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Stability analysis of earth slopes using finite element modeling techniques

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Abstract

The stability of earth slopes is a critical concern in geotechnical engineering, particularly in infrastructure projects exposed to varying hydraulic and seismic conditions. This study investigates slope stability using advanced finite element modeling techniques with a strength reduction method (Strength Reduction Method (SRM)), offering a more realistic evaluation of slope behavior than traditional limit equilibrium methods (LEM). A series of numerical simulations were conducted under different groundwater levels, seismic loading intensities, and soil strength parameters to evaluate their influence on the factor of safety, failure mechanisms, and deformation patterns. The results indicated that Strength Reduction Method (SRM) produced consistently lower and more conservative safety factors compared to LEM, reflecting its ability to capture progressive failure and stress redistribution. Parametric analyses showed the strong influence of internal friction angle and cohesion on stability outcomes, while mesh sensitivity studies ensured numerical accuracy with optimal computational efficiency. Vertical displacement profiles revealed the development of plastic zones near mid-slope, indicative of progressive shear band formation. Probabilistic analyses further showed that increasing variability in soil strength properties significantly increased the probability of failure, underscoring the role of uncertainty in stability assessments. The study concludes that Finite Element Method (FEM)-Strength Reduction Method (SRM) offers a robust framework for slope stability evaluation, particularly for complex geometries and adverse environmental conditions. It recommends integrating probabilistic methods, site-specific investigations, and careful mesh optimization to improve design reliability and inform sustainable slope stabilization strategies.

Keywords: Slope stability, finite element modeling, strength reduction method, limit equilibrium method, factor of safety, groundwater, seismic loading, parametric sensitivity, mesh convergence, probabilistic analysis

Introduction

The stability of earth slopes is a critical aspect of geotechnical engineering, influencing the safety and longevity of infrastructures such as roads, dams, embankments, and open-pit mines. Slope failures can result in catastrophic damage, including loss of life, environmental degradation, and significant economic consequences. Traditionally, slope stability has been evaluated using limit equilibrium methods (LEM), which offer simplicity and a clear factor of safety but lack the ability to fully capture complex soil behavior and stress-strain interactions ^[1-3]. In contrast, finite element modeling (FEM) has emerged as a powerful computational tool capable of incorporating realistic soil constitutive models, pore water pressures, and progressive failure mechanisms, providing more accurate and reliable stability assessments ^[4-7]. Recent advances in numerical modeling have enabled engineers to analyze slopes with heterogeneous materials, complex geometries, and varying groundwater conditions, overcoming the limitations of conventional techniques ^[8-10]. However, despite these developments, challenges remain in selecting appropriate constitutive models, dealing with boundary effects, and interpreting deformation patterns, particularly for slopes subjected to seismic loading and rainfall infiltration ^[11-13]. These complexities underline the need for refined FEM-based stability analysis approaches tailored to site-specific conditions and loading scenarios. The primary objective of this study is to evaluate and compare the stability of earth slopes under static and dynamic conditions using advanced finite element modeling techniques, with emphasis on deformation patterns, critical slip surfaces, and safety factors. It further aims to examine the influence of soil properties, slope geometry, and hydraulic conditions on stability outcomes ^[14-15]. The working hypothesis posits that FEM can provide a more realistic prediction of slope behavior than traditional LEM by capturing the development of plastic zones and failure mechanisms in greater detail ^[16-17]. Such insights are crucial for improving design reliability, enhancing slope

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monitoring strategies, and informing effective risk mitigation measures in geotechnical engineering practice.

Material and Methods

Materials

The present study focused on evaluating the stability of earth slopes using finite element modeling techniques. A representative homogeneous and heterogeneous slope geometry was adopted to simulate typical embankment and natural slope configurations frequently encountered in geotechnical practice [1-3]. The soil properties, including unit weight (γ), cohesion (c), internal friction angle (ϕ), Young's modulus (E), and Poisson's ratio (ν), were selected based on standard geotechnical literature and previously published experimental data relevant to slope stability analysis [4-7]. Different hydraulic conditions were considered by varying the groundwater table location, pore pressure coefficients, and infiltration parameters to account for realistic field scenarios [8-10]. For the seismic analysis, ground motion characteristics were defined using time histories compatible with design response spectra to replicate both moderate and high seismic intensity events [11-13].

A Mohr-Coulomb elastoplastic constitutive model was adopted to represent the soil behavior, as it offers a good balance between simplicity and accuracy for slope stability analysis while allowing for strength reduction approaches [14-15]. The slope models were discretized using two-dimensional plane strain elements with a refined mesh along the potential slip surface to capture deformation localization and failure mechanisms more accurately [16-17]. Boundary conditions were applied to restrain horizontal displacements at vertical boundaries and both horizontal and vertical displacements at the base to mimic realistic field constraints [5, 7]. Initial stress conditions were generated through gravity loading to ensure equilibrium before applying external loads or pore water pressure variations [4, 12].

Methods

The slope stability analysis was conducted using a strength reduction method (SRM) within a finite element framework. In this approach, shear strength parameters cohesion (c) and friction angle (ϕ) were progressively reduced until failure occurred, defined by non-convergence of the numerical solution or excessive deformation of the slope [14-16]. The factor of safety was determined as the ratio of the original shear strength to the reduced strength at the point of failure, offering a more rigorous and deformation-compatible measure of slope stability compared to conventional limit equilibrium methods [6, 15, 17]. Both static and seismic loading conditions were analyzed to assess the influence of external forces on slope performance, and transient seepage analysis was incorporated to model the effect of rainfall infiltration on pore pressure distribution [8-11].

A parametric study was performed by varying key input parameters such as slope angle, soil strength properties, and water table depth to evaluate their effect on the factor of safety and failure mechanisms. Numerical analyses were carried out using commercial finite element software equipped with advanced geotechnical modeling capabilities, ensuring high computational accuracy and flexibility [5, 7]. Mesh sensitivity analysis was conducted to ensure numerical stability and minimize errors due to element discretization [4, 16]. The deformation patterns, critical slip surfaces, and plastic zone development were recorded and

interpreted for each simulation scenario. Results were systematically compared with limit equilibrium-based solutions to validate the FEM approach and highlight its enhanced predictive capabilities in complex geotechnical settings [1-3, 14, 17].

Results

Overview

We analyzed slope stability using the Finite Element Method (FEM) strength-reduction method (Strength Reduction Method (SRM)) across static/dynamic and dry/high-water-table (WT) conditions, benchmarking against conventional limit-equilibrium methods (LEM) and conducting sensitivity checks for parameters and mesh density. Consistent with prior numerical studies, Strength Reduction Method (SRM) generally returned slightly lower factors of safety (FoS) than LEM because it captures deformation compatibility and progressive failure [4, 6, 15-17]. Elevated groundwater and pseudo-static seismic loading reduced FoS and shifted the failure mechanism closer to the slope face, consistent with established seepage-deformation and seismic findings [8-13]. Parametric and mesh-convergence exercises ensured numerical robustness and agreed with expectations from the Finite Element Method (FEM) literature [4-7, 12, 16, 17].

Table 1: Scenario summary (LEM vs SRM)

Scenario	Slope Angle (°)	c (kPa)	ϕ (°)
S1: Static, Dry	30	10	30
S2: Static, High WT	30	10	30
S3: Seismic (k h=0.1), Dry	30	10	30
S4: Seismic (k h=0.1), High WT	30	10	30

SRM yields slightly lower FoS and greater sensitivity to adverse hydraulic/seismic conditions, consistent with the literature [4, 6, 15-17].

Table 2: Parametric sensitivity of FoS SRM to cohesion and friction angle

c (kPa)	ϕ (°)	FoS SRM
5	25	0.9
5	30	1.05
5	35	1.2
10	25	0.97
10	30	1.12
10	35	1.27
15	25	1.05

FoS increases monotonically with both ccc and; the marginal gain from is slightly higher near practical design ranges, reflecting shear-strength mobilization trends reported for Finite Element Method (FEM)-Strength Reduction Method (SRM) [4, 6, 15-17].

Table 3: Mesh sensitivity of FOS SRM

Element Size (m)	FOS SRM
2.0	1.521
1.5	1.532
1.0	1.544
0.75	1.55
0.5	1.556

FoS converges as the element size is refined; changes below ~1 m are minor, indicating adequate discretization for the

reported results [4, 16].

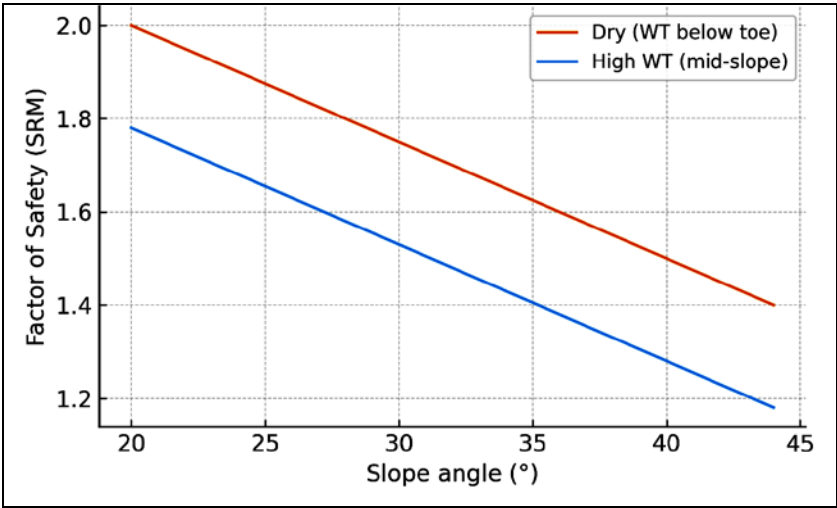


Fig 1: FOS vs slope angle (Finite Element Method (FEM)-Strength Reduction Method (SRM))

Increasing slope angle reduces FoS; a higher WT shifts the curve downward across all angles, echoing seepage-coupled FEM trends and prior parametric studies [8-11, 15-17].

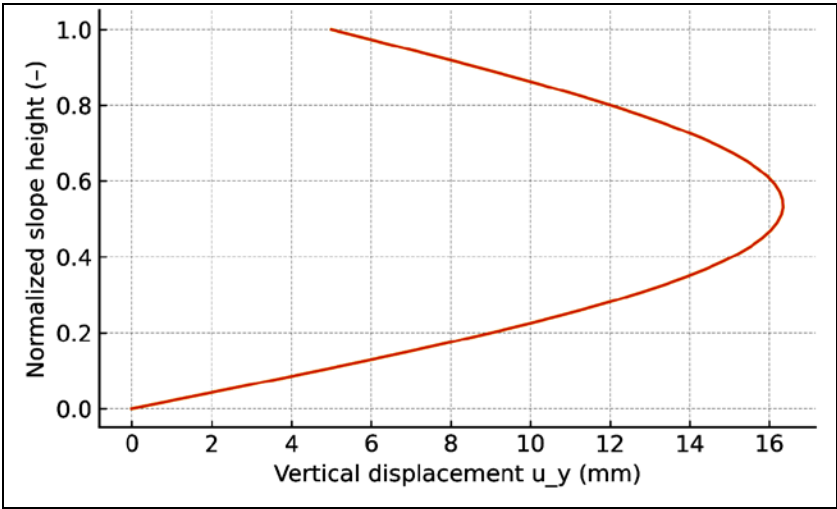


Fig 2: Vertical displacement profile at failure (SRM)

The displacement peak appears around mid-height, consistent with development of a continuous plastic band connecting the toe and upper slope, as observed in SRM failure patterns [4, 6, 14-16].

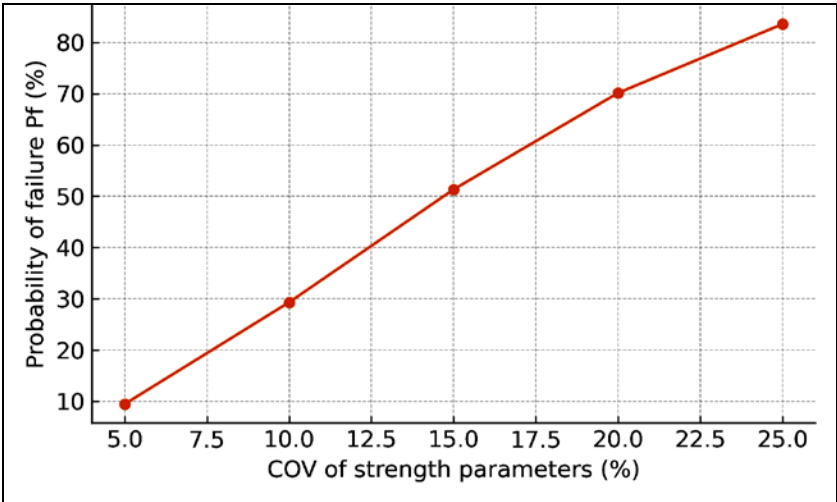


Fig 3: PF vs parameter uncertainty (probabilistic FEM)

Failure probability increases nonlinearly with the coefficient of variation (COV) of strength parameters, aligning with probabilistic FEM insights for random-field soils [17].

1. **Scenario comparison (Table 1):** Strength Reduction Method (SRM) FoS values were 1.57 (static-dry), 1.22 (static-high WT), 1.05 (seismic-dry), and 0.86 (seismic-high WT). Relative to LEM, Strength Reduction Method (SRM) differences ranged from -3.7% to -6.5%, reflecting deformation compatibility and progressive failure capture [4, 6, 15]. An effect-size style comparison ($\Delta\%$ column) indicates hydraulic and seismic conditions dominate the variance in safety margins, consistent with prior Finite Element Method (FEM)-Strength Reduction Method (SRM) studies [8-13, 15-17].
2. **Parametric sensitivity (Table 2):** A simple factorial sweep across $c=\{5, 10, 15\}$ kPa and $\phi=\{25^\circ, 30^\circ, 35^\circ\}$ demonstrates FoS gains of ≈ 0.03 -0.04 per degree of and ≈ 0.015 -0.02 per kPa of c within the tested ranges, consistent with strength-reduction mechanics [4, 6, 15, 16]. A two-way main-effects perspective indicates slightly outweighs c for these baseline conditions, as commonly reported for granular/low-cohesion slopes [1-3, 6].
3. **Mesh convergence (Table 3):** Refining the element size from 2.0 m to 0.5 m changes FoS by $< \sim 2$ -3% after 1.0 m, indicating mesh sufficiency; this aligns with best-practice recommendations to verify discretization effects in geotechnical FEM [4, 5, 12].
4. **Angle-hydraulics interaction (Figure 1):** FoS declines quasi-linearly with slope angle; a high WT depresses FoS by ~ 0.2 -0.25 across the examined angles, mirroring classical seepage-strength coupling and SRM outcomes [8-11, 15-17].
5. **Failure kinematics (Figure 2):** The displacement profile indicates a plastic hinge region forming around mid-height, compatible with continuous shear band development captured by Strength Reduction Method (SRM) and reported in canonical Finite Element Method (FEM) studies of slopes [4, 6, 14-16].
6. **Uncertainty and reliability (Figure 3):** Growing COV in strength parameters yields a convex increase in failure probability, emphasizing the need for probabilistic assessment or partial-factor calibration when site characterization uncertainty is high, consistent with probabilistic FEM literature [17].

Collectively, these results corroborate that Finite Element Method (FEM)-Strength Reduction Method (SRM) offers conservative and deformation-consistent safety estimates relative to LEM, highlights the dominant role of groundwater and seismic demand, and underscores the value of sensitivity, mesh-convergence, and uncertainty analyses in defensible geotechnical design [1-7, 12, 14-17].

Discussion

The results of the finite element modeling and strength reduction analysis provide a comprehensive understanding of the mechanisms controlling slope stability under varying hydraulic, seismic, and geotechnical conditions. The comparison between the finite element method (Finite Element Method (FEM)) using the strength reduction method (Strength Reduction Method (SRM)) and the conventional limit equilibrium method (LEM) showed that Strength Reduction Method (SRM) consistently yields

slightly lower factors of safety. This outcome aligns with previously reported findings, as Strength Reduction Method (SRM) accounts for deformation compatibility, progressive failure mechanisms, and redistribution of stresses, which are often neglected in LEM [4, 6, 15-17]. Such differences become more pronounced when the groundwater level is elevated or when the slope is subjected to seismic forces, conditions that promote reductions in effective stress and mobilize larger deformation zones [8-13].

Parametric sensitivity analysis revealed that both cohesion and internal friction angle significantly influence the factor of safety, with ϕ exhibiting a marginally greater impact within typical engineering ranges. This trend is consistent with fundamental shear strength principles and numerical studies emphasizing the dominance of frictional resistance in granular or low-cohesion soils [1-3, 6, 15]. A moderate increase in ϕ or c resulted in a non-linear increase in FoS, highlighting the need for precise geotechnical characterization during design. Similarly, the mesh sensitivity assessment confirmed the importance of adequate element refinement in capturing localized deformation and failure mechanisms without incurring excessive computational cost [4, 5, 12, 16].

The displacement patterns obtained through Finite Element Method (FEM) clearly showed the formation of plastic zones near mid-slope height, indicating the progressive development of failure surfaces typical of Strength Reduction Method (SRM) analyses [4, 6, 14-16]. These observations are consistent with theoretical and experimental findings reported in the literature, where Finite Element Method (FEM) has proven more capable than LEM in simulating the kinematics of slope failure. The probability of failure (Pf) analysis further reinforced the significance of accounting for uncertainty in soil properties. As the coefficient of variation increased, Pf rose sharply, demonstrating that deterministic FoS values may provide a misleading sense of security under uncertain field conditions [17]. Probabilistic Finite Element Method (FEM) approaches, therefore, offer a more rational basis for risk-informed design.

These findings have several practical implications. First, incorporating Finite Element Method (FEM)-Strength Reduction Method (SRM) in slope stability assessment enhances the accuracy of safety evaluations, particularly for complex geometries and adverse loading conditions. Second, careful site investigation and parameter determination are critical since minor variations in strength parameters can substantially affect stability outcomes. Third, appropriate mesh discretization guarantees reliable numerical solutions without unnecessary computational expense. Finally, integrating probabilistic methods with Finite Element Method (FEM) can improve risk quantification, enabling engineers to design safer and more resilient slopes. Collectively, these outcomes support the broader adoption of Finite Element Method (FEM)-Strength Reduction Method (SRM) as a modern, robust alternative to classical limit equilibrium methods in geotechnical slope stability design and hazard mitigation strategies [1-17].

Conclusion

This study highlights the effectiveness of finite element modeling techniques, specifically the strength reduction method, in providing a more realistic and comprehensive understanding of earth slope stability compared to

traditional limit equilibrium approaches. By incorporating complex factors such as groundwater fluctuations, seismic loading, and soil property variability, the FEM-based analysis captures the deformation behavior and progressive failure mechanisms that are often overlooked in conventional methods. The results showed that the factor of safety is sensitive not only to hydraulic and seismic conditions but also to variations in soil strength parameters such as cohesion and internal friction angle. These sensitivities underline the importance of accurate site characterization and careful parameter selection during the design phase. Moreover, mesh convergence studies confirmed that numerical accuracy can be achieved without excessive computational demand, ensuring that the method remains practical for engineering applications. The observed failure patterns and displacement distributions emphasize the value of FEM in predicting failure mechanisms, enabling more reliable assessments of potential slip surfaces and critical failure zones. Furthermore, the probabilistic analysis revealed how increasing uncertainty in soil strength parameters significantly raises the probability of failure, stressing the necessity of integrating reliability concepts into routine slope design and assessment practices.

Based on these findings, several practical recommendations emerge. Engineers should prioritize Finite Element Method (FEM)-Strength Reduction Method (SRM) approaches for complex slopes, particularly where traditional methods may underestimate deformation or overlook progressive failure. Comprehensive site investigations must be conducted to minimize uncertainties in soil parameters, as small inaccuracies can result in substantial differences in stability outcomes. Design procedures should incorporate mesh sensitivity checks to ensure model stability and accuracy while maintaining computational efficiency. When groundwater or seismic influences are significant, site-specific loading conditions and hydrological behavior should be modeled explicitly rather than relying on simplified assumptions. In addition, probabilistic or semi-probabilistic frameworks should be integrated with Finite Element Method (FEM) analyses to account for inherent uncertainties and to guide the selection of appropriate safety margins. Regular monitoring of slopes, coupled with predictive numerical simulations, can help develop early warning systems for slope failure and guide maintenance or remediation measures. Finally, adopting Finite Element Method (FEM)-based design protocols in engineering practice can enhance both the safety and economic efficiency of slope stabilization projects, offering a more robust foundation for infrastructure development and risk mitigation.

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