

Slope Stability Assessment of a Natural Hill Slope Using Manual Methods and Geostudio Slope/W

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Abstract

Slope stability assessment is an important aspect of geotechnical engineering for ensuring the safety of natural and engineered slopes. The present study evaluates the stability of a natural hill slope located at Swaminarayan Hills, Narhe, Pune, Maharashtra, using both manual and numerical analysis techniques. Three representative soil samples were collected from different locations on the slope and subjected to laboratory investigations including moisture content determination, density measurement, Atterberg limits, and Triaxial Compression Tests.

The results showed that the moisture content of the soil samples varied from 15.49% to 22.77%, while the dry density ranged from 1.19 g/cc to 1.41 g/cc. The Atterberg limit tests indicated liquid limit values between 44% and 45% and plasticity index values ranging from 14% to 19.44%. Shear strength parameters obtained from triaxial testing and Mohr–Coulomb failure analysis revealed cohesion values of 80–90 kPa and angles of internal friction ranging from 22.53° to 25°. These geotechnical parameters were utilized for slope stability evaluation through the Infinite Slope Method and GeoStudio SLOPE/W software.

A numerical slope model was developed using field-measured geometry and laboratory-derived soil properties to assess the stability of the selected hill slope. The results obtained from manual calculations and software-based analysis were compared to evaluate the applicability and reliability of both methods. The study demonstrates that the integration of laboratory testing, analytical calculations, and numerical modelling provides a comprehensive approach for slope stability assessment. The findings can be useful for the planning, design, and management of slopes in similar hilly terrains subjected to environmental and geotechnical influences.

1. Introduction

Slope stability is a critical aspect of geotechnical engineering that ensures the safety and long-term performance of natural and engineered slopes. Rapid urbanization, infrastructure development, road construction, and land-use changes in hilly regions have increased the need for reliable slope stability assessment. Failure of natural slopes can result in landslides, causing damage to infrastructure, environmental degradation, economic losses, and threats to human life. Therefore, evaluating slope stability and identifying potential failure mechanisms are essential for planning and designing safe engineering structures.

Landslides are among the most common geological hazards occurring in hilly terrains and are influenced by several factors, including slope geometry, soil properties, groundwater conditions, rainfall infiltration, vegetation cover, and external loading. During prolonged rainfall, water infiltrates into the soil mass, increasing pore water pressure and reducing the effective stress and shear strength of the soil. Consequently, slopes that remain stable under dry conditions may become unstable during wet conditions. Understanding the influence of these factors is necessary for assessing slope behaviour and developing suitable mitigation measures.

The stability of a slope is generally evaluated using the Factor of Safety (FOS), which is defined as the ratio of resisting forces to driving forces acting along a potential failure surface.

$$\text{FOS} = \text{Resisting Forces} / \text{Driving Forces}$$

The factor of safety is widely used as an indicator of slope performance. A slope with a higher factor of safety is considered more stable, whereas a lower value indicates a greater probability of failure. In engineering practice, slope stability is commonly classified as shown in Table 1.

Table 1. Slope Stability Classification Based on Factor of Safety

Factor of Safety (FOS)	Stability Condition
$FOS < 1.0$	Unstable
$FOS = 1.0$	Critical Condition
$1.0 < FOS < 1.5$	Marginally Stable
$FOS \geq 1.5$	Stable

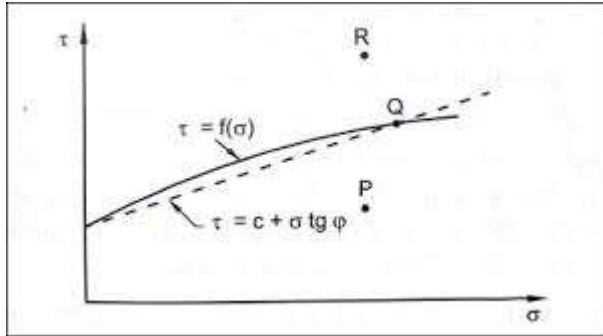


Figure 1

The shear strength of soil, which governs slope stability, is commonly represented by the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma \tan \phi$$

where τ is the shear strength of soil, c is the cohesion, σ is the normal stress acting on the failure plane, and ϕ is the angle of internal friction. These parameters play a significant role in determining the resistance of soil against sliding and are essential inputs in slope stability analysis.

Advancements in computational geotechnics have led to the development of software-based approaches for slope stability analysis. GeoStudio SLOPE/W is one of the most widely used geotechnical software packages for evaluating slope stability using the Limit Equilibrium Method (LEM). The software enables engineers to analyse multiple potential slip surfaces, incorporate groundwater conditions, and determine the critical factor of safety with greater efficiency and accuracy. Consequently, GeoStudio has become an effective tool for validating conventional manual calculations and improving confidence in engineering decisions.

The present study focuses on the natural hill slopes of the Narhe Hills region in Pune, Maharashtra. Three soil samples were collected from different locations within the study area to determine the geotechnical properties influencing slope stability. The analysis was carried out under both dry and wet conditions to evaluate the effect of moisture variation on slope performance. Factor of Safety values were determined manually using the Infinite slope Formula and numerically using GeoStudio SLOPE/W.

2. Theoretical Background and Literature Context

Slope stability refers to the ability of a soil or rock slope to resist failure under the action of gravity and external loads. A slope becomes unstable when the driving forces exceed the resisting forces provided by the shear strength of the soil. Therefore, slope stability analysis is performed to evaluate the safety of a slope and determine its susceptibility to failure.

The most important parameter used in slope stability analysis is the Factor of Safety (FOS), defined as the ratio of resisting forces to driving forces. A higher factor of safety indicates a more stable slope. Previous studies suggest that a

slope is generally considered safe when the FOS exceeds 1.5. The factor of safety is influenced by soil properties, groundwater conditions, slope geometry, external loading, and environmental factors such as rainfall.

The shear strength of soil is governed by two key parameters: cohesion (c) and angle of internal friction (ϕ). Cohesion represents the bonding force between soil particles, while the friction angle represents the resistance generated by particle interlocking. An increase in either parameter improves slope stability, whereas increased moisture content and pore water pressure reduce shear strength and increase the likelihood of failure.

The Limit Equilibrium Method (LEM) is the most widely used technique for slope stability analysis. In this method, the potential sliding mass is divided into slices and equilibrium conditions are applied to determine the factor of safety. Common LEM techniques include the Ordinary Method of Slices, Bishop Simplified Method, and Morgenstern–Price Method. Manual calculations are generally based on these methods and provide a theoretical understanding of slope behavior.

Modern slope stability analysis frequently utilizes GeoStudio SLOPE/W, a software package based on the Limit Equilibrium Method. SLOPE/W automatically identifies critical slip surfaces and computes the factor of safety using various analysis methods. Compared with manual calculations, the software offers faster computation, reduced human error, and the ability to analyze complex slope geometries.

Siregar et al. (2024) compared slope stability results obtained using PLAXIS and GeoStudio SLOPE/W for highway slopes. The study reported safety factor values of 1.387, 1.315, and 1.265 using PLAXIS, while SLOPE/W produced values of 1.295, 1.226, and 1.015 for the same locations. The difference between the two approaches was generally less than 10%, indicating that software-based methods provide consistent and reliable results despite differences in calculation procedures.

Kinasih et al. (2025) investigated the effect of weather conditions on slope stability using GeoStudio SLOPE/W. The study found that rainfall significantly reduced slope stability because water infiltration increased pore water pressure and decreased soil shear strength. At the most critical location, the factor of safety decreased from 10.179 during dry conditions to 6.209 during rainy conditions. These findings confirm that groundwater and moisture conditions are major factors affecting slope performance.

The reviewed studies consistently identify cohesion, friction angle, unit weight, groundwater conditions, and slope geometry as the primary parameters controlling slope stability. They also demonstrate that software-based analysis provides results comparable to analytical methods. However, limited studies have directly compared manual slope stability calculations with GeoStudio SLOPE/W using identical soil parameters and slope geometry. Therefore, this study aims to compare the factor of safety obtained from manual calculations and GeoStudio SLOPE/W analysis to evaluate the accuracy and reliability of software-based slope stability assessment.

3. Methodology

The study was conducted on a natural hill slope located in Narhe, Pune, to evaluate its stability under existing conditions. A field investigation was carried out to assess the slope geometry, including slope height, inclination, drainage conditions, and surface characteristics. Soil samples were collected from different locations along the slope and subjected to laboratory testing. The testing programme included moisture content, bulk density, specific gravity, Atterberg limits, direct shear test, and triaxial compression test. The results of these tests were used to determine the engineering properties of the soil, particularly unit weight (γ), cohesion (c), and angle of internal friction (ϕ), which are essential parameters for slope stability analysis.

The stability of the slope was analysed using both manual and software-based approaches. Manual calculations were performed using the Manual Analysis Using Infinite Slope Formula, where the factor of safety was determined by comparing resisting and driving forces acting on the potential failure surface. GeoStudio SLOPE/W software was then used to model the slope and perform stability analysis using the Bishop Simplified Method. The obtained factor of

safety values from both methods were compared to evaluate the reliability of the software analysis and to identify the critical stability condition of the slope.

Study Area Selection



Field Investigation and Reconnaissance Survey



Slope Geometry Measurement



Soil Sample Collection



Laboratory Testing

(Moisture Content, Density, Atterberg Limits, Triaxial Test)



Determination of Geotechnical Parameters (c , ϕ , γ)



Manual Analysis Using Infinite Slope Formula



GeoStudio SLOPE/W Analysis



Comparison of FOS Values



Interpretation of Results and Conclusions

4. Analytical Results and Quantitative Evaluation

4.1 Physical Properties of Soil

The physical properties of soil samples collected from the study area were determined through laboratory testing. These properties provide essential information regarding the engineering behavior of the soil and its suitability for slope stability analysis. The test results obtained for the three soil samples are presented in Table 5.1.

Table 4.1 Physical Properties of Soil Samples

Property	Sample 1	Sample 2	Sample 3
Natural Moisture Content (%)	17.59	22.77	15.49
Bulk Density (g/cm^3)	1.53	1.47	1.63
Dry Density (g/cm^3)	1.30	1.19	1.41
Liquid Limit (%)	44	25	19.44
Plastic Limit (%)	45	26	19
Plasticity Index (%)	44	20	14

Table 4.1 presents the physical and index properties of the collected soil samples. The natural moisture content varied from 15.49% to 22.77%, with Sample 2 exhibiting the highest moisture content. Bulk density ranged between 1.47 g/cm³ and 1.63 g/cm³, while dry density varied from 1.19 g/cm³ to 1.41 g/cm³, indicating moderate to good compaction characteristics.

The Atterberg limit results showed liquid limit values between 44% and 45% and plasticity index values ranging from 14% to 19.44%. These results indicate that the soils possess moderate plasticity and cohesive characteristics, which contribute positively to their shear strength and overall slope stability.

4.2 Shear Strength Parameters

The shear strength parameters of the soil samples were determined using laboratory testing. Cohesion (c) and angle of internal friction (φ) are important parameters that influence the resistance of soil against shear failure and slope instability. The values obtained from the tests are presented in Table 5.2

Table 4.2 Shear Strength Parameters of Soil Samples

Sample	Cohesion, c (kPa)	Angle of Internal Friction, φ (°)
Sample 1	80	25
Sample 2	84	22.53
Sample 3	90	23.02

The shear strength parameters obtained from the triaxial compression tests are presented in Table X. The cohesion values ranged from 80 kPa to 90 kPa, while the angle of internal friction varied between 22.53° and 25°. Sample 3 exhibited the highest cohesion value (90 kPa), indicating greater resistance to shear failure, whereas Sample 1 showed the highest friction angle (25°). The obtained results indicate that the soils possess adequate shear strength characteristics, which contribute significantly to the stability of the selected hill slope.

4.3 Manual Slope Stability Analysis

Manual slope stability analysis was performed using the **Infinite Slope Method** for cohesive soils. This method assumes that the potential failure surface develops parallel to the ground surface and is suitable for long, uniform slopes. The analysis is based on the balance between the resisting shear strength of the soil and the driving shear stress acting along the potential failure plane.

The shear strength of the soil was evaluated using the Mohr–Coulomb failure criterion, incorporating the cohesion (c), angle of internal friction (φ), unit weight (γ), slope angle (i), and depth of the failure plane (H). The factor of safety (FOS) was then determined as the ratio of the available shear strength to the mobilized shear stress.

Factor of Safety equation for an infinite slope in cohesive soil is:

$$F_s = \frac{c' + (\gamma H \cos^2 i) \tan \phi'}{\gamma H \cos i \sin i}$$

Where:

- F_s = Factor of Safety
- c' = Effective cohesion
- ϕ' = Effective angle of internal friction
- γ = Unit weight of soil

- H = Depth of failure plane
- i = Slope angle

Parameters	Effective Cohesion	Internal Friction	Slope Angle	Unit weight	Depth of Failure Plane	Factor of Safety
Sample 1	80	25	16	15.01	3.7	7.1
Sample 2	84	22.53	16	14.42	3.4	7.44
Sample 3	90	23.02	16	15.99	3.6	7.28

The factor of safety (FOS) was calculated using the Infinite Slope Method for the three soil samples. The obtained FOS values ranged from 7.10 to 7.44. Sample 2 exhibited the highest factor of safety (7.44), while Sample 1 showed the lowest value (7.10). The results indicate that the selected hill slope is stable under the existing conditions and possesses adequate resistance against potential failure.

4.4 GeoStudio SLOPE/W Analysis

A numerical model of the selected hill slope was developed in GeoStudio SLOPE/W using the slope geometry obtained from field measurements at Swaminarayan Hills, Narhe, Pune. The measured slope had an approximate length of 441.63 m and a maximum slope angle of 15.5° , which was rounded to 16° for modelling purposes. These values were obtained from the help of google earth. The geotechnical parameters obtained from laboratory investigations, including cohesion (c), angle of internal friction (ϕ), and unit weight (γ), were assigned to the soil model.

GeoStudio SLOPE/W was used to evaluate the stability of the slope by automatically generating and analysing multiple potential circular slip surfaces. The software identified the critical slip surface corresponding to the minimum factor of safety and calculated the stability of the slope under existing conditions. The generated slip surfaces and critical failure surface provided a comprehensive assessment of the slope behaviour and served as a basis for comparison with the manual Infinite Slope Method.

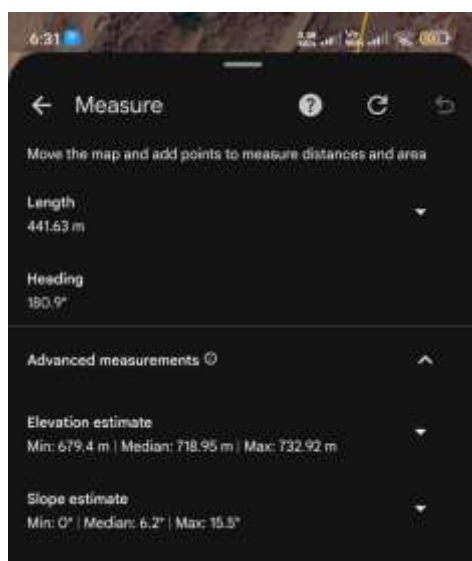


Figure 2



Figure 4

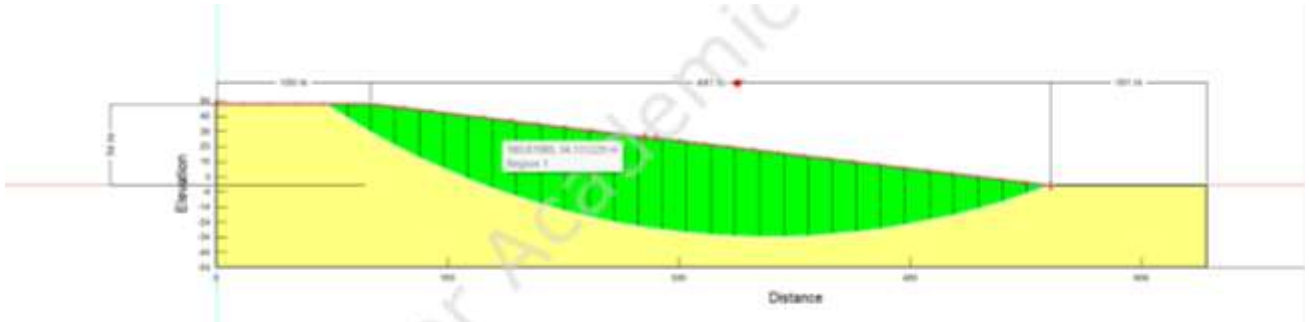


Figure 3

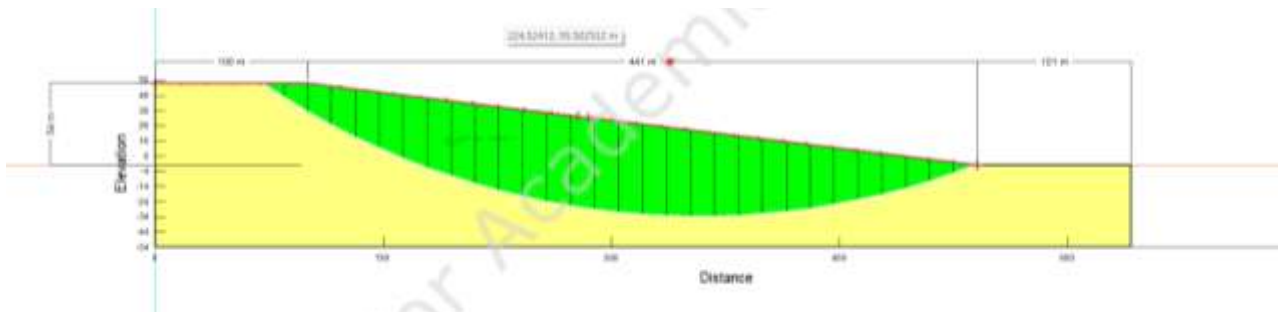


Figure 6

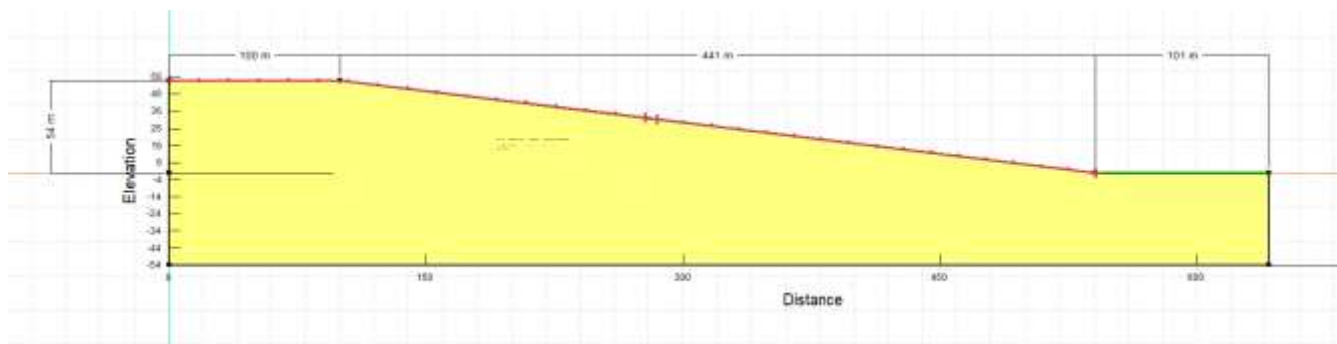


Figure 5

For all three samples, the critical slip surface extends from the upper portion of the slope towards the toe region, indicating a potential rotational mode of failure. The shape and extent of the slip surfaces are similar due to the comparable slope geometry and soil conditions used in the analysis. However, slight variations in the slip surface profile were observed because of differences in cohesion, angle of internal friction, and unit weight among the samples.

The GeoStudio analysis produced factor of safety values of **5.47, 5.11, and 5.16** for Samples 1, 2, and 3, respectively as shown in figure 3, figure 4, figure 5. Sample 1 exhibited the highest factor of safety, indicating relatively greater stability, while Sample 2 showed the lowest value among the three samples. Nevertheless, all factor of safety values is considerably greater than unity, indicating that the selected hill slope remains stable under the existing conditions. The critical slip surfaces identified by the software represent the most probable failure mechanism and provide a realistic assessment of slope behaviour.

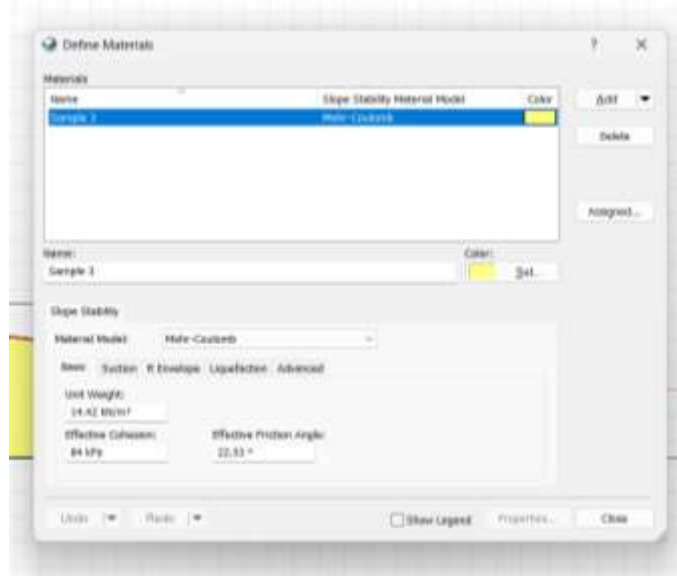


Figure 7

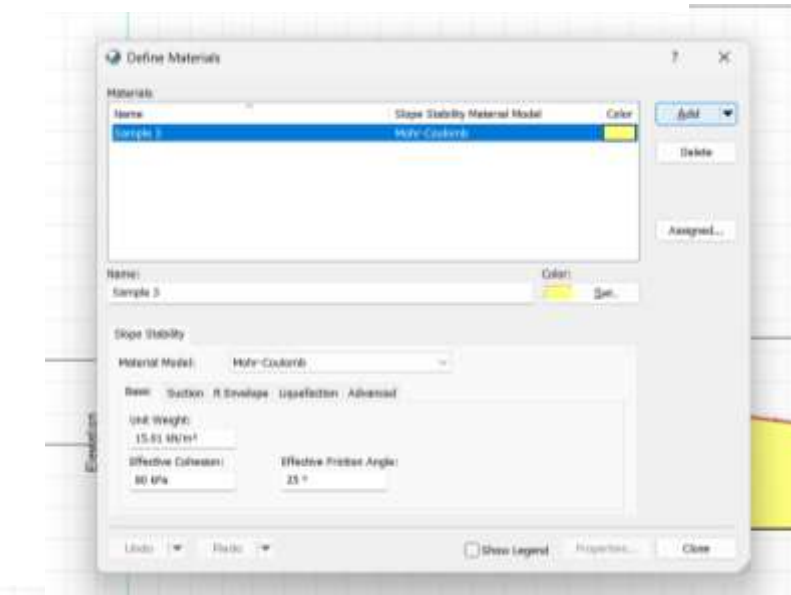


Figure 8

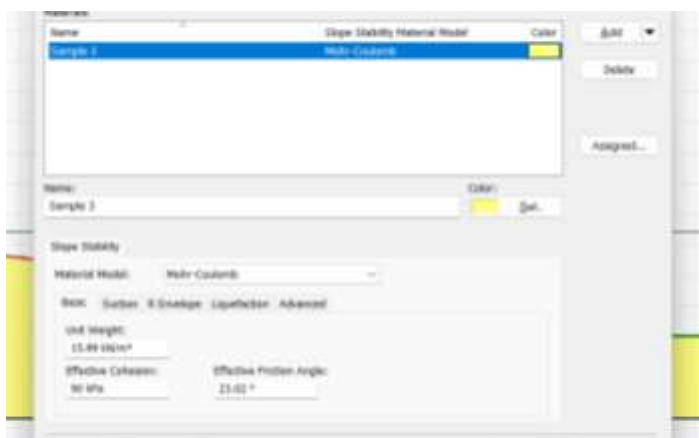


Figure 9

The slope material in GeoStudio SLOPE/W was defined using the Mohr–Coulomb failure criterion. The geotechnical parameters obtained from laboratory testing, including unit weight, effective cohesion, and effective angle of internal friction, were assigned to the soil model for each sample. The assigned unit weight values ranged from 14.42 kN/m³ to 15.99 kN/m³, while cohesion values varied between 80 kPa and 90 kPa. The effective angle of internal friction ranged from 22.53° to 25°. These parameters were used by the software as shown in figure 7, figure 8, figure 9 to evaluate the stability of the slope and determine the critical slip surface and corresponding factor of safety.

Table 4.4 GeoStudio SLOPE/W Analysis Results

Sample	GeoStudio FOS
Sample 1	5.47
Sample 2	5.11
Sample 3	5.16

The factor of safety values obtained from GeoStudio SLOPE/W for Samples 1, 2, and 3 were 5.47, 5.11, and 5.16, respectively. Sample 1 exhibited the highest factor of safety, indicating comparatively greater stability, while Sample 2 showed the lowest value among the three samples. The variation in factor of safety is mainly attributed to differences in the soil shear strength parameters and unit weight. However, all the obtained values are significantly greater than unity, indicating that the selected hill slope remains stable under the existing conditions. The GeoStudio analysis confirms that the available shear strength of the soil is sufficient to resist potential slope failure.

4.5 Comparison of Manual and GeoStudio Results

Table 4.5 Comparison of Manual and GeoStudio Results

Sample	Manual FOS	GeoStudio FOS	Difference (%)
Sample 1	7.10	5.47	22.96
Sample 2	7.44	5.11	31.32
Sample 3	7.28	2.16	29.12

Table 4.5 compares the factor of safety values obtained from the Infinite Slope Method and GeoStudio SLOPE/W analysis. The manual method produced higher FOS values (7.10–7.44) compared to the GeoStudio results (5.11–5.47). This difference is due to the simplified assumptions adopted in the manual analysis, whereas GeoStudio evaluates numerous potential slip surfaces and identifies the critical failure surface. Despite the variation in FOS values, both methods indicate that the selected hill slope is stable under the existing conditions.

5. Discussion

The laboratory test results indicated that the soil possesses adequate shear strength characteristics, with cohesion values ranging from 80 to 90 kPa and friction angles between 22.53° and 25°. The factor of safety obtained from the Infinite Slope Method ranged from 7.10 to 7.44, while GeoStudio SLOPE/W produced values between 5.11 and 5.47. The minimum factor of safety obtained from GeoStudio was 5.11 for Sample 2, which is considerably higher than the generally accepted minimum permissible factor of safety of 1.5 for permanent slopes. Although the manual method produced higher values than the software analysis, both methods confirmed that the selected hill slope is stable under the existing conditions.

6. Conclusion

The stability of the selected hill slope was assessed using the Infinite Slope Method and GeoStudio SLOPE/W. The obtained factor of safety values ranged from 7.10–7.44 for manual analysis and 5.11–5.47 for GeoStudio analysis. The minimum factor of safety obtained was 5.11, which is significantly higher than the recommended minimum value of 1.5. Therefore, the selected hill slope is considered stable under the existing conditions. The study also showed that GeoStudio provides a more realistic assessment of slope stability compared to manual calculations.

7. References

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