

Influence of Slope Angle and Height on the Failure Criteria and Safety Factor of a Homogeneous Slope in 3D Using the Finite Element Method

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Abstract

The control of slope angle and slope height in identifying stability condition of slopes is a ready reckoner for fast screening of slopes covered with soil and debris material. The heterogeneity of the material in the slope though plays a major role, however, understanding the behaviour of the homogenous material throws light on generic principle of stability and types of failure. The present study therefore intends to derive the relationships of the safety factor of a homogeneous material that is only subjected to self-weight in three dimensions. The bearing of slope geometry on the safety factor of a predefined homogeneous slope is analysed in 3D following the finite element-based strength reduction technique for establishing the relationships and the resultant failure modes. The type of failure and shape of the sliding mass is found guided by the slope geometry. The results indicate that FOS decreases nonlinearly with increasing height but decreases linearly with increasing slope angle. The findings indicate that the height and angle of the slope control the failure process of a particular “material type” and the expected type of failure. The 3D finite element method (FEM) with strength reduction (SRM) is a reliable approach for analyzing high and steep slopes, as it effectively captures complex, non-circular failures and progressive instability by reducing shear strength parameters. This insight can guide practicing professionals from making informed designs on geometry alteration of slopes for effective stabilization.

Keywords

Slope Stability, 3D, FOS, Slope Angle, Slope Height

1. Introduction

Unstable slopes can cause significant social and financial consequences. Identification and rapid screening of slope covered with soil and debris is one of the most challenging tasks during field studies for identifying slope instabilities. Besides the material in the slope, two most important visual parameters are slope angle and slope height can provide insight to the stability of the material lying on the slope at certain angle with a certain height. This also indirectly provide an assessment of the exposed excavated slope or a natural slope. The need for assessment of these type of slope forming material and the FOS at variation with the slope angle and height requires rigorous slope stability analysis for defining their interrelationships as well as type of failure mode. Modified slopes like road cuts, dams, landfills, embankments are particularly vulnerable to slope stability issues [1]. As such, slope stability is a common concern for geoscientists and engineers alike in populated areas and in large civil engineering projects. Here, thorough geological and geotechnical investigations backed by reliable slope stability analysis can only serve as the cardinal task for project safety. Soil type, slope geometry, stratification, groundwater and infiltration all contribute to different types of slope failures [2] [3]. While most of the contributory factors for slope instability are intrinsic to the slope, the slope geometry (height and angle) can be considered extrinsic which can be manipulated to a certain extent for safety of the slopes. By altering the geometry of the slope, the probability to failure can be reduced.

Types of slope failure on a soil slope can be translational, rotational, compound or flow [4] [5]. In fine-grained homogeneous soils, rotational failure may occur in three different ways: Face failure or Slope failure, Toe failure and Base failure (**Figure 1**).

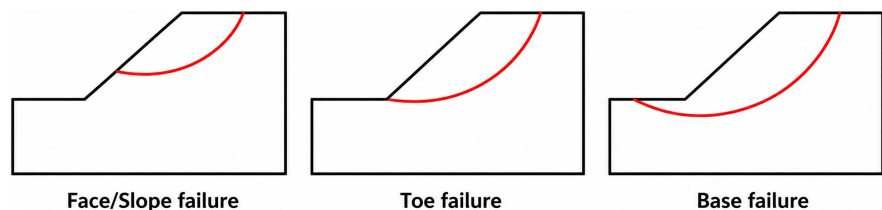


Figure 1. Types of rotational failure in a slope.

The geometric shape of a slope surface significantly influences slope stability [6]-[11]. Failure to fully evaluate the impact of irregular morphology on slope stability can result in significant human and material losses, particularly in slope reinforcement design and construction. [3] analysed three homogeneous slopes of different soil characteristics (sandy-clay, clay and sandy soils) in 2D and con-

cluded that decreasing slope angle increases the factor of safety nearly linearly while a decrease in height increases the factor of safety at a parabolic rate. [12] carried out a similar study in 3D following the limit equilibrium method (LEM) and found that decrease in slope height raises the safety factor nonlinearly while a decrease in slope angle increases the safety factor almost linearly. Their study with respect to different slope material also indicated that toe slip is the predominant slope collapse for clay and sandy-clay soils, while slope failure is the dominant failure mode for sandy soils.

The geometric shape of a slope surface significantly influences slope stability [6]-[8]. Failure to fully evaluate the impact of irregular morphology on slope stability can result in significant human and material losses, particularly in slope reinforcement design and construction. Researchers have concentrated on the stability study of slopes with single-slope surface geometries such as convex, concave, and stepped slopes, and investigated the impact of convex or concave slope. A sliding surface generating technique based on concave and convex slope models was presented by [13].

In the case mining activity scaling in term of slope height and angle of dump material is very crucial. The stability of overburden material is critical for smooth mining operations; thus, adequate dump management is required in the mining lease area to minimize slope failure. Improper dump management poses a significant risk to mining activities [14]-[18]. Due to limited available land space and the massive volumes of overburden removed in an ordinary surface mining operation, higher and steeper overburden dumps are constantly required to handle increasing amounts of material in a given land area [15] [19]. Though the dimensions of these dumps are normally restricted by local mining legislation, the size of dumps defines a large part of mine economics, since even a minor adjustment in slope angle can lead to huge cost savings.

Recent advancements in computing technology have propelled the three-dimensional (3D) finite element numerical approaches as a popular alternative to traditional limit equilibrium methods (LEM) for slope stability analysis. The advantages of 3D methodologies over 2D approaches in determining slope stability are well established [20] [21]. This study describes the results of a 3D Finite Element investigation to the influence of slope morphology in terms of slope height and angle on its stability conditions and different modes of failure for a pre-defined set of material properties.

In the mountainous terrains with high relative relief such as Himalayas, with a given aspect the slope length and its continuity either across a road cut or a break in the natural slope has a higher relative relief. With a preferential higher degree of homogeneity, the impact of these on initiating slope instability has not been studied earlier, though workers have studied the impact of only cut slope height, slope angle within a modest range [3] [12] [22]. However, the impact of self-weight of the slope material lying on natural slope either from the base of the bench of the cuts or natural benches along a slope profile has never been attempted with high slope. So novelty of this work provides an insight on the effect

and impact on the stability condition of the slope material resting on a high slope and moderately larger relative reliefs.

Also zero-waste designs eliminate waste by using soil that has been excavated from slope reduction for other construction projects. Increased safety, cost effectiveness, environmental sustainability, and scalability are other novelties of this effort.

These developments show that lowering slope height and angle can be accomplished in ways that go beyond standard procedures, utilizing state-of-the-art technology and environmentally friendly techniques to increase safety and resilience.

Slope Stability Analysis in 3D Using Finite Element Method (FEM)

Slope stability refers to the resistance of inclined slopes (man-made or natural) to failure by sliding. Any exposed inclined slope, in general, may be prone to deformation and mass movement under the influence of gravity. Slope failures are determined by the slope angle, slope height, soil type, soil stratification, groundwater, and seepage. Calculating the factor of safety (FOS) is the standard approach in slope stability analysis [23]. FOS is computed as the ratio of the soil's shear strength (τ_f) to the mobilized shear (τ_m) at the failure surface, as shown in equation 1.

$$FS = \tau_f / \tau_m \quad (1)$$

There are several approaches for analysing slope stability and computing the factor of safety. FEM is a computational technique used to obtain approximate solutions of boundary value problems in science [24]. The most common approach to 3D slope stability analysis is still the LEM, which is usually a direct extension of the various 2D slices method to 3D columns method; for example, the ordinary, modified Bishop, Morgenstern and Price, Spencer, and Janbu methods [25]-[29] and numerous improvements to these methods [30]-[34]. The 3D LEM is simple and quick. Unfortunately, the 3D LEM relies on a number of assumptions and cannot be easily adjusted to account for true third-dimension boundary constraints. Moreover, another limitation of the 3D LEM is the difficulty of locating the critical general 3D failure surface in both shape and location [35] [36]. A primary advantage of FEM in slope stability analysis is that no prior assumptions regarding the critical failure surface are required. In this study, FEM-based stability modelling in 3D was carried out by adopting the strength reduction technique wherein the shear strength parameters (c , Φ) of the slope are gradually reduced by a safety factor called the strength reduction factor (SRF). The analysis is repeated for different values of SRF; until the model becomes unstable. The slope's FS is then calculated as the proportion of the soil's real shear strength characteristics to its reduced (critical) shear strength parameters. The strength reduction approach defines the FS as in Equation (2) [37].

$$FS = \tan \phi_{\text{input}} / \tan \phi_{\text{reduced}} = c_{\text{input}} / c_{\text{reduced}} \quad (2)$$

2. Methodology

2.1. Aim

The objective of this paper is to understand the influence of slope height and slope angle in the computation of safety factor of a slope in 3D. By altering the slope height and slope angle, the changes in the FS values and variation in the predicted failure modes are to be understood by establishing their inter-relationships.

2.2. Approach

Past experimental on the relationship between slope and height has been carried out at only for low height slope mainly for embankment and cut slope stability cases [12]. The research of slope stability along the highways and roads in the Himalayan areas is of great interest since slope instability has resulted in transportation issues, human deaths and injuries, property loss, and environmental degradation. We used a structured methodology to evaluate the FOS on varied slope height and slope angle. Generally, FOS is computed to evaluate slope stability using site specific geotechnical properties under varying geometrical conditions. The geotechnical properties of the material were acquired when the geometry was first specified using slope height and slope angle. The overlying debris along the lesser Himalayas has been found that most of the material properties [38]–[42] of Himalaya terrain is varies between the rage of given values in **Table 1**. Therefore, the actual properties acquired by has as a median has chosen and assumed to represent the material in the slope, varies withing used properties (**Table 1**). After that it has also been following that, an appropriate FEM analysis chosen which can give a balance stress distribution in 3D environment. In this a natural slope from 10 m to 50 m height and angle up to 63 degree have been taken where homogeneous exposure debris material are has been taken as case and numerical modelling has been performed with different combination of slope angle and height. In this study examines the safety factor in 3D and resultant failure surfaces at various heights and base inclination angles for a certain soil type. Three analytical cases with soil properties as presented in **Table 1** were adopted and simulated. For simplification, a homogeneous medium is assumed in the study.

- a) Height variation to compute the safety factor at a specific slope angle.
- b) Progressively change the slope angle while keeping the slope height constant.
- c) Simultaneous increase in slope height and angle.

Table 1. Geotechnical properties of soil from Himalayan terrain [42].

<i>Sl no.</i>	<i>Properties</i>	<i>Values</i>
1	Unite Weight (Dry)	12.85 kN/m ³
2	Unite Weight (Saturated)	16.48 kN/m ³
3	Cohesion	22.5 kN/m ²

Continued

4	Angle of Internal friction	37.4°
5	Poisson Ration	0.33
6	Modulus of elasticity	10000 kN/m ²

2.3. Geometry and Modelling

Majority of the parameters in the study of slope through FEM are slope geometry specially height and angle, soil mechanical characteristics, and groundwater conditions to estimate the factor of safety assuming all other parameters to be constant [43]. This underlines the significance of slope geometry in determining the safety factor of a slope. A 3D slope geometry (dimensions, 100 m × 120 m × 50 m) created in CAD environment. A Mohr-Coulomb material model (elastic-perfectly plastic) was simulated using software MIDAS's Soil Works and GTS NX. Fundamental ideas in physics, mechanics, and material behavior form the basis of the underlying physical laws or mechanisms of failure criterion. When and how a material (rock and soil) moves from a stable condition to failure is what these criteria are meant to explain. Cohesion is the intrinsic stickiness or connection between particles, independent of stress, and Coulomb's Law describes the shear strength of a material as a combination of two elements. The interlocking of particles and normal stress applied on the material is known as frictional resistance, and it is frequently used in geotechnical engineering to assess stability under various stress scenarios.

A finite element-based program, to compute the factor of safety for several slope models in respect of different slope height and angle (**Figures 2(a)-(b)**). In this study, the one soil/ debris types of slopes are modelled in Midas GTS NX. The geotechnical properties are given in **Table 1**. Three slope models are created in Midas GTS NX software. The first model is where the slope height is increased gradually from 10 m in height to 50m in height at 10 m interval. The second model is where the slope angle is increased systematically by keeping the height constant for a certain level. Third type of model, where height and slope angle are increasing simultaneously. From the developed geometry, a plain/plane strain model was used for the 3D FEM analysis with a hybrid Mesher type with medium coarse mesh element of 5 m size as illustrated in **Figure 2(c)** is generated and used in the study. [44] looked into how mesh size affected the transition from fine to coarse. A smaller mesh size (finer mesh) generally leads to more accurate results by capturing finer details of the slope geometry and stress distribution, providing a better representation of potential failure mechanisms. Further [45] study that the finer mesh size (1 m and 0.5 m) yield constant FOS in both the dry as well as saturated condition. These results are also in line with those reported in the study by [46] which used 2D and 3D FEM to examine slopes. Higher mesh density models produced lower FOS values; for coarse and extremely fine mesh sizes, the percentage error between FOS values was 18%. [47] found that crucial FOS values can be produced with more elements and nodes than with fewer elements and nodes in his FEM modeling of weak soil layers

for slope stability analysis. [48] discovered a nonlinear correlation between calculation time and mesh size. It demonstrates how the calculation time dramatically drops as the mesh size increases. With a small fluctuation between 1.0 and 1.05 in relation to the mesh size between 0.5 and 5 meters, the safety factor essentially remains constant. 3D FEM analysis are highly time consuming and required high computing performance, thus for R & D with repeated cycles and scenarios and for optimizing the computational time 5m mesh size has been adopted as the mesh size. Thus, in this work, the influence of slope height and slope angle with respect to FOS is seen while maintaining a constant medium size of mesh (5 m).

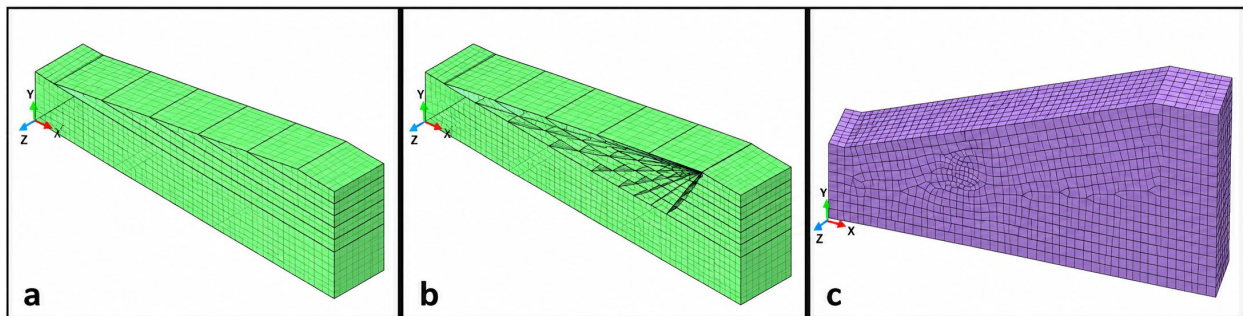


Figure 2. The slope geometry used in modelling, a) Slope geometry at constant 10° angle with changing height at 10 m interval, b) Slope geometry with constant height and changing slope angle at 10° interval, c) Medium coarse meshing of the model.

3. Result and Discussions

3.1. Deformation

The conditions under which a slope becomes unstable and fails are described by the failure criteria for slopes. This is mostly because the geotechnical materials do not have enough shear strength. The connection between geotechnical materials and failure criteria is predicated on how these materials' characteristics affect failure mechanics. Granular soils have low c values but high ϕ , while cohesive soils have high c values but low ϕ . Higher cohesion materials are more resistant to slope failure, especially when it comes to short-term stability. Cohesion values are essential inputs for bearing capacity calculations and slope stability analyses. The shear strength of the material, drainage conditions, and stress distribution all play a role in the failure criterion for slopes and how they relate to geotechnical materials. Failure type on slopes is determined by a number of factors such as soil type and slope geometry. Understanding how changes in slope height and angle affect the safety factor is essential for developing effective strategies to improve slope stability. Engineers must thoroughly investigate the influence of geometric shapes on slope stability through three-dimensional analysis, as this approach is suitable for all types of slopes, including those that do not satisfy plane-strain conditions. [12] under LEM reported that reducing slope height increases the safety factor nonlinearly, while decreasing the slope angle results in an almost linear increase. For slopes below 4.0 m height and 18° inclination, base failure is most likely. Similarly for low height [49] have also reported that the geometric features signifi-

cantly affect the FoS of 3D slopes under heavy rainfall; steeper gradients and convex zones are more prone to instability. 3D slope stability is commonly analysed using LEM [28] [32] [33] [35] [50]-[53] and FEM por FDM with strength-reduction techniques [20] [36] [54]-[58]. Although time-consuming, 3D FEM is more effective as it provides safety factors, critical slip surfaces, and stress-deformation behavior, whereas 3D LEM has limitations in identifying slip surfaces [35] [36]. Moreover, 3D analysis accurately represents complex slope geometry and boundary conditions in x-y-z directions. In the view of the above study a high slope angle and height have tried to simulate under dry condition with FEM. By keeping the soil type and properties constant, the mode of failure and safety factors were examined for various heights and inclination angles. At 50 m fixed slope height, base failure has been observed for slope angle up to 20 degrees (**Figure 3(a)**). For slope angle greater than 20 degrees up to 51 degrees, toe failure (**Figure 3(b)**) has been observed. Face/slope failure has been observed for slope angles of 75 degrees or more (**Figure 3(c)**). However, with decrease in the slope height base failure occurs at greater angle. For instance, at 20 m fixed slope height (**Figure 4**), base failure occurred up to an angle of 20 degrees (**Figure 4(a)**) while toe failure occurred at 57 degrees (**Figure 4(b)**). At higher angles of 75 degrees and more, face/slope failure is observed (**Figure 4(c)**). No failure plane (NFP) has been consistently observed at 10 degrees slope angle for any slope height from 5 m to 50 m. In slope stability analysis, failure criteria are essential for determining whether a slope may collapse in specific circumstances. These requirements frequently rely on the material qualities, slope height, and slope angle. Additionally, the failure criteria may change based on the approach taken. **Table 2** provides a summary of the evolving failure scenarios and criteria as the slope angle and slope height change. The table shows that, regardless of slope height, slope failure happens at greater angles, whereas base failure happens at lower angles. In this case, slope angle appears to be the factor affecting the failure criteria; slope height has minimum effect (**Table 2**). Further it explains that the when slope failures take place over an arc that encloses the entire slope, the base slide happens. When the failure arch goes through the slope's toe, the toe slide happens. When there is a slope failure, the slope slide happens.

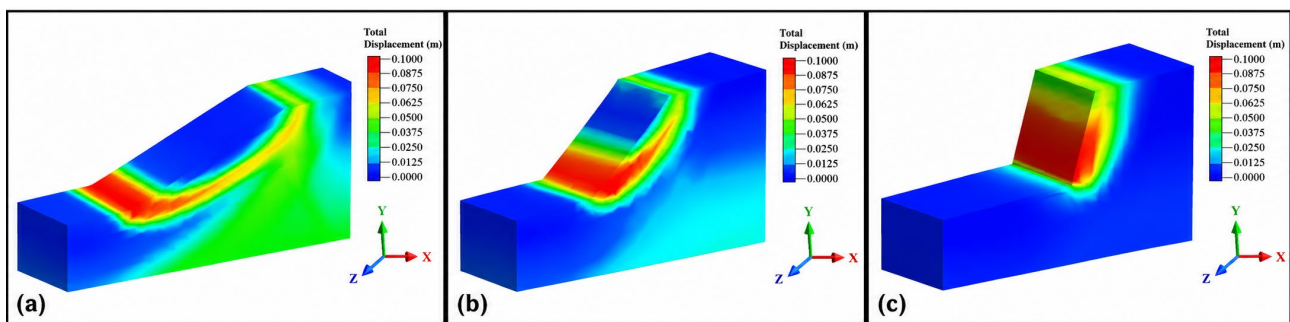


Figure 3. Critical failure surface at 50 m slope height with varying slope angles; a) base failure at 20° slope angle, b) toe failure at 51° slope angle, c) face/slope failure at 75° slope angle.

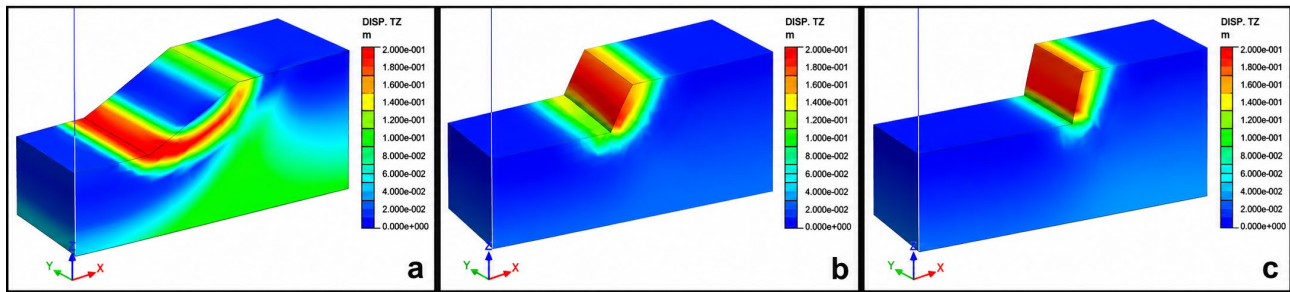


Figure 4. Critical failure surface at 20 m slope height with varying slope angles; a) base failure at 20° slope angle, b) toe failure at 57° slope angle, c) face/slope failure at 75° slope angle.

Table 2. Criteria of failure based on height and slope angle.

Slope angle (degree)	10	20	30	45	51	57	63	69	75
Slope height (m)									
05	NFP	Base	Base	Base	Base	Toe	Slope	Slope	Slope
10	NFP	Base	Base	Base	Toe	Toe	Slope	Slope	Slope
20	NFP	Base	Base	Base	Base	Toe	Slope	Slope	Slope
30	NFP	Base	Base	Base	Toe	Toe	Slope	Slope	Slope
40	NFP	Base	Base	Base	Toe	Toe	Slope	Slope	Slope
50	NFP	Base	Base	Base	Toe	Toe	Slope	Slope	Slope

3.2. Slope Height and FOS

In the first analytical case, the slope height is gradually increased from 05 m to 50 m at intervals of 5 - 10 m to see its variation at a defined slope angle. This variation was analysed at 10, 20, 30, 45, 51, 57, 63, 69 and 75 degree angles. **Table 3** shows that the safety factor decreases with increasing slope height for specific material types at a constant slope angle. Also, a high slope generates more weight due to the greater volume of material, increasing the driving force that decrease FOS and promotes slope failure. The shear stresses along potential slip surfaces increase with height and ultimately decreases the FOS, which can destabilize the slope.

Table 3. Slope height and FOS at a specific slope angle.

Slope angle (degree)	10	20	30	45	51	57	63	69	75
Slope height (m)									
05	13.04	9.44	7.84	6.1	5.52	4.58	4.21	3.13	2.51
10	7.22	5.3	4.7	4.26	4.01	3.68	3.51	2.33	2.31
20	4.04	3.56	3.12	2.6	2.43	2.29	2.16	1.94	1.76
30	3.46	3.12	2.53	1.97	1.79	1.73	1.61	1.33	1.15
40	3.18	2.89	2.21	1.68	1.47	1.23	1.13	1.02	1.01
50	3.32	2.82	2.03	1.47	1.35	1.19	1.12	1.12	1.05

The intricate interplay between the forces causing instability and the resisting

forces causes a slope's FOS to vary nonlinearly with changes in slope height. As slope height varies, FOS may first decline, then rise, and finally fall once more (**Table 3**) as it can be seen on the height 30, 40 and 50 m with respective slope angle at 57 and 69 degrees. Due to variations in the distribution of stress, the slope geometry may occasionally momentarily stabilize as height increases. The stresses may surpass the material's capacity with additional height increases, leading to progressive failure mechanisms.

3.3. Slope Angle and FOS

In the second case, the slope angle was progressively increased while maintaining the slope's height and soil characteristics constant. This investigation was conducted at 10, 20, 30, 45, 51, 57, 63, 69, and 75 degrees with heights ranging from 05 to 50 meters. The factor of safety decreases as the slope angle increases as illustrated in **Table 3**.

3.4. Slope Height and Angle

In the third analytical case, the slope height and angle were simultaneously increased while keeping the soil parameters constant. Modelling was carried out from a height of 40 m to 68 m (failure point) with a 2 m interval. Similarly, the slope angle was increased from 35 degrees to 63 degrees (failure point) with a 2-degree interval. As can be seen from **Table 2** and **Table 3** that slope angle and slope height are affecting FOS, where **Table 4** shows the computed safety factor for various slope heights and angles and the associated failure criteria. The combination of increased slope height and a slope angle amplifies the driving forces, which decreases FOS and making the slope much more unstable.

Table 4. Slope height, slope angle, FOS and failure criteria.

Slope height (m)	Slope angle (degree)	FOS	Failure criteria
40	35	1.876	Base
42	37	1.80	Base
44	39	1.72	Base
46	41	1.56	Base
48	43	1.57	Base
50	45	1.47	Base
52	47	1.36	Base
54	49	1.31	Toe
56	51	1.29	Toe
58	53	1.19	Toe
60	55	1.19	Toe
62	57	1.14	Toe
64	59	1.15	Toe
66	61	1.04	Slope
68	63	0.89	Slope

3.5. Discussion

3.5.1. Influence of Slope Height on FOS and Failure Criteria

As seen in **Figure 5**, decreasing slope height beyond 20 m always shows sharp rise in factor of safety. This is more pronounced for the 10, 20, 30-degree slopes. At heights ranging from 5 to 20 meters of the graph is extremely steep and abrupt in relation to the safety factor. For slope heights ranging from 30 to 50 meters, the slope of the line remains relatively shallow giving rise to a half-parabola. This indicates that the change in FOS change up to a height of 20 m, a very small rate from 20 m to 30 m, and fairly constant from 30 m onwards for any particular slope angle. Also, FOS is influenced at higher rate up to the angle of 51 degree and smaller rate from 63 degree onwards in the height between 5 m to 20 m. So, if height increases from 30 m onwards, there will be very little influence on FOS. In terms of failure types, it has been noted that at any slope height, base failure occurs up to 45 degrees, mixed base and toe failure up to 57 degrees and all face/slope failure occurs above this angle. This implies that steeper slopes are more vulnerable to slope collapse.

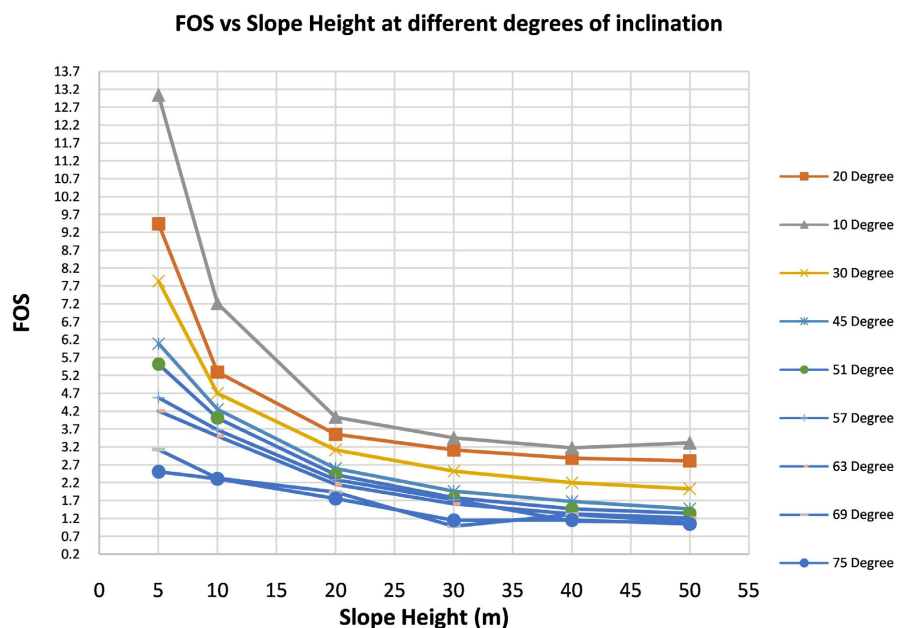


Figure 5. Relationship between slope height and FOS at different degrees of slope inclination.

3.5.2. Influence of Slope Angle on FOS and Failure Criteria

Figure 6 indicates that the relationship between slope angle and factor of safety is almost linear for any slope height *i.e.*, 5, 10, 20, 30, 40, and 50 metres. FOS has a lesser rate of influence when the slope height increases beyond 20 m. It also indicates that at a given height of 10, 20, 30, 40 and 50 m there is fairly constant FOS beyond the 69 degree slope. In terms of failure types, gentle slopes are indicating base failure whereas steeper slopes are more vulnerable to slope collapse.

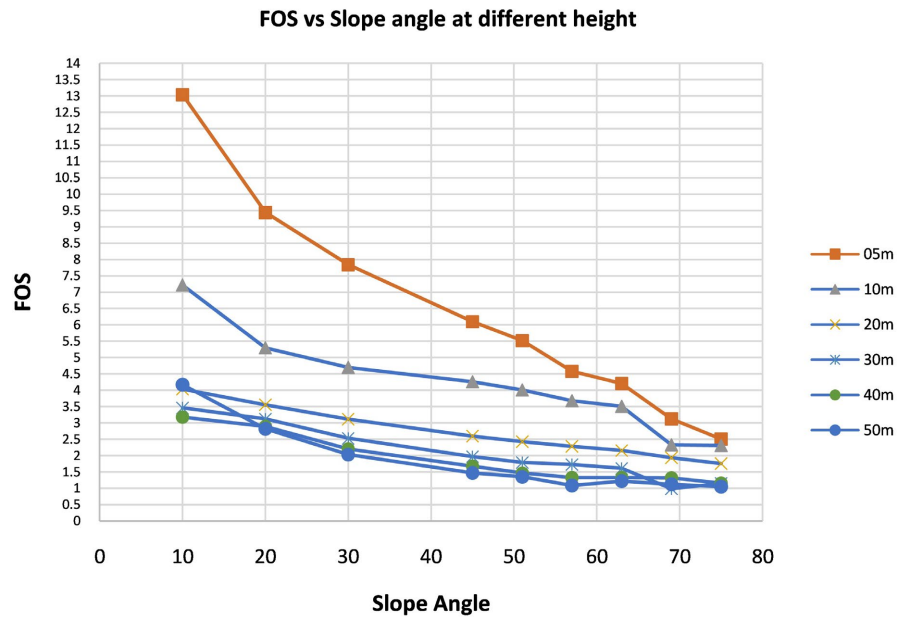


Figure 6. Relationship between slope angle and FOS at different slope height.

3.5.3. Influence of Slope Height-Slope Angle on FOS and Failure Criteria

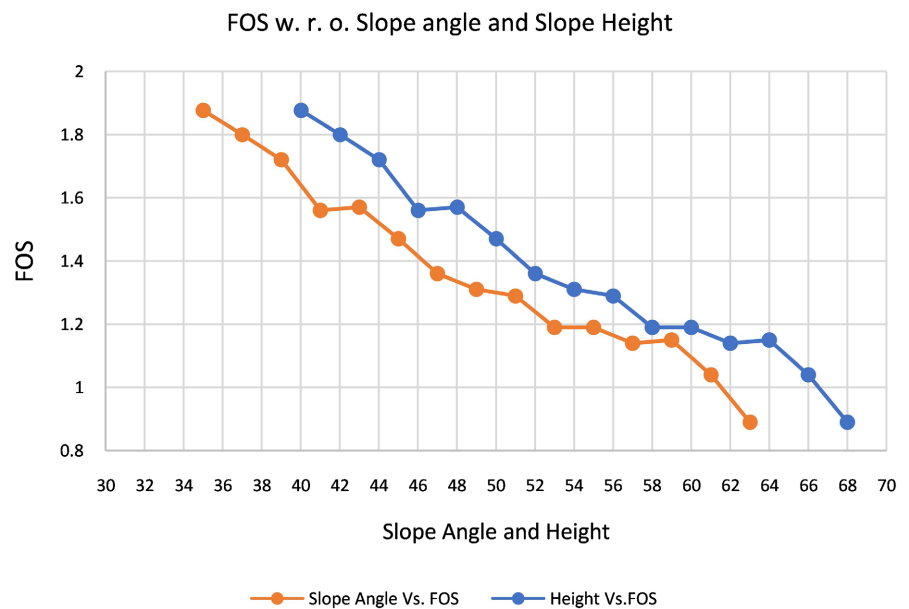


Figure 7. Comparative analysis of the relationship between slope angle, slope angle and FOS.

Optimize slope height and angle for maximum safety factor. **Table 4** shows how lowering slope height and angle concurrently affects the factor of safety, which is crucial for slope stability during scaling. Using the FS presented in **Table 4**, researchers and engineers may investigate the impacts of lowering slope height and angle. As demonstrated in **Figure 7**, slope height and slope angle have a common connection to the FOS; as height and slope rise, the FOS de-

creases at a faster pace. As slope height increases, the safety factor drops. Furthermore, it is observed that the safety factor increases as the slope angle lowers. The results also show that the slope's height and angle determine how and when specific soil types collapse. Base failure occurs most frequently when the slope angle is less than 49 degrees and the height less than 54 m (**Figure 8**). Toe failure is the most common cause of slope collapse on mild slopes (**Figure 9**). Slope failure occurs most commonly on steep slopes greater than 59 degrees (**Figure 10**). This analysis therefore gives an insight to optimizing slope height and angle for maximum safety factor.

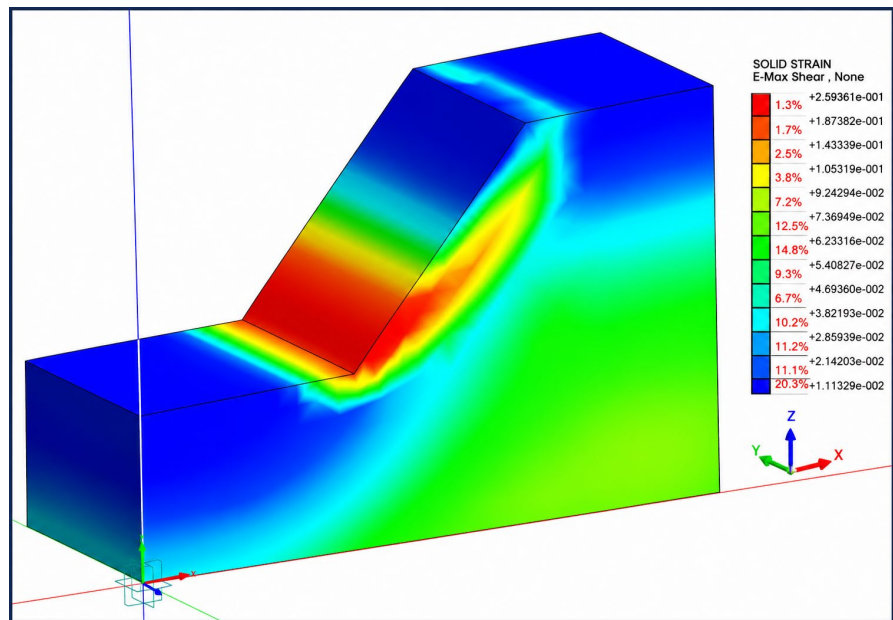


Figure 8. Base failure at 47° angle and 52 m height.

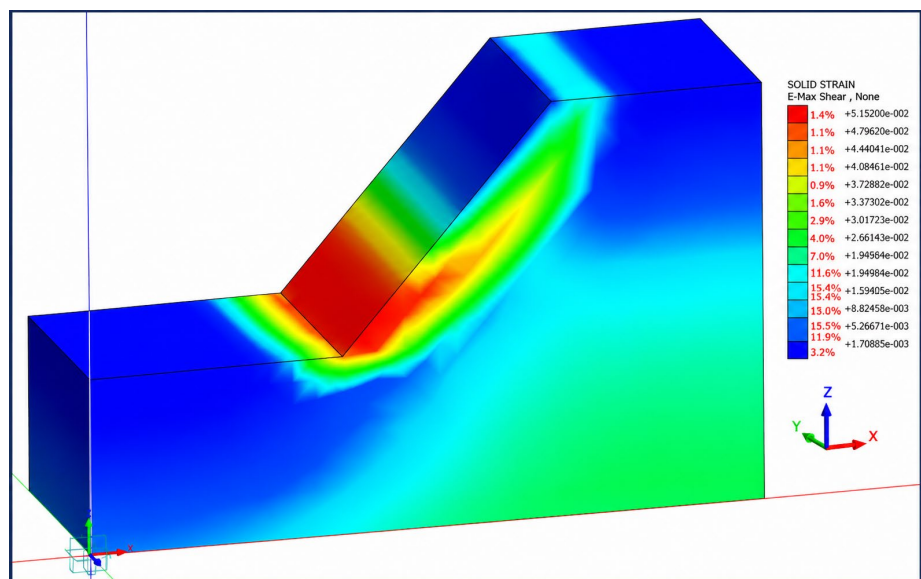


Figure 9. Toe failure at 49° angle and 54 m height.

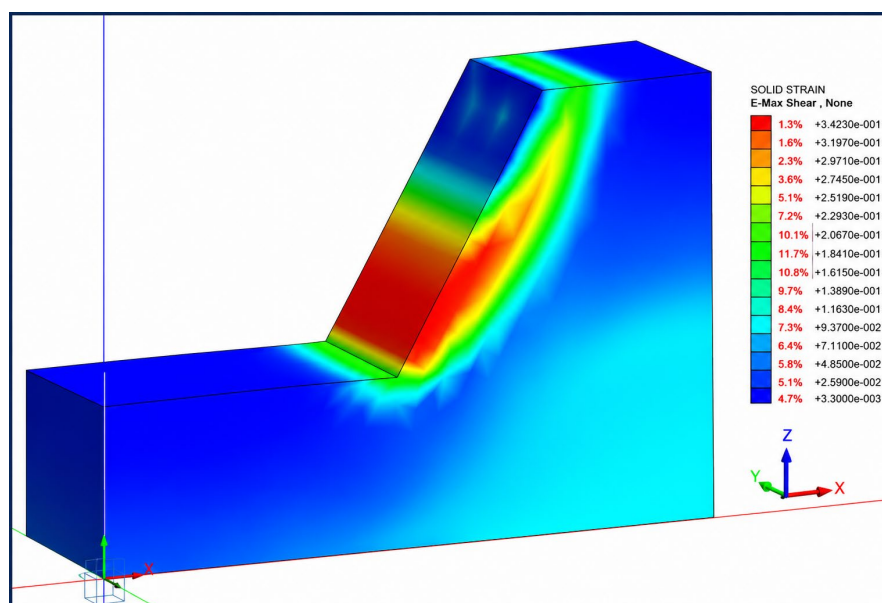


Figure 10. Slope failure at 61° angle and 66 m height.

4. Conclusion

The three-dimensional finite element method (3D FEM) combined with the strength reduction method (SRM) has proven to be a robust and reliable approach for analyzing slope stability, particularly for slopes with high angles and large heights. Unlike conventional limit equilibrium methods, 3D FEM-SRM can simulate complex, non-circular failure mechanisms and capture progressive failure behavior by systematically reducing shear strength parameters until instability occurs. The study presents the variation in the safety factor of a 3D homogeneous slope and the associated failure modes under changing slope angle and height subjected to self-weight alone. The results show that the slope's height and angle determine how and when specific soil types collapse. Base failure occurs most frequently when the slope angle is less than 45 degrees and the height is low. Toe failure is the most common cause of slope collapse on moderately steep slopes (45 - 55 degrees). Slope failure occurs most commonly on steep slopes greater than 55 degrees. Slope safety normally improves linearly as the slope angle reduces, although the safety factor climbs at different rates when the slope height drops. At heights between 5 and 20 meters, the slope of the curve drastically changes in response to the safety factor. As the height grows to 30 meters, the factor of safety drops more quickly but the FOS remains reasonably consistent throughout slope heights ranging from 30 to 50 meters. The results demonstrates that although the FOS decreases nonlinearly with increasing height (half-parabolic), it decreases linearly with increasing slope angle. As a result, for lower-height slopes, lowering the slope angle increases the factor of safety more quickly. Lowering the height on lesser slopes results in a higher safety factor than steeper slopes. Linear and non-linear relation varies with Strength attenuation condition of the material. Strength attenuation is rarely linear c and ϕ may vary differently with strain, stress path, or

environmental conditions. In high granular circumstances, friction angle determines long-term resistance, whereas cohesiveness largely affects short-term strength loss. Variations in loading circumstances, environmental impacts, and material characteristics lead to their uneven attenuation rates. Because of bond breaking, weathering, or repeated loading, cohesiveness tends to deteriorate more quickly in materials with weak bonds. In fine-grained soils, where attenuation becomes more noticeable as strain increases, it predominates. However, because it depends on both friction and particle interlocking, the friction angle varies less than that of cohesion. So, in respect of internal friction angle (ϕ), materials with a high ϕ can better resist failure at greater heights due to greater frictional resistance along potential slip surfaces. Similarly for steeper slopes, higher cohesion is needed to maintain stability and low-cohesion materials may fail even at moderate slope angles. So, the understanding the influence of slope height and angle on the safety factor of a slope is vital for practicing geoscientists and geotechnical engineers for reducing the probability of a slope towards failure or for adopting effective geometric alteration techniques for slope stabilization depending upon the condition of c and ϕ of material.

5. Practical Applications

In engineering and construction, lowering the slope's height and angle is a common safety precaution to reduce the dangers of slope instability. Mining operations (open pit and dump slope), road and railway embankments, construction projects (foundation, dam, and reservoir), landslide mitigation (scaling), agriculture (flattening hilly land for farming and forestry), urban development (hillside housing, parking, and recreation), and hydrological projects (river banks and canals) are all examples of these. Also, its, 1) Increased Stability: Because lower slopes lessen gravitational forces, there will be more structural stability. 2) Less Erosion: Lower runoff velocity due to flatter slopes reduces soil loss. 3) Safer Workplace: Employees are less vulnerable to unexpected collapses or falling debris. 4) Long-term Sustainability: Better environmental compatibility and lower maintenance expenses. Projects including environmental preservation, geotechnical stability, and civil engineering all depend on these applications.

6. Limitation and Future Scope

Based on the scope of the paper "Influence of Slope Angle and Height on the Failure Criteria and Safety Factor of a Homogeneous Slope in 3D Using the Finite Element Method" the following limitations and future scope can be included in a research paper.

1) Homogeneous Material Assumption: The numerical analysis assumes a homogeneous and isotropic soil/rock mass, whereas natural slopes are generally heterogeneous, anisotropic, and contain discontinuities such as joints, faults, and bedding planes that significantly influence slope stability.

2) Simplified Geotechnical Properties: Constant engineering properties (cohe-

sion, friction angle, unit weight, Young's modulus, and Poisson's ratio) were used throughout the slope model. Spatial variability and uncertainty in geotechnical parameters were not considered.

3) Idealized Slope Geometry: The study employed regular three-dimensional slope geometries with varying slope angles and heights. Complex natural terrain, irregular topography, and geomorphological features were not incorporated.

4) Static Loading Conditions: The analysis focused primarily on static loading conditions. Dynamic effects such as earthquakes, blasting, traffic-induced vibrations, and cyclic loading were not evaluated.

5) Absence of Hydro-Mechanical Coupling: Rainfall infiltration, groundwater fluctuations, pore-water pressure evolution, seepage forces, and unsaturated soil behaviour were not included, although these factors strongly influence slope failure.

Future Scope of the Study:

1) Integration of AI and Machine Learning: Future research may integrate AI and ML algorithms such as Random Forest, Support Vector Machine, Artificial Neural Networks, Extreme Gradient Boosting (XGBoost), and Deep Neural Networks to rapidly predict slope stability and failure probability using numerical and field datasets.

2) Development of Hybrid FEM-AI Models: Finite Element simulation outputs can be used to train machine learning models capable of providing near real-time prediction of Factor of Safety (FoS), displacement, and failure mechanisms with significantly reduced computational effort.

3) Climate Change Impact Assessment: Future research may investigate the influence of projected changes in rainfall intensity, duration, and frequency under climate change scenarios on slope stability and long-term hazard evolution.

4) Integration with Early Warning Systems: AI-assisted numerical modelling can be coupled with rainfall thresholds and real-time sensor networks to support intelligent Landslide Early Warning Systems (LEWS) for risk reduction.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Consent for Publication

All authors have read and approved the final manuscript and consent to its publication.

Author Contributions

Dhananjai Verma: Conceptualization, Methodology, Software, Modelling, Data curation, Writing-Original draft preparation, Visualization, Investigation, data analysis, software, Megotshe Chasie: Writing-Reviewing, A K Mishra: Investigations, methodology, Sumit Kumar: Editing, A K Verma: Writing-Reviewing and Editing, T. N. Singh: Writing-Reviewing and Editing, Supervision.

Conflicts of Interest

The authors declare no competing interests.

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