOS decreases significantly. When working at a height of 60 meters, the slope was found to be steady. After the construction of one bench, FOS for an internal dump slope that is 80 meters high fell to less than one

ii. Effects of spatial variability of soil properties on slope stability

A numerical method for a probabilistic slope stability study based on a Monte Carlo simulation that takes into account the spatial variability of the soil parameters is described, according to Sung Eun Cho's (2007) statement in this paper. The study sheds light on how uncertainty treatment is applied to slope stability and highlights the significance of soil property spatial variability in terms of a probabilistic assessment's outcome. To determine the fluctuation in failure probability with variation of the soil properties in layered slopes, probabilistic stability evaluations were carried out. The locations on the searched crucial probabilistic surfaces differed slightly from those on the critical deterministic surface.

iii. Slope Stability Analyses in Stiff Fissured Clays

Based on the outcomes of torsion ring shear, direct shear, and triaxial compression tests on clays, mudstones, and shale, Timothy stark (1997) made the following conclusions. The type of clay mineral and quantity of clay size particles

iv. Influence the stress dependence and regulation of the fully softened shear strength. Only 29% of the soil-covered slopes in the study area are guaranteed to be stable under all circumstances, according to RL Ray's (2008) investigation of slope stability on a regional scale using GIS and a case study from Dhading, Nepal. This shows that these soils are susceptible to failure with a gradual rise in saturation because of their low cohesion and anthropogenic perturbations.

1.2 SLIDE by Rocscience:

For assessing the safety factor of circular or non-circular failure surfaces on soil or rock slopes, SLIDE is a 2D slope stability program. SLIDE is incredibly easy to use while also allowing for the quick and simple creation and analysis of complex models. Modeling options for external loading, groundwater, and support are numerous. SLIDE employs vertical slice limit equilibrium techniques to examine the stability of slip surfaces. To identify the crucial slip surface for a specific slope, one can evaluate individual slip surfaces or use search techniques.

Features include:

- For circular or non-circular slip surfaces, perform a critical surface search.
- Bishop, Janbu, Spencer, and GLE are some analysis techniques.
- Various materials: Mohr Coulomb materials that are anisotropic, non-linear, and other strength models
- Groundwater analysis using steady state groundwater or piezo surfaces, Ru factors, pore pressure grids, etc.
- Tension crack (dry or water filled)
- External loading – line, distributed or seismic

• Support – soil nails, tiebacks, geo textiles, piles. Infinite strength (slip surface exclusion) zones
• View any or all surfaces generated by search
• Detailed analysis results can be plotted for individual slip surfaces

2. Numerical Analysis of slope

The Modified (or Simplified) Bishop's Method is an extension of the Method of Slices and is generally used for calculating safety factors of slopes. As shown in Figure 1, weight of i^th^ slice (W_i) acts vertically downward. The resistive force (T_i) and normal force (N_i) act at the base of the slice. By simplifying the assumptions that forces on the sides of each slice are horizontal and no shear force exists at the vertical sides of the slice, the problem becomes statically determinate and suitable for hand calculations. The method has been shown to produce factor of safety values within a few percentage of the "correct" values. The equation 5 represents the safety factor of the slope based on the Bishop's Method.

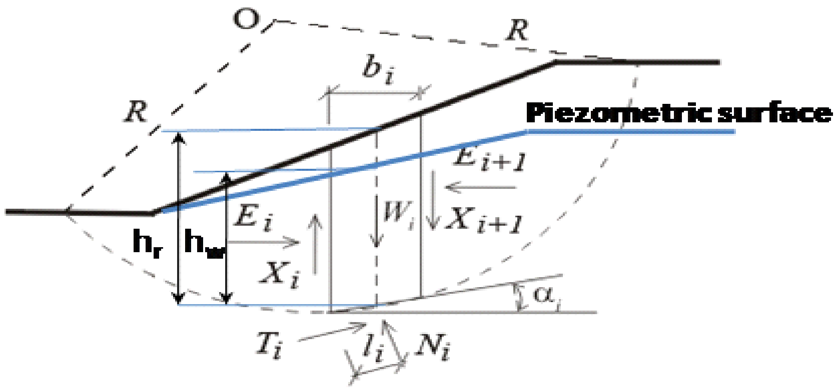

Figure: 1Bishop's Simplified Method of Slices

c' is the effective cohesion, φ' is the effective angle of internal friction, b_i is the width of eachslice, assuming that all slices have the same width, W_i is the weight of each slice, r_{u_i} is the pore water pressure of each slice and is expressed as r_u = (h_w/h_r) (γ_w / γ_r), γ_w and γ_r are bulk density of water and geo-material respectively. The parameters, h_w and h_r are height of piezometric surface and that of slice respectively as shown in Figure 7. SF is obtained by iterative method. An initial value of SF is assumed and then Newton-Raphson or other iterative techniques are applied to estimate the final SF until difference between SFs for two consecutive iteration is minimal.

3. FIELD DATA

The following data has been collected from a south Indian mine for the purpose of this project

Overburden properties:

Property	Value
Unit weight	19 KN/m^3

Cohesion	18.33 KPa
Angle of internal friction	36.12°
Dump density	2.5
Bulk modulus	0.35 MPa

Table: 1 Overburden properties

Direct shear test data of overburden dump material at 0% moisture:

Test no.	Normal stress (KPa)	Shear stress (KPa)
1	50	57
2	100	87
3	150	130

Table: 2 overburden dump material at 0% moisture

4. MODEL PREPARATION

In our study 9 models have been prepared and analysed with different bench parameters

- 3 bench heights have been considered as 5 meters, 10 meters, 15 meters
- 3 bench angles have been considered as 23°, 37.5° and 45°
- And models have been prepared with 3 benches, for the analysis

So, with the above varying bench parameters a total of 9 models have been analysed i.e., 3 with varying bench height and 3 with bench angle (3x3=9)

All the models are prepared in the software called SLIDE by Rocscience

4.1 STEPS IN MODEL PREPARATION

The following steps are to be performed to prepare and analyse a model in Slide software

- Defining project settings
- Defining material properties
- Preparing the slope geometry
- Computing and interpretation

4.2 Defining project settings

1. After opening the slide software, in the tabs bar select analyse
2. Then select project settings
3. Next select the failure direction of the slope that needs to be analysed i.e., whether the slope is inclined from right to left or from left to right direction
4. In our analysis all the slopes have been designed from left to right orientation

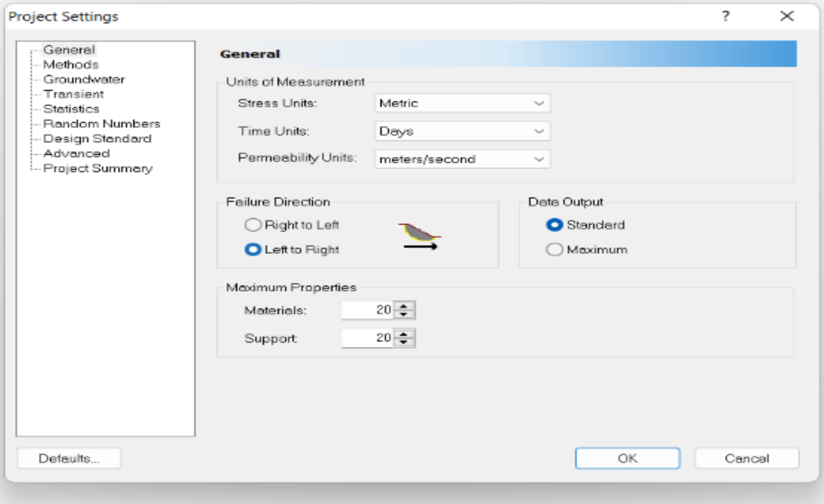

Figure: 2 Defining project settings

4.3 Defining material properties

In this step, the properties of the material forming the slope have to be defined

1. First select properties tab from the tabs bar
2. Then select define material
3. Next assign values of the material properties. The following 3 material properties needs to be assigned
    a. Unit weight in KN/m^2
    b. Cohesion in KPa
    c. Angle of internal friction in degrees
4. In this study, the following values have been assigned to the material properties according to the field data

Properties	Value
Unit weight	19 KN/m^2
Cohesion	18.33 KPa
Angle of internal friction	36.12°

Table: 3 material properties

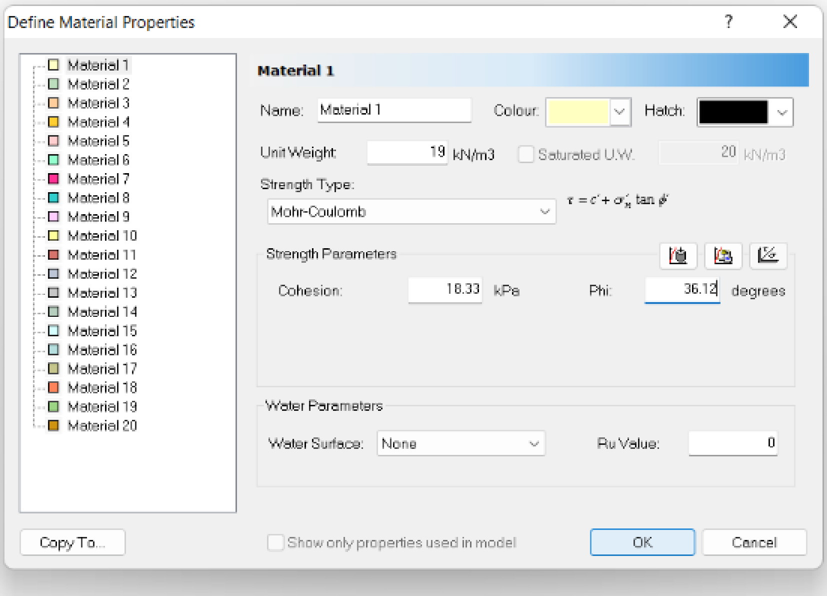

Figure: 4 Defining material properties

4.4 Preparing the slope geometry

1. In this step the geometry of the slope has to be prepared i.e., the outline of the slope has to be drawn according to its dimensions
2. For this select boundaries from the tabs bar
3. Then click on external boundaries
4. After that the coordinates of the slope outline have to be entered to prepare the slope geometry

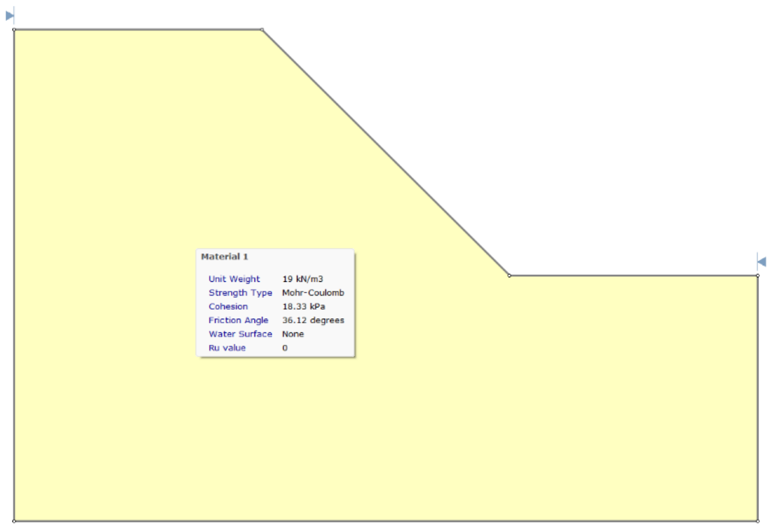

Figure: 5 preparing the slope geometry

4.5 Computing and interpretation

1. After the preparation of the slope geometry, click on surfaces tab and select auto grid and click enter
2. After selecting auto grid , a square shaped grid is formed above the slope model as shown in the below figure

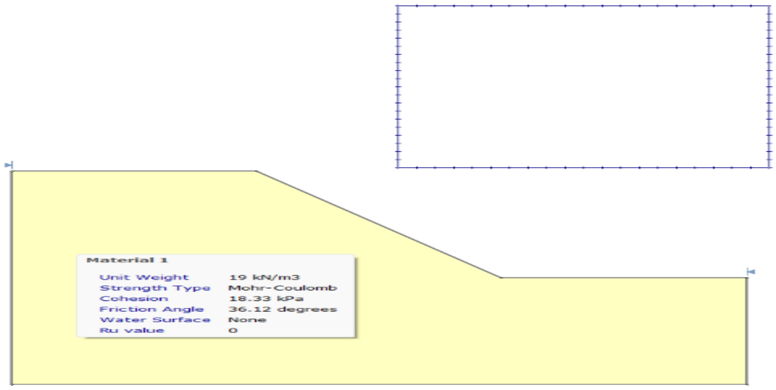

Figure: 6 Slope geometry after auto grid

3. Next the file should be saved
4. After that it should be computed and interpreted
5. For this click on analysis tab, and select compute
6. Next select interpret in the same analysis tab
7. Then, only one failure surface with least factor of safety will be displayed as shown below

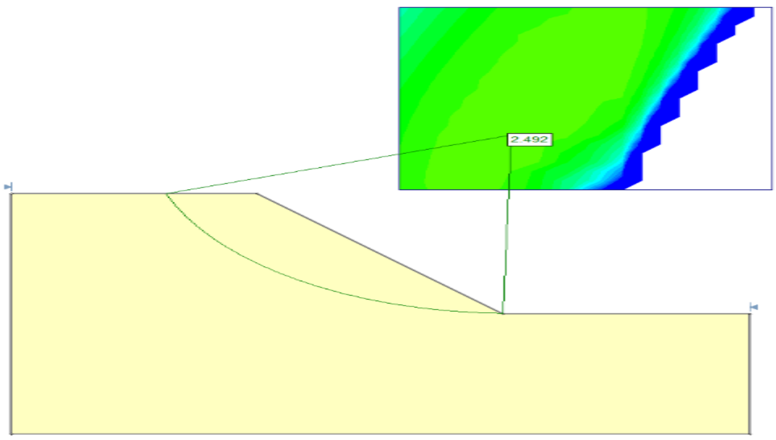

Figure: 7 Model showing single failure surfaces

8. To show all the failure surfaces, select data tab and click on all surfaces
9. Then all the probable failure surfaces will be shown in a colour code
10. Blue and green colour surfaces indicate safe surfaces , orange and red colour surfaces indicate unsafe surfaces

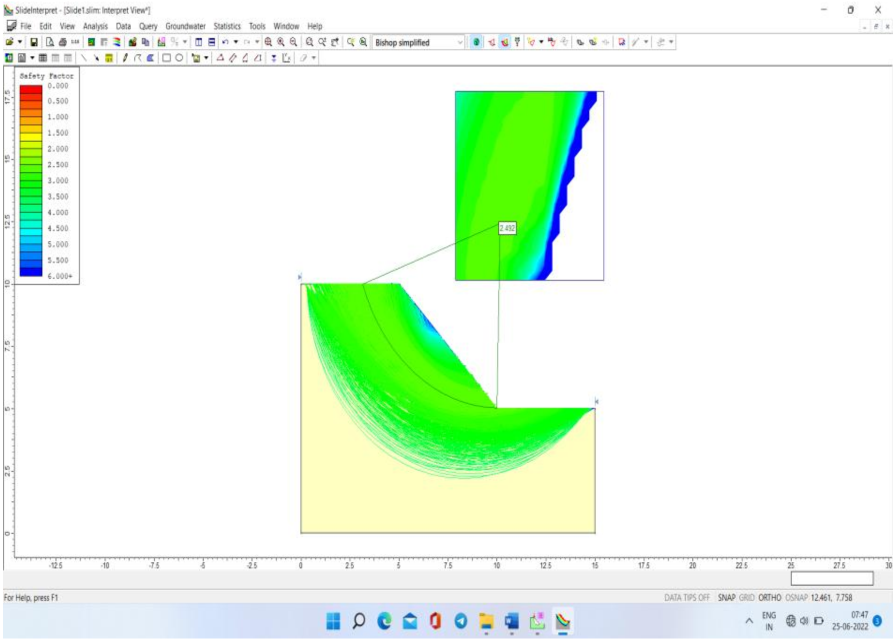

Figure: 8 Model showing all failure surfaces

5. Models with 3 Benches

The following 9 models are formed by considering 3 benches, one on top of the other. The bench angle or the bench height was increased with every consecutive model

Model 1: bench height -5m, bench angle – 23°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 5 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 23°

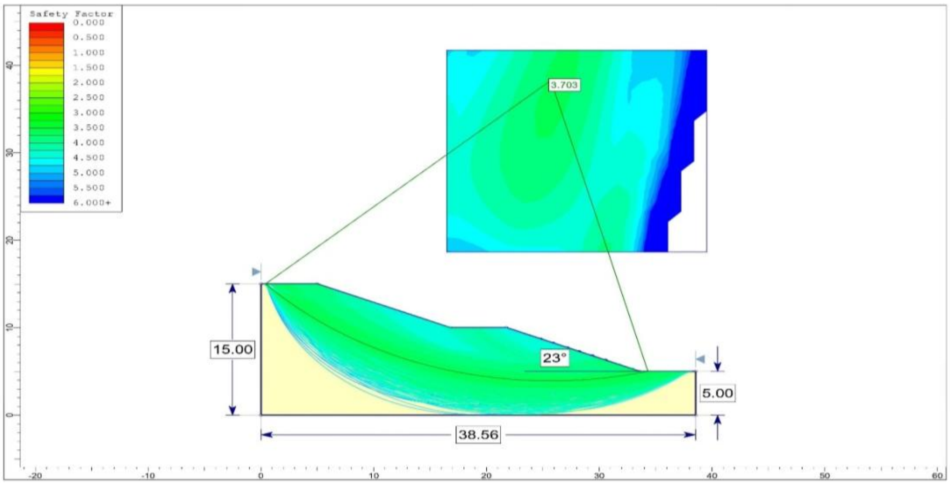

Figure: 9 Model 1

The factor of safety obtained from the analysis of this model is 3.703

Model 2: bench height -10m, bench angle – 23°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 10 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 23°

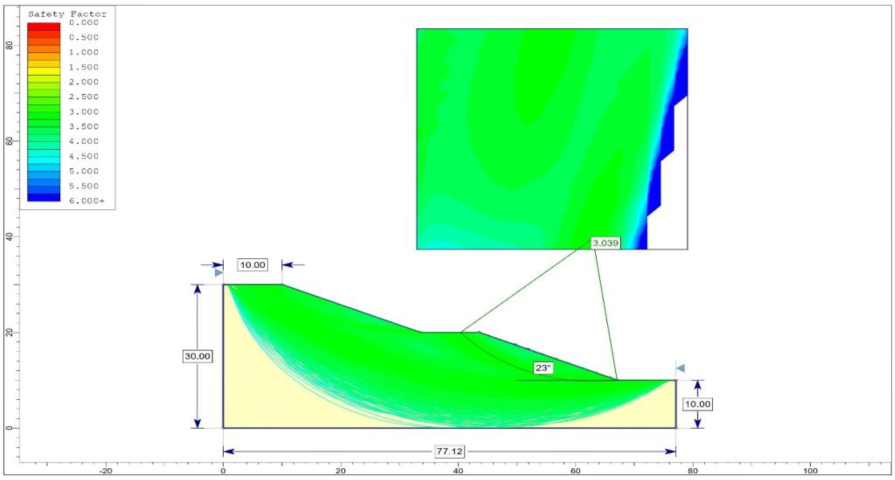

Figure: 10 Model 2

The factor of safety obtained from the analysis of this model is 3.039

Model 3: bench height -15m, bench angle – 23°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 15 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 23°

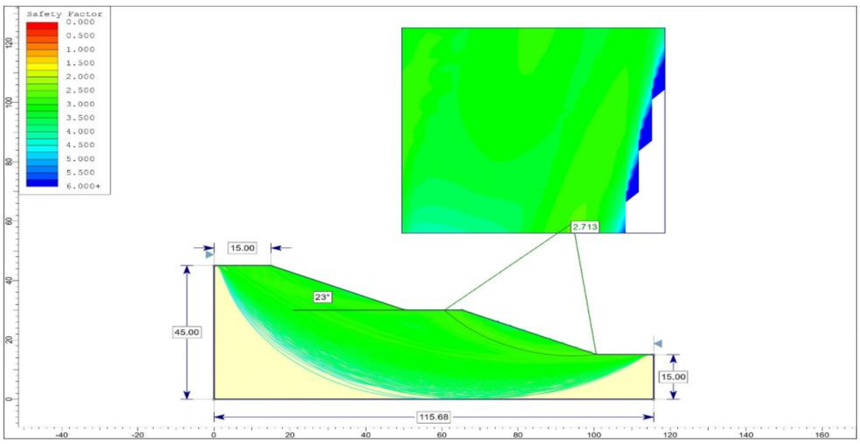

Figure: 11 Model 3

The factor of safety obtained from the analysis of this model is 2.713

Model 4: bench height -5m, bench angle – 37.5°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 5 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 37.5°

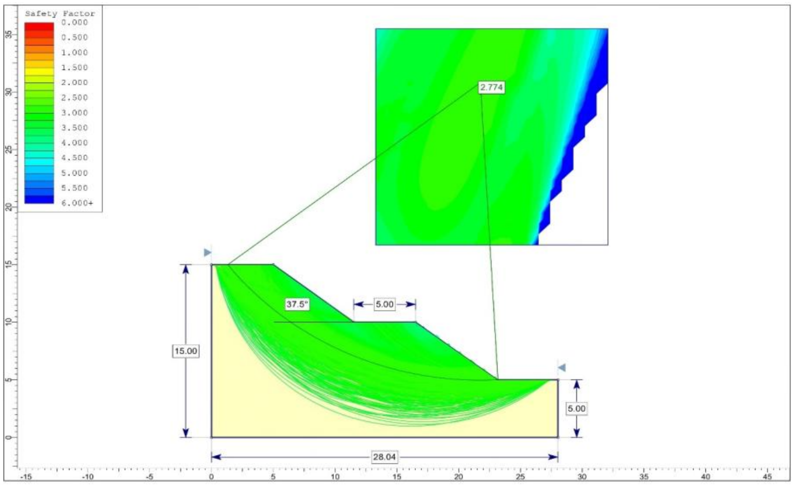

Figure: 12 Model 4

The factor of safety obtained from the analysis of this model is 2.774

Model 5: bench height -10m, bench angle – 37.5°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 10 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 37.5°

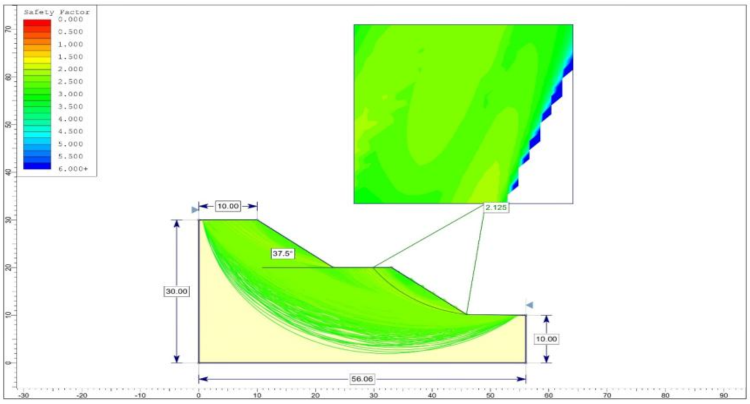

Figure: 13 Model 5

The factor of safety obtained from the analysis of this model is 2.125

Model 6: bench height -15m, bench angle – 37.5°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 15 meters
    - And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 37.5°

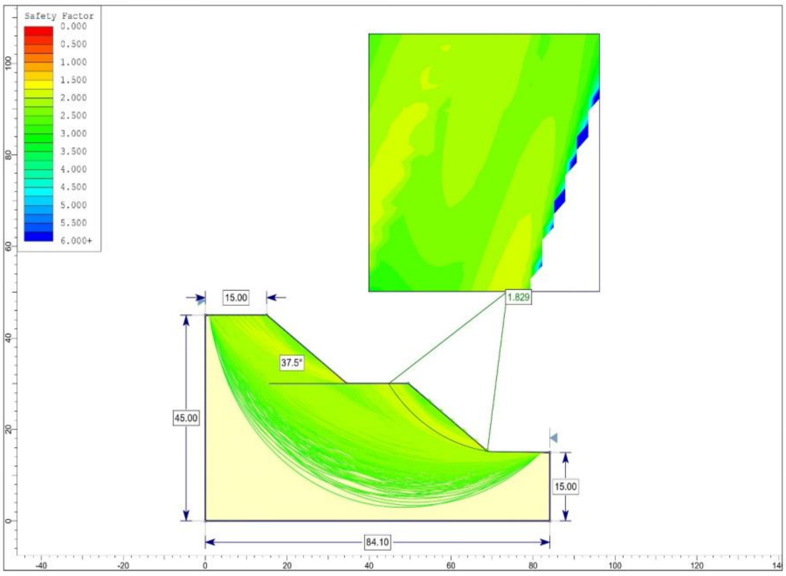

Figure: 14 Model 6

The factor of safety obtained from the analysis of this model is 1.829

Model 7: bench height -5m, bench angle – 45°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 5 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 45°

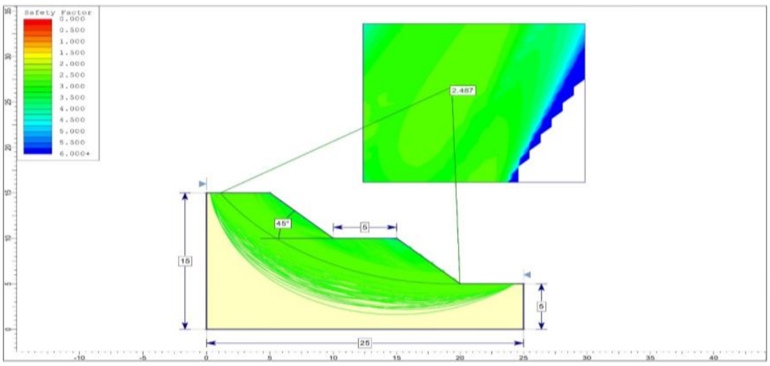

Figure: 15 Model 7

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The factor of safety obtained from the analysis of this model is 2.487

Model 8: bench height -10m, bench angle – 45°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 10 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 45°

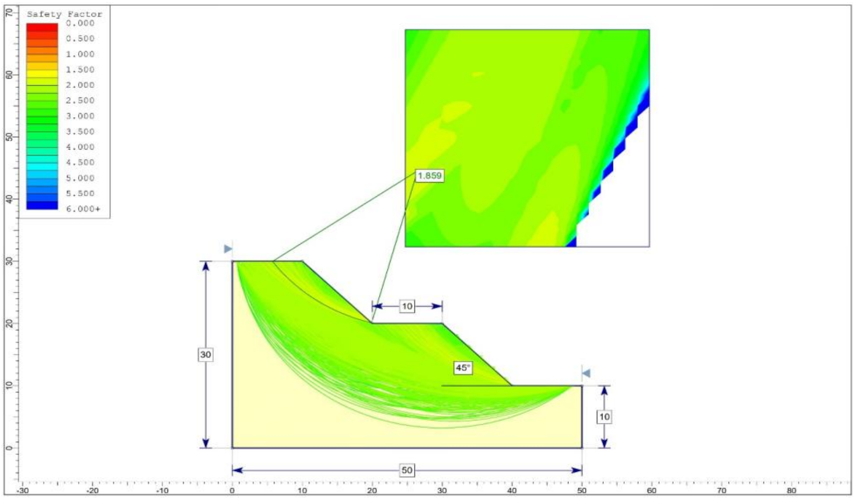

Figure: 16 Model 8

The factor of safety obtained from the analysis of this model is 1.859

Model 9: bench height - 15m, bench angle – 45°

In the following model

- 3 benches have been considered for the analysis
- The bench height considered is 5 meters
- The bench width is also considered as 15 meters
- And the bench angle i.e., the angle between the inclined slope of the bench with the horizontal as 45°

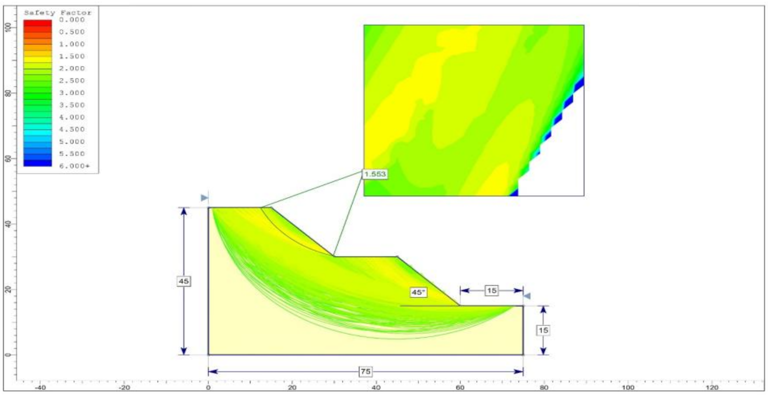

Figure17 Model 9

The factor of safety obtained from the analysis of this model is 1.553

6. RESULTS AND OBSERVATIONS

The results obtained from the analysis can be represented in tabular form as shown below:

S. No	Bench Height	Bench Angle	No. Of Benches	Factor Of Safety
1	5	23	3	3.703
2	10	23	3	3.039
3	15	23	3	2.713
4	5	37.5	3	2.774
5	10	37.5	3	2.125
6	15	37.5	3	1.829
7	5	45	3	2.487
8	10	45	3	1.859
9	15	45	3	1.553

Table: 4 Results and observations

7. CONCLUSION

From this analysis the following points can be concluded:

- At constant bench angle, the factor of safety of the slope decreases as the bench height increases and vice versa
- So, the bench angle of a slope should be designed to be as low as possible
- At constant bench height, the factor of safety of the slope decreases as the bench angle increases and vice versa
- So, the bench height of a slope should be designed to be as low as possible
- The factor of safety in all the cases which are considered varied from 3.703 to 1.553
- So, the slope is stable in all the conditions of the bench geometry which are considered for this study

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