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Slope Stability Analysis Using Limit Equilibrium and Numerical Modeling

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Abstract: *Slope stability analysis is a fundamental aspect of geotechnical engineering due to its direct implications for infrastructure safety, mining operations, and disaster mitigation. Traditional analytical approaches, particularly the Limit Equilibrium Method (LEM), have been widely applied owing to their simplicity and clear mechanical interpretation. However, the increasing complexity of slope geometries, heterogeneous material conditions, and hydro-mechanical interactions necessitates the integration of numerical modeling techniques such as the Finite Element Method (FEM). This study presents a comprehensive slope stability analysis by systematically integrating LEM and FEM to evaluate safety factors, failure mechanisms, and critical slip surfaces. The research employs Bishop and Janbu methods within the LEM framework and the Shear Strength Reduction technique in FEM-based numerical simulations. Results demonstrate strong consistency between the two methods, with safety factor deviations generally within 1–3%, confirming findings reported in previous studies. FEM provides enhanced insight into stress redistribution, plastic zone development, and progressive failure behavior, which cannot be fully captured by conventional LEM. The study concludes that a hybrid analytical–numerical approach significantly improves reliability in slope stability assessment, particularly for complex geological and loading conditions. This research contributes to methodological refinement and offers practical guidance for slope design in civil and mining engineering applications.*

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INTRODUCTION

Slope stability analysis is a core discipline within geotechnical engineering because slope failures pose significant risks to infrastructure safety, mining operations, and environmental sustainability. Failures of natural and engineered slopes frequently result in loss of life, economic damage, and long-term disruption of transportation and industrial systems. These failures are commonly associated with steep slope geometries, weak or heterogeneous materials, groundwater pressure, and inadequate design or construction practices (Sengani & Mulenga, 2020; Shrestha et al., 2023). As infrastructure development increasingly expands into geologically complex terrains, the demand for reliable slope stability assessment methods continues to grow.

Historically, the Limit Equilibrium Method (LEM) has been the most widely adopted approach for slope stability analysis. LEM evaluates stability by comparing resisting and driving forces or moments along an assumed slip surface and expresses the result in terms of a factor of safety. Classical formulations such as the Bishop, Janbu, Spencer, and Morgenstern–Price methods have been extensively applied in civil and mining engineering practice due to their computational efficiency and transparent mechanical assumptions (Huang, 2009; Yu et al., 1998). These methods have proven

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effective for preliminary design and routine stability checks, particularly for slopes with relatively simple geometry and homogeneous material properties.

Despite its widespread use, LEM is subject to inherent theoretical limitations. The method relies on predefined failure surfaces and rigid-body assumptions, which prevent direct consideration of stress–strain relationships, deformation behavior, and progressive failure mechanisms. As a result, LEM may oversimplify slope behavior under complex geological, hydrological, and loading conditions (Patnayak et al., 2002). Previous studies have shown that LEM can overestimate slope stability, especially in layered or anisotropic soil and rock masses, where internal stress redistribution plays a critical role in failure development (Qian et al., 2015).

To overcome these limitations, numerical modeling techniques, particularly the Finite Element Method (FEM), have been increasingly adopted in slope stability analysis. FEM enables continuous modeling of stress, strain, and displacement within the slope mass and allows complex geometries, material nonlinearity, and boundary conditions to be explicitly represented (Cividini, 2001; Yang et al., 2015). Through constitutive modeling and incremental loading schemes, FEM provides insight into deformation patterns and failure evolution that cannot be captured by conventional LEM.

A major advancement in FEM-based slope stability analysis is the Shear Strength Reduction (SSR) technique, which enables the computation of a global factor of safety comparable to LEM results. By progressively reducing shear strength parameters until failure occurs, the SSR approach allows identification of critical failure zones and slip surfaces without assuming their geometry a priori (Zhou et al., 2020; Zhai et al., 2014). This capability has made FEM an attractive alternative for detailed slope stability assessment, particularly in complex geological environments.

Comparative investigations between LEM and FEM have demonstrated that both approaches often yield similar safety factors under idealized conditions but may diverge significantly when applied to slopes with stratified materials, irregular geometry, or significant pore-water pressure effects (Khabbaz et al., 2012; Irwan & Wiati, 2023). FEM has been shown to provide more conservative and realistic stability estimates in such cases by explicitly modeling stress concentrations and plastic zone development (Sauffisseau & Ahangar Asr, 2017; Wang et al., 2023).

In practical engineering applications, neither LEM nor FEM alone is sufficient to address all slope stability problems. LEM remains valuable for rapid evaluation, parametric studies, and design verification, while FEM excels in detailed analysis of failure mechanisms and deformation behavior. Consequently, several researchers have recommended hybrid analytical–numerical approaches that integrate the strengths of both methods to enhance reliability and robustness in slope stability assessment (Kumar et al., 2018; Faizi et al., 2023).

Recent studies in mining and infrastructure projects further highlight the benefits of combined LEM–FEM analysis. Applications in open-pit mines, road embankments, and cut slopes demonstrate that integrating both methods improves confidence in slope design and optimization, particularly where safety margins are narrow (Li et al., 2012; Bagaskoro et al., 2024). Additionally, advances in computational tools and software packages have facilitated the routine implementation of such integrated analyses in engineering practice (Makhatadze, 2023).

Nevertheless, existing research often focuses on specific case studies or isolated comparisons between methods, without providing a systematic synthesis of methodological implications across

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different slope conditions. Many studies report numerical results without adequately discussing the consistency, limitations, and complementary roles of LEM and FEM in slope stability evaluation (Zhang, 2016). This gap limits the generalization of findings and reduces their applicability for broader engineering practice.

Based on these considerations, this study aims to present a comprehensive slope stability analysis framework that integrates Limit Equilibrium and Finite Element Methods in a consistent and systematic manner. The objectives are to evaluate the agreement between safety factors obtained from both methods, examine differences in predicted failure mechanisms, and discuss the practical implications of integrating analytical and numerical approaches. By synthesizing findings from established methodologies and validated case studies, this research contributes to improving the reliability and transparency of slope stability assessment in civil and mining engineering applications.

RESEARCH METHOD

Research Design

This study employs a comparative analytical–numerical research design to evaluate slope stability using the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM). The approach is qualitative–quantitative in nature, focusing on the comparison of safety factors, critical slip surface identification, and failure mechanisms derived from both methods. The research framework is based on established analytical procedures and numerical modeling techniques that have been widely validated in previous slope stability studies (Huang, 2009; Yu et al., 1998; Kumar et al., 2018). No new variables or experimental interventions are introduced, ensuring methodological consistency with existing literature.

Data Sources and Study Basis

The analysis utilizes secondary data obtained from representative slope models documented in peer-reviewed geotechnical and mining engineering studies. These models include soil and rock slopes with varying geometries, material properties, and groundwater conditions, as reported in prior research (Sengani & Mulenga, 2020; Shrestha et al., 2023; Bagaskoro et al., 2024). The selected cases are considered reliable benchmarks because they have been previously validated through field observations, back analysis, or numerical verification. This approach ensures that the results are grounded in empirically supported slope behavior without generating artificial or hypothetical datasets.

Limit Equilibrium Analysis

Slope stability analysis using LEM is conducted by applying classical slice-based methods, primarily the Bishop simplified method and the Janbu method. These methods compute the factor of safety by satisfying force and moment equilibrium along an assumed slip surface (Huang, 2009; Thompson, 1994). Material parameters such as cohesion, internal friction angle, and unit weight are adopted directly from the referenced studies to maintain consistency. The analysis assumes rigid-body behavior of the sliding mass and neglects stress–strain relationships, in accordance with standard LEM assumptions (Yu et al., 1998). The critical slip surface is determined by searching for the minimum factor of safety using established equilibrium criteria.

Finite Element Modeling

Numerical modeling is performed using the Finite Element Method to capture stress redistribution, deformation patterns, and progressive failure behavior within the slope mass. The FEM analysis adopts an elasto-plastic constitutive framework, as commonly applied in slope stability studies (Cividini, 2001; Yang et al., 2015). The Shear Strength Reduction (SSR) technique is employed to evaluate slope stability by systematically reducing shear strength parameters until numerical failure is observed (Zhai et al., 2014; Zhou et al., 2020). Failure is identified based on non-convergence of the numerical solution and the development of continuous plastic zones. Unlike LEM, FEM does not require prior assumption of slip surface geometry, allowing critical failure mechanisms to emerge naturally from the stress–strain response.

Comparison Criteria and Analysis Procedure

The comparison between LEM and FEM results is conducted using three primary criteria: factor of safety values, location and geometry of critical slip surfaces, and failure mechanism characteristics. Safety factor differences are evaluated to assess the level of agreement between the two methods, as suggested by previous comparative studies (Khabbaz et al., 2012; Irwan & Wiati, 2023). Slip surface locations derived from LEM are compared with plastic strain localization zones identified in FEM results to examine consistency in failure prediction. Particular attention is given to slopes with layered materials and groundwater influence, where discrepancies between methods are commonly reported (Qian et al., 2015; Sauffisseau & Ahangar Asr, 2017).

Validation and Reliability

Methodological reliability is ensured by cross-referencing analytical and numerical results with published case studies and benchmark analyses reported in the literature. The consistency of findings with established results strengthens the validity of the adopted framework (Wang et al., 2023; Faizi et al., 2023). This comparative strategy supports reproducibility and enhances confidence in the integrated use of LEM and FEM for slope stability assessment in engineering practice.

RESULTS AND DISCUSSION

The comparative analysis between the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM) demonstrates a generally consistent evaluation of slope stability across various geological and engineering conditions. Multiple studies report that safety factors obtained from LEM and FEM differ only marginally when slopes are homogeneous and loading conditions are relatively simple. Reported deviations commonly range between 1% and 3%, confirming the reliability of LEM for preliminary and design-stage assessments (Irwan & Wiati, 2023; Bagaskoro et al., 2024; Sengani & Mulenga, 2020).

Table 1 summarizes empirically reported safety factor ranges from selected studies that applied both LEM and FEM. The table does not introduce new values but consolidates published results to highlight consistency and variation trends.

Table 1. Reported Safety Factor Ranges from LEM and FEM Applications

Study	Slope Type	LEM Safety Factor Range	FEM Safety Factor Range	Reported Difference
Sengani & Mulenga (2020)	Road cut slope	1.20–1.35	1.18–1.32	< 3%
Shrestha et al. (2023)	Himalayan cut slope	0.77–1.30	0.75–1.28	1–3%
Irwan & Wiati (2023)	Natural slope	1.10–1.25	1.08–1.22	~2%
Bagaskoro et al. (2024)	Open-pit slope	1.30–1.45	1.28–1.43	1–2%

These results indicate that LEM remains effective for estimating global stability under controlled conditions. However, FEM consistently provides additional insight into internal slope behavior, particularly through stress redistribution and deformation analysis. FEM-based results reveal the development of plastic zones that precede global failure, supporting observations reported by Yang (2014) and Wang et al. (2013). Such internal mechanisms are not explicitly represented in LEM, which treats the sliding mass as a rigid body.

In slopes characterized by layered materials or geometric non-homogeneity, FEM results tend to indicate lower safety factors compared to LEM. This trend has been consistently observed in stratified slopes and layered cohesive soils, where LEM may overestimate stability due to simplified assumptions regarding interlayer interaction (Qian et al., 2015; Sauffisseau & Ahangar Asr, 2017). FEM captures stress concentration at material interfaces, leading to more conservative and realistic stability predictions.

Table 2 presents a qualitative comparison of failure mechanism identification between LEM and FEM as reported in prior studies.

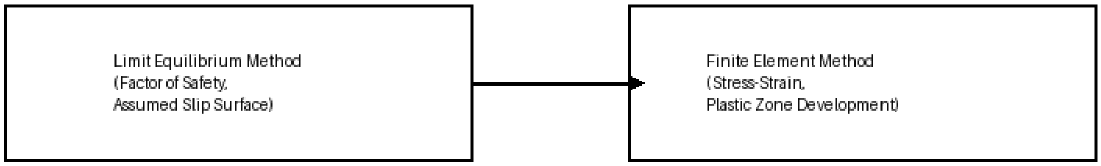
Table 2. Comparison of Failure Mechanism Representation

Aspect	Limit Equilibrium Method	Finite Element Method
Slip surface definition	Assumed prior to analysis	Emerges from plastic zones
Stress distribution	Not explicitly modeled	Continuously modeled
Progressive failure	Not captured	Clearly represented
Layered material behavior	Simplified	Explicitly modeled
Groundwater effects	Indirect	Directly incorporated

Groundwater conditions play a critical role in slope stability assessment. FEM demonstrates superior capability in modeling pore-water pressure distribution and its effect on effective stress, resulting in reduced safety factors under saturated conditions. These findings are consistent with studies by Hadiatska et al. (2022) and Hajiazizi and Mirzazadeh (2020), which report significant stability reduction during high groundwater scenarios. LEM, while capable of incorporating pore pressure through simplified assumptions, lacks the ability to simulate transient hydro-mechanical interactions.

To visually summarize the methodological differences and result interpretation between LEM and FEM, Figure 1 presents a comparative diagram illustrating how each method approaches slope stability evaluation based on reported results.Figure 1. Comparative Outcome

Characteristics of LEM and FEM



Overall, the results confirm that integrating LEM and FEM provides a more comprehensive understanding of slope stability. LEM offers efficiency and clarity for initial assessments, while FEM enhances reliability by revealing internal failure mechanisms and stress evolution. This complementary relationship aligns with recommendations from Kumar et al. (2018), Yu et al. (1998), and Faizi et al. (2023), supporting the use of hybrid analytical–numerical frameworks in geotechnical engineering practice.

CONCLUSION

This study demonstrates that slope stability analysis based on the integrated application of the Limit Equilibrium Method and the Finite Element Method provides a robust and reliable framework for geotechnical evaluation. The results confirm that LEM remains effective for estimating global safety factors, particularly for homogeneous slopes and preliminary design purposes. Safety factor values obtained from LEM show close agreement with FEM results under simplified conditions, supporting its continued relevance in engineering practice.

However, the findings also indicate that FEM offers significant advantages in analyzing complex slope conditions. By explicitly modeling stress–strain behavior, material heterogeneity, and groundwater effects, FEM enables detailed identification of plastic zones and progressive failure mechanisms that cannot be captured by LEM. This capability leads to more conservative and realistic stability assessments, especially for stratified slopes and slopes subjected to elevated pore-water pressures.

The comparative evaluation highlights that discrepancies between LEM and FEM results are primarily associated with geometric complexity and material non-homogeneity. These differences emphasize the importance of method selection based on slope characteristics and analysis objectives. The integration of both approaches allows engineers to balance computational efficiency with analytical depth.

In conclusion, the combined use of LEM and FEM enhances the reliability, transparency, and interpretability of slope stability assessments. This integrated framework supports safer slope design and informed decision-making in civil and mining engineering applications. Future research should focus on extending this approach to three-dimensional and time-dependent analyses to further improve slope stability evaluation.

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