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Numerical Modelling and Predictive Analysis of Slope Stability Using the Limit Equilibrium Method: A Parametric Study

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ABSTRACT
Slope instability poses a persistent threat to infrastructure, human settlement, and the natural environment, particularly in rain-intensive regions such as the Indian subcontinent. This study presents a comprehensive numerical investigation of slope stability employing the Limit Equilibrium Method (LEM) as implemented in Rocscience Slide, supported by manual validation using the Ordinary Method of Slices (Fellenius method) in Microsoft Excel. A structured parametric study examines the individual and combined influences of internal friction angle (φ), cohesion (c), unit weight (γ), water table height, and slope inclination on the Factor of Safety (FOS). The software-computed FOS of 1.239 compared favourably with the manually calculated value of 1.060, confirming a theoretically expected conservative deviation of approximately 14% attributable to the neglect of interslice forces in the Fellenius formulation. Parametric results demonstrate that friction angle is the dominant stability parameter for drained granular soils, whilst cohesion governs the stability of undrained cohesive soils. Rising water table height consistently reduces FOS, with full saturation producing the most critical conditions.
Keywords: *Slope stability; Limit Equilibrium Method; Factor of Safety.*

1. INTRODUCTION

Slope instability is widely acknowledged as one of the most critical and destructive geotechnical hazards affecting both natural and engineered environments worldwide. Landslides and slope failures account for thousands of fatalities each year and result in substantial economic losses due to damage to infrastructure, transportation networks, and human settlements. Natural hillslopes, highway cuttings, embankments, earth dams, and retaining structures are inherently vulnerable to instability when the driving forces acting on a soil mass exceed the resisting shear strength mobilized along a potential failure surface [Stokes et al. 2014]. This imbalance between destabilizing and resisting forces governs the initiation and progression of slope failure, making slope stability assessment a fundamental aspect of geotechnical engineering practice.
The problem of slope instability is particularly pronounced in regions characterized by complex geology, steep terrain, and intense climatic influences. In India, for instance, diverse geomorphological and environmental conditions significantly increase landslide susceptibility. The Himalayan region exhibits steep gradients and fragile geological formations, while the Western Ghats are dominated by highly weathered lateritic soils that exhibit considerable strength degradation under environmental exposure. Additionally, seasonal monsoon rainfall induces rapid changes in pore water pressure, which further exacerbates slope instability. According to national hazard assessments, more than 12% of the country's land area is prone to landslides, placing millions of people at risk annually [Bishop. 1955]. These conditions highlight the urgent need for reliable and efficient slope stability assessment techniques that can support both design and hazard mitigation efforts.
The stability of slopes is conventionally quantified using the Factor of Safety (FOS), defined as the ratio of available shear strength to the mobilized shear stress along a potential failure surface. A slope is considered stable when the FOS exceeds unity, whereas values equal to or less than unity indicate limiting equilibrium or failure conditions, respectively [Duncan et al. 2014]. The accurate estimation of FOS depends on several interrelated parameters, including soil shear strength characteristics such as cohesion (c) and angle of internal friction (φ), unit weight (γ), slope geometry, and pore water pressure distribution. In real-world scenarios, these parameters exhibit significant spatial and temporal variability, making slope stability analysis inherently complex. Consequently, parametric and sensitivity analyses are essential for understanding how variations in these parameters influence the overall stability of slopes.

Over the past century, the Limit Equilibrium Method (LEM) has emerged as the most widely used analytical framework for slope stability analysis. The method is based on the equilibrium of forces and/or moments acting on a discretized soil mass, typically divided into slices. Early contributions by Petterson established the concept of circular failure surfaces, which was subsequently formalized by Fellenius through the Ordinary Method of Slices. Although simple and computationally efficient, the Fellenius method neglects interslice force interactions, resulting in conservative estimates of FOS that may underestimate stability by approximately 10–15% compared to more rigorous solutions.

Subsequent developments in LEM sought to improve accuracy while maintaining computational feasibility. Bishop introduced a modified method that incorporates the normal component of interslice forces, significantly enhancing accuracy for circular slip surfaces without excessive computational complexity [Griffiths, & Lane, 1999]. Janbuextended the analysis to non-circular failure surfaces, making the method suitable for slopes with complex stratigraphy and irregular geometries [Janbu 1995]. Spencer later developed a rigorous formulation that satisfies both force and moment equilibrium simultaneously, assuming a constant inclination of interslice forces [Carpenter, 1985]. This was further generalized by Morgenstern and Price (1965), who introduced a variable function to describe interslice force distribution, resulting in one of the most comprehensive LEM formulations available. Comparative studies have demonstrated that rigorous methods such as Spencer and Morgenstern–Price yield highly consistent FOS values, while simpler methods tend to either underestimate or slightly overestimate stability depending on the problem configuration.

The advent of computational tools has significantly advanced the application of LEM in engineering practice. Modern software packages such as Rocscience Slide integrate multiple LEM formulations with advanced features including automated critical slip surface search, groundwater modelling, and probabilistic analysis. These tools enable engineers to evaluate thousands of potential failure surfaces efficiently, thereby improving the reliability and robustness of stability assessments. Duncan 1966 highlighted the transformative role of such numerical tools in enabling systematic sensitivity analysis and automated optimization of slope designs. Similarly, Malkawi et al.2001 demonstrated the effectiveness of advanced search algorithms in accurately identifying critical slip surfaces with improved computational efficiency.

In parallel, the Finite Element Method (FEM), particularly when combined with shear strength reduction (SSR) techniques, has emerged as a powerful alternative for slope stability analysis [Seyed-Kolbadi et al. 2019]. FEM-based approaches provide additional insights into stress–strain behaviour, deformation patterns, and progressive failure mechanisms that are not captured by LEM. Griffiths and Lane (1999) showed that FEM-SSR produces FOS values comparable to those obtained using rigorous LEM methods for homogeneous slopes, while offering enhanced capability for modelling complex material behaviour. However, the increased computational cost and complexity associated with FEM modelling have limited its widespread adoption for routine engineering applications, where LEM remains the preferred method due to its simplicity and efficiency. Benchmarking studies by Cheng and Yip (2007) further confirm that modern LEM software produces highly accurate results, typically within a 2–5% deviation from reference solutions across a wide range of slope configurations.

A substantial body of research has focused on the parametric sensitivity of slope stability to various geotechnical and geometric factors. Abramson et al. (2002) demonstrated that friction angle is the dominant parameter influencing stability in granular soils, whereas cohesion plays a critical role in fine-grained materials. Chatterjee and Krishna (2013) reported significant variations in FOS with changes in cohesion for expansive soils commonly found in India, highlighting the importance of accurate parameter characterization. Similarly, Rao et al. (2010) emphasized the impact of weathering on lateritic soils, which can lead to substantial reductions in effective shear strength and increased susceptibility to failure during monsoon seasons.

Slope geometry is another critical factor influencing stability. Faizi et al. (2015) showed that increasing slope inclination leads to a near-linear reduction in FOS for both cohesive and cohesionless soils. These findings underscore the importance of geometric optimization in slope design. Furthermore, groundwater conditions play a pivotal role in slope stability, as changes in pore water pressure directly affect effective stress and shear strength. Iverson (2000) provided a theoretical framework for rainfall-induced landslides, demonstrating how rapid infiltration can lead to critical pore pressure buildup within short timeframes. Rahimi et al. (2011) extended this understanding through coupled seepage–stability analyses, highlighting the influence of antecedent moisture conditions on slope response to rainfall events.An interesting phenomenon observed in several studies is the non-linear relationship between water table position and slope stability [Alonso 2003; Johansson, 2014]. In certain cases, partial saturation conditions may lead to lower FOS values compared to full saturation due to complex interactions between pore pressure distribution and hydrostatic forces. The stabilizing effect of toe submergence, which can counteract destabilizing pore pressures, has been documented in previous research and remains an important consideration in slope analysis.

Despite extensive research in slope stability analysis, a notable gap remains in the development of simple, reliable, and interpretable predictive models calibrated specifically for conditions representative of Indian geotechnical environments. Existing studies often focus on either detailed numerical analysis or advanced machine learning techniques, with limited emphasis on bridging the gap between these approaches. In particular, there is a lack of regression-based models derived from systematically validated numerical simulations that can provide rapid estimates of FOS without compromising accuracy.

To address this gap, the present study proposes an integrated framework combining numerical modelling, parametric analysis, and statistical prediction. Numerical simulations are performed using Rocscience Slide, and the results are validated against conventional analytical solutions based on the Fellenius method. A comprehensive parametric study is conducted to evaluate the sensitivity of FOS to key variables, including cohesion, friction angle, unit weight, slope geometry, and groundwater conditions. Based on the generated dataset, a Multiple Linear Regression model is developed to predict FOS as a function of these parameters.

The specific objectives of this study are threefold: (i) to validate numerical results obtained from LEM-based software against classical analytical methods; (ii) to systematically investigate the influence of geotechnical and environmental parameters on slope stability through parametric analysis; and (iii) to develop and validate a regression-based predictive model that can serve as a practical tool for preliminary slope stability assessment. The proposed framework aims to provide a balance between computational rigor and practical applicability, offering a transparent and efficient approach for predicting slope stability in real-world engineering scenarios.

The outcomes of this research are expected to contribute to both academic and practical domains by enhancing the understanding of parameter interactions in slope stability and providing a simplified predictive tool for engineering applications. Furthermore, the integration of numerical modelling with statistical analysis represents a step toward more data-driven approaches in geotechnical engineering, aligning with emerging trends in computational and predictive modelling.

2.0 METHODOLOGY

The present study adopts a comprehensive and systematic methodological framework integrating numerical modelling, analytical validation, parametric investigation, and statistical prediction to evaluate slope stability under varying geotechnical and environmental conditions.

2.1 Validation: Fellenius vs. Slide

To ensure the accuracy and reliability of the results obtained from Rocscience Slide, a validation exercise was carried out through manual calculations using the Ordinary Method of Slices, commonly referred to as the Fellenius method. This comparison was intended to assess the consistency between numerical and analytical approaches in slope stability evaluation. A representative slope profile with a geometry of 1V:2H was selected for this purpose, corresponding to a vertical height of 12 m and a horizontal length of 24 m. The slope was carefully constructed using a consistent scale to maintain precision in geometric representation, where 170 units corresponded to 24 m horizontally and 85 units represented 12 m vertically. This scaled model facilitated accurate discretization of the slope into slices for manual computation and ensured meaningful comparison with the numerical simulation results.

Table 1 presents the slice-by-slice breakdown of the manual Fellenius calculation for the primary 1V:2H slope model. Seven slices were used to discretise the critical circular failure surface. The sum of resisting forces was computed as 6,788.19 kN/m and the sum of driving forces as 6,402.76 kN/m, yielding a manual FOS of 1.060. Slide computed an FOS of 1.239 for the same failure surface using the Fellenius (Ordinary) method (Fig 1a, b). The difference of 14.3% is theoretically expected and consistent with established geotechnical literature, confirming that the Slide model correctly implements the Fellenius algorithm whilst the manual calculation successfully verifies the computational logic of the software.

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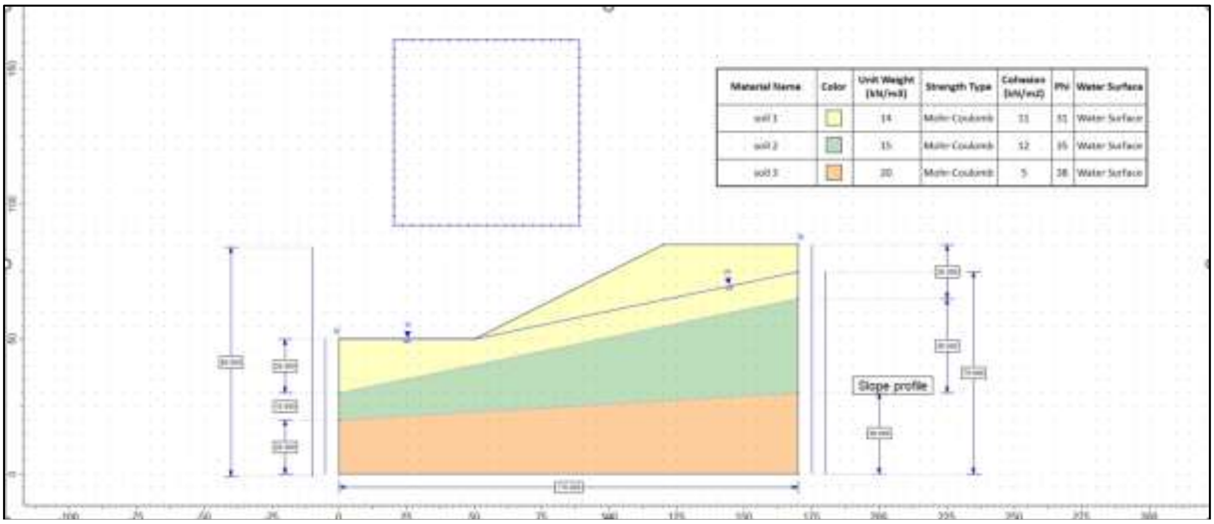
Table1. Manual Fellenius Calculation — Slice Data Summary (1V:2H Slope, H = 12 m)

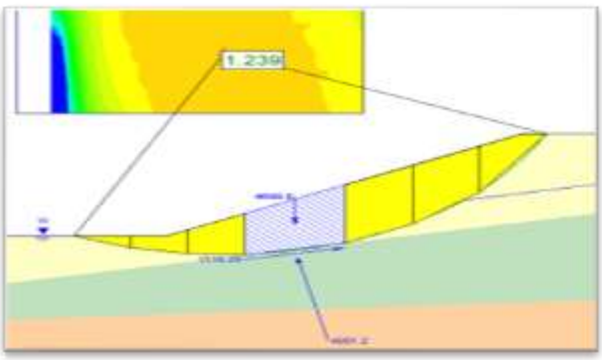
Slice	W (kN/m³)	α (°)	(l) (m)	(u) (kN/m²)	(c) (kN/m²)	resisting force=$[c'l_i + (w_i \cos\alpha_i - u_i l_i) \tan\emptyset']$	driving force=$w_i \sin\alpha_i$
1	327.212	20.3131	11.9826	20.4035	11	169.2876246	113.5916719
2	882.836	10.6452	11.4342	51.1674	11	295.5698225	163.0833986
3	1780.30	1.28465	11.2402	82.8671	11	633.4182057	39.9134246
4	4699.80	11.6336	20.0048	95.8219	11	1834.177626	947.725665
5	3749.61	26.0421	14.8379	77.7278	11	1494.484367	1646.196706
6	3367.72	39.2943	17.2262	19.5105	11	1553.560515	2132.790159
7	1632.14	56.4011	24.0910	0.0000	11	807.6901295	1359.461414
Sum	—	—	—	—	—	6788.188291	6402.762439

All interslice forces are neglected, meaning both normal and shear interactions between adjacent slices are assumed to be zero. Accordingly, the lateral and shear forces acting on either side of each slice are taken as $(E_L = E_R = X_L = X_R = 0)$simplifying the equilibrium analysis.

$$FOS = \frac{\sum[c'l_i \; + (w_i \cos\alpha_i \; - u_i l_i) \; \tan\emptyset']}{\sum w_i \sin\alpha_i}$$



(a). Slope Model with different Soil Properties



(b). Model for FOS

Fig. 1. Slope and FOS using Slice 6

3.0 RESULTS AND DISCUSSIONS

3.1 Effect of Friction Angle on Factor of Safety

A sensitivity analysis was conducted to evaluate slope stability for drained sand by examining the relationship between friction angle (ϕ) and Factor of Safety (FOS) with zero cohesion. A 1V:2H slope profile, representing 12 m height and 24 m horizontal length, was developed using a consistent scale of 170 units to 24 m. The results demonstrate a clear and systematic increase in Factor of Safety (FOS) with increasing friction angle (ϕ) for a cohesionless soil (C = 0), highlighting the dominant role of frictional resistance in slope stability. At ϕ = 20°, the FOS is 0.607, indicating a highly unstable slope condition. As the friction angle increases to 25° and 30°, the FOS rises to 0.777 and 0.962, respectively, approaching the limiting equilibrium state. A further increase to 35° results in an FOS of 1.167, indicating a stable slope configuration. This trend reflects the direct relationship between friction angle and shear strength, where higher ϕ values enhance resistance along the potential failure surface. The nearly linear progression suggests strong sensitivity of FOS to friction angle variations (Fig. 2). These findings emphasize that even small increases in friction angle can significantly improve stability in granular soils, making accurate determination of ϕ critical in slope design and analysis.

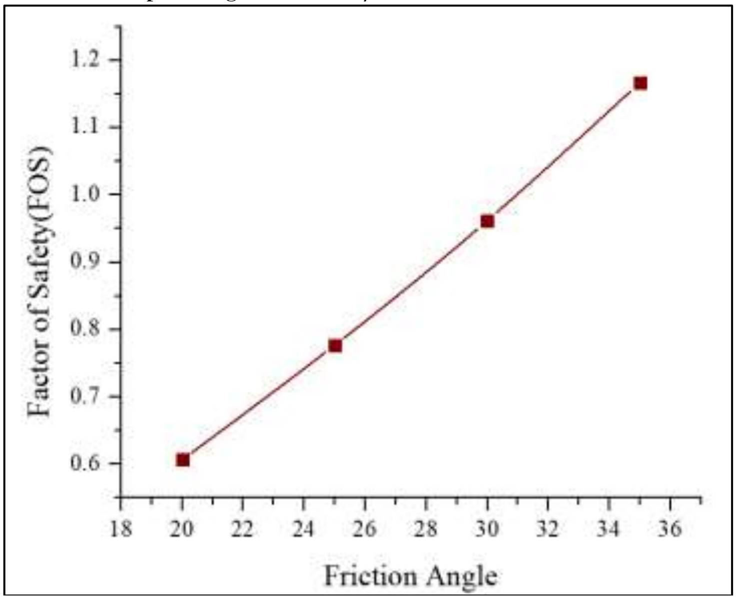


Fig.2. Friction Angle vs Factor of Safety

3.2 Effect of Cohesion on Factor of Safety

The results show a consistent increase in Factor of Safety (FOS) with increasing cohesion for a purely cohesive soil (ϕ = 0), highlighting the critical role of cohesion in undrained slope stability (Fig 3). At low cohesion (20 kN/m²), the FOS is only 0.241, indicating a highly unstable condition. As cohesion increases progressively, the FOS rises almost linearly, reaching 0.966 at 80 kN/m² and exceeding unity (1.026) at 85 kN/m², which marks the transition to a stable slope. This trend demonstrates that cohesion directly contributes to shear strength along the failure surface, thereby enhancing resistance against sliding. The near-linear relationship suggests strong sensitivity of slope stability to cohesion in clayey soils. These findings emphasize that accurate estimation of cohesion is essential, as even moderate increases can significantly improve stability, particularly in undrained conditions commonly encountered in fine-grained soils.

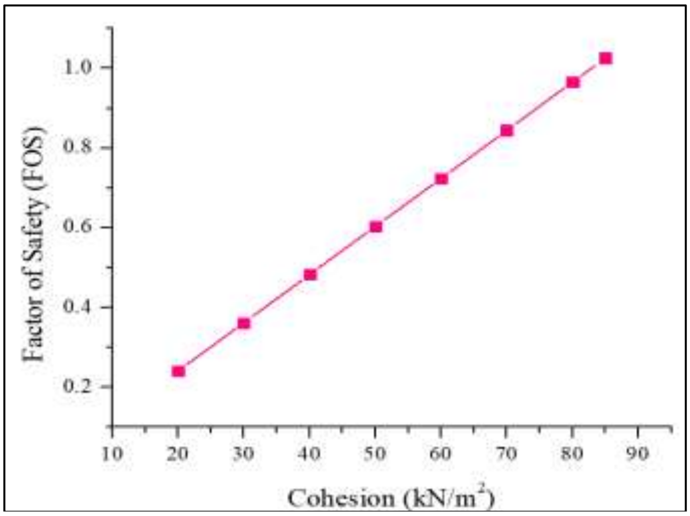


Fig. 3. Cohesion vs Factor of Safety

3.3 Effect of Groundwater Level on Factor of Safety

For the numerical modelling and slope stability analysis, a representative 1V:2H slope geometry was developed with a vertical height of 12 m and a horizontal length of 24 m, reflecting typical embankment and natural slope conditions encountered in geotechnical engineering practice. The slope profile was constructed using a consistent geometric scale in which 170 units represented 24 m horizontally and 85 units represented 12 m vertically, ensuring dimensional accuracy throughout the modelling process. Three different soil materials—Lateritic Silty Soil, Firm Clay, and Clayey Sand—were incorporated into the model using the Mohr–Coulomb failure criterion. The geotechnical parameters assigned to these materials included unit weight, cohesion, and friction angle based on representative soil properties. Lateritic Silty Soil was defined with a unit weight of 13.83 kN/m^3, cohesion of 8.34 kN/m^2, and friction angle of 28.46°, while Firm Clay and Clayey Sand were assigned corresponding engineering properties. Groundwater conditions were simulated using an assigned water surface within the slope model.

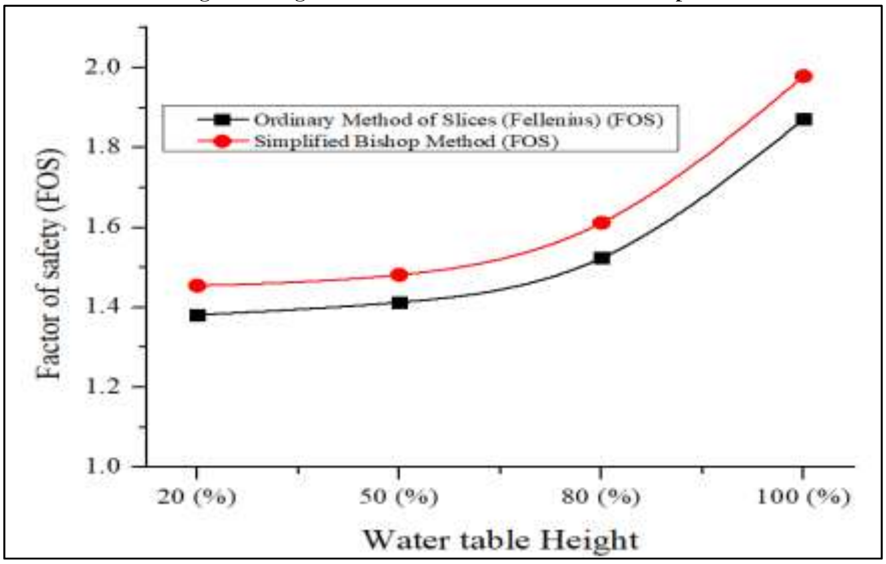


Fig. 4. Effect of water table

The results indicate a progressive increase in the Factor of Safety (FOS) with rising water table height for both the Ordinary Method of Slices (Fellenius) and the Simplified Bishop Method. At a water table level corresponding to 20% of the slope height, the FOS values were 1.382 and 1.455, respectively, indicating stable slope conditions under relatively low groundwater influence. As the water table increased to 50% height, only a marginal improvement in stability was observed, with FOS values increasing slightly to 1.413 and 1.482. However, a more significant increase occurred at 80% water table height, where the FOS reached 1.524 using the Fellenius method and 1.612 using the Bishop method. The maximum stability was recorded under fully saturated conditions (100% water table height), yielding FOS values of 1.871 and 1.979, respectively. This trend suggests that the external hydrostatic pressure generated by full saturation may have produced a stabilizing buttressing effect at the slope toe, which counteracted the destabilizing influence of pore water pressure within the slope mass. Such behaviour is often observed in submerged or partially submerged slopes where confining water pressure enhances overall resistance against sliding. Furthermore, the Simplified Bishop Method consistently predicted higher FOS values than the Fellenius method across all groundwater conditions. This difference arises because the Bishop method incorporates interslice normal forces and satisfies moment equilibrium more rigorously, resulting in comparatively less conservative and more realistic stability estimates. Overall, the analysis highlights the strong influence of groundwater conditions on slope stability behaviour.

3.4 Effect of Slope Geometry on Stability:

The numerical model was developed to evaluate the influence of slope geometry and soil properties on slope stability using different geotechnical conditions. Three slope configurations with inclinations of 1V:2H, 1V:1.8H, and 1V:1.5H were considered to investigate the effect of slope steepness on the Factor of Safety (FOS). The analyses were performed using the Mohr–Coulomb failure criterion, incorporating representative soil parameters such as unit weight, cohesion, and friction angle. Four different soil cases were modelled to represent a range of engineering soil conditions. Soil-1 was assigned a unit weight of 15 kN/m^3, cohesion of 12 kN/m^2, and friction angle of 31°. Soil-2 represented lateritic silty soil with γ = 13.83 kN/m^3, c = 8.34 kN/m^2, and ϕ = 28.46°. Soil-3 and Soil-4 were characterized by properties corresponding to firm clay and clayey sand, respectively. This modelling framework enabled systematic comparison of stability behaviour under varying soil strength and slope geometry conditions.

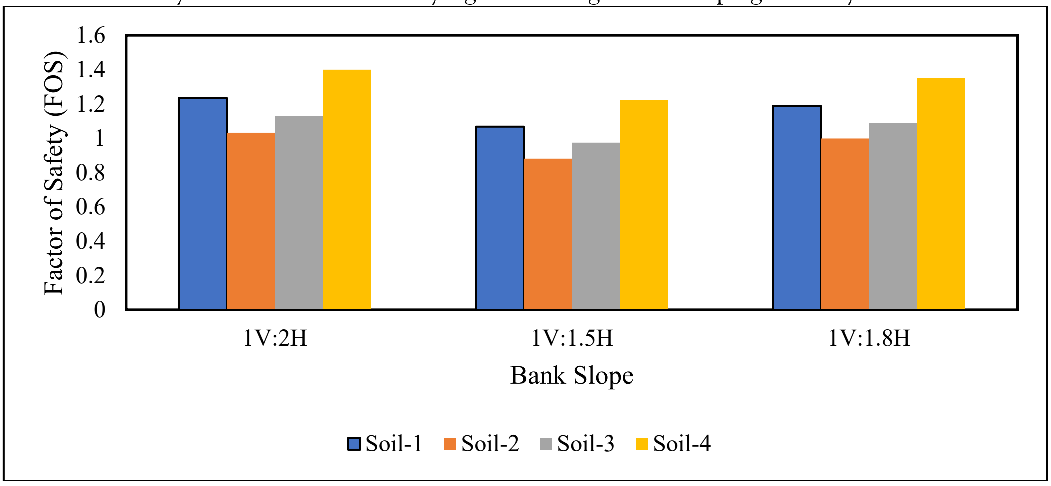


Fig.5. Effect of Slope Geometry on Stability

Figure.5 demonstrate that both soil properties and slope geometry have a significant influence on the Factor of Safety (FOS) and overall slope stability. Among the three slope configurations analysed, the 1V:2H slope consistently produced the highest FOS values for all soil cases, indicating that gentler slopes provide greater resistance against failure due to reduced driving shear stresses. In contrast, the steepest slope configuration, 1V:1.5H, exhibited the lowest FOS values, confirming that increasing slope inclination adversely affects stability by increasing the gravitational driving forces acting along the potential failure surface. For Soil-1, characterized by moderate cohesion and a friction angle of 31°, the FOS decreased from 1.236 for the 1V:2H slope to 1.068 for the 1V:1.5H slope, reflecting a noticeable reduction in stability with increasing slope steepness. A similar trend was observed for Soil-2, which exhibited the lowest stability among all cases due to its relatively low cohesion (8.34 kN/m^2) and friction angle (28.46°). The FOS for Soil-2 dropped below unity for the 1V:1.5H slope (0.880) and approached limiting equilibrium for the 1V:1.8H slope (0.999), indicating potentially unstable conditions. Soil-3 showed moderate stability behaviour, with FOS values ranging from 0.974 to 1.128, while Soil-4 exhibited the highest stability across all slope geometries. The superior performance of Soil-4 can be attributed to its higher friction angle (34°), which significantly enhances shear resistance despite its comparatively higher unit weight. The maximum FOS of 1.400 was obtained for Soil-4 under the 1V:2H configuration. Overall, the results highlight that slope stability is strongly controlled by the combined effects of slope inclination, cohesion, and friction angle, with frictional resistance playing a dominant role in improving stability.

4.0 CONCLUSION

This study presented a comprehensive and integrated framework for slope stability assessment that combines numerical modelling using Rocscience Slide, classical analytical validation through the Fellenius Ordinary Method of Slices, systematic parametric investigation, and the development of a Multiple Linear Regression (MLR)-based predictive model. Together, these components form a cohesive methodology that bridges computational rigor with practical engineering applicability.

The validation exercise established a sound basis for the numerical approach. The software-computed FOS of 1.239 compared against the manually derived value of 1.060, yielding a deviation of 14.3% — consistent with the well-documented conservative tendency of the Fellenius method, which neglects interslice normal and shear forces. This theoretically expected discrepancy, widely reported in geotechnical literature as falling in the range of 10–15%, confirms that Slide correctly implements the algorithm and that the manual computation accurately reflects the classical formulation. The validation thus provides confidence in the reliability of the numerical simulations that underpin the broader parametric study.

The parametric analysis revealed clear and physically consistent trends across all investigated variables. Friction angle was identified as the dominant stability parameter for cohesionless drained soils, with FOS increasing systematically from 0.607 at $\varphi = 20°$ to 1.167 at $\varphi = 35°$, demonstrating strong sensitivity even over moderate angular ranges. For purely cohesive undrained soils, cohesion was found to govern stability, with the slope transitioning from critical instability at low cohesion values to stable conditions as cohesion exceeded approximately 85 kN/m^2. These findings reinforce the Mohr–Coulomb framework and highlight the importance of accurate shear strength characterisation in geotechnical design.

Slope geometry analysis confirmed that steeper configurations consistently produce lower FOS values, with the 1V:1.5H slope approaching or falling below limiting equilibrium for lower-strength soils. The groundwater study yielded a notable observation: under full saturation, FOS values increased relative to intermediate water table levels, a behaviour attributed to the stabilising influence of external hydrostatic pressure at the slope toe. This toe-buttressing effect, documented in prior literature, represents a non-trivial consideration in the design of submerged or partially submerged slopes and should not be overlooked in routine stability assessments.

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