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Research Article

Computational Modelling and Finite Element Analysis for Slope Stability Validation

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ABSTRACT
The validation of slope stability through computation modelling and finite element analysis (FEA), more specifically to clarify the dynamics of slopes in various circumstances. A conventional approach applied was two- and three-dimensional FEA versus the traditional LEM. The research used a variety of geometries, soil types, and boundary conditions that would present a bigger picture than what LEM normally does by considering all those in a summarized manner. The results indicated FEA as an accessible tool in showing the detailed slope stability much more closely to reality, particularly involving complicated geometries and varied materials, comparing LEM. Stability in the slope could therefore be better predicted using this method than when attempting it with LEM since it fails to take into account many real complexities of the conditions. In summary, the results obtained indicate that FEA can significantly improve the accuracy and the reliability in "geotechnical applications".

Keywords: slope stability, finite element analysis, limit equilibrium, computational modelling, geotechnical engineering.

1. Introduction

The natural slopes have always been a source of concern, especially when such concerns referred to safety matters in residential areas. Urban development continues with construction sprawling into areas previously slopes [1-3. Homes, commercial buildings, and other structures are very often constructed either directly on or next to these slopes. This expansion, coupled with massive cuttings, fills, and earth dams, has raised the question of understanding slope behaviour under static and dynamic conditions [4-5. This is not only a question of direct safety to the infrastructure but is often an important issue affecting or including communities and environments.

Figure 1

Figure 1. Represents "**Crown cracks**" appear in some soil slopes: (a). A potential landslide with obvious deformation in Jilin province in 2016, (b). A potential landslide in a waste dump in Sichuan province in 2016,

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(c). A potential landslide with obvious deformation in Jilin province in 2015 and (d) A potential landslide in Liaoning province in 2019. Red Arrows denote to the direction of slides.

The most common slope stability analysis method is the limit equilibrium method (LEM), with present-day applications still relying on this method as much as ever [6]. The major weakness of the LEM is that instead of accurately computing these features, it bases itself on assumptions regarding the shape and location of possible failure surfaces. In effect, the method considers soil as a rigid body whose movement is confined to predetermined failure planes. This eventually results in inaccurate results when dealing with more complex slope geometries and non-homogeneous soil conditions [7-8].The methods used are diverse, and the precision that they can deliver varies significantly according to the assumptions behind each of them. For many of them, computational models for slope stability are used to develop input data for training and cross-validation of predictive models to estimate the stability of rock or soil slopes. Most modern day 2D and 3D slope stability analysis methods are assumed to simplify their calculations by using force equilibrium in only two planes, thus omitting the third direction orthogonal to the x-y plane. As a result, most studies never use the third dimension to perform any kind of analysis and most of them compute the safety factors without taking into account the shapes that the slip surfaces [9].

1.1 Stability Analysis

Traditionally, slope stability analysis has been carried out using conventional two-dimensional limit equilibrium methods. For most applications, these have been of good use, especially in assessing soil slopes [10]. For example, Bishop's simplified method is well accepted and has gained great support from authors like “Hoek” and Bray. The method is widely used but still developed from simplifying assumptions that do not take care of real-world complexities concerning slopes with irregular geometries and material properties that vary in all directions. In recent years, methods such as “Sarma” have been viewed with significant interest because of their ability to take account of inclined interfaces that are capable of simulating discontinuities in structures, hence a closer resemblance of the inward forces acting on the slope [11-12]. However, even these advanced methods are primarily two-dimensional so incapable of capturing the three-dimensional nature of a landslide as clearly as it could be in direct experimentation.

LEMs have been studied extensively. Like has been noted, Duncan had a review of several papers on LEMs which concluded that basically, most of the LEMs subdivided the failure mass into several vertical columns and then resolved the static equilibrium principles to determine the factor of safety [13-14]. Although two-dimensional as well as three-dimensional models exist, relatively few papers have addressed the application of these techniques to practical problems and design. The upper bound approaches have also been studied extensively, mainly with two-dimensional applications for geotechnical problems; however, several authors have generalized this into three-dimensional settings. Most of these analyses have relied on the analytical method of splitting the failure mass into several sections, and a simplified slip surface geometry like a linear or logarithmic form has often been assumed [15]. Such simplifications often severely restrict the practical applicability of the solutions that have been developed, at least in the more complicated conditions. Reduction of Slope Geometry: The techniques can be further limited in applicability to real scenarios in that slope geometry is typically reduced to a two dimensional plane defined by linear equations and material homogeneity, with underestimates of groundwater conditions [16].

1.2 Applications of Finite Element Analysis

Finite Element Analysis is a computational technique for simulating a situation that is now very common in modern engineering due to its important application in disciplines such as structural, civil, aerospace, mechanical, and manufacturing engineering [17-18]. Application of FEA gives important benefits over traditional methods of analysis, especially for systems where geometric complexities and various types of materials cannot easily represent conventional approaches [19-22]. It is critical in providing predictions for the structural behaviour of systems, optimizing design, and demonstrating an understanding of physical behaviour under loading and of boundary conditions in general, thus minimizing the need for costly experimental trials [21-24].

The FEA process therefore involves dividing a structure into thousands of small elements, and an approximate model of the overall behaviour is then developed through mathematical models to represent each [25-26]. This numerical approach provides very crucial insights into stress, strain, and deformation across different materials [27]. Advanced computational tools, such as ABAQUS, ANSYS, and MATLAB, have made the application of FEA far more accessible to the engineers and even the students trying to solve real-world engineering problems. Use of such tools provides intuitive interfaces to model creation, application of loads, and interpretation of results, hence treating FEA as a black box that produces valuable outputs from well-defined inputs. FEA is admirably versatile and can solve an enormous range of problems-from linear

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elasticity to plastic deformation, and even viscoelastic behaviour, in materials [28]. It proves to be quite useful when the problems contain complex boundary conditions or nonlinear material behaviour wherein traditional methods fail quite often [29-31].

1.3 Advanced Constitutive Models in Finite Element Analysis

An advanced constitutive model can further be used in FEA that renders predictions more accurately as regards the response of materials under loading, especially under conditions, than simple traditional approaches [29-30]. FEA differs from the Limit Equilibrium Method, which frequently relies on rather crude assumptions; rather it is possible to use more complex material models, such as Mohr-Coulomb and Hardening Soil models. Such models also allow detailed analysis of stress-strain for a structure element-wise, which makes for much better understanding of the responses of a structure, especially in cases with inhomogeneous materials or any irregular geometry [31]. Another distinguishing aspect of FEA from the traditional approaches is that it can simulate actual boundary conditions, which most traditional methods use idealized boundary conditions that have little resemblance to the real structural behavior. FEA permits different external loads of mechanical, thermal, or dynamic **conditions to analyze more reliably how materials and structures behave to such influences** [32-33].One of the significant advantages of FEA is that it can be used to solve even the most complicated load conditions, which could be either static or dynamic transients. The ability to apply boundary conditions realistically and to simulate multiple types of loading greatly adds to the effectiveness of the results delivered by FEA as compared with traditional practice [31].

1.4 Dynamic Loading and Seismic Analysis

Dynamic loading, especially during earthquake events, has been recognized to be one of the critical loading conditions that may define slope stability [34]. FEA has emerged as a suitable framework for dealing with complications that soil behavior poses in dynamic loading, thus being appropriate for assessing slope stability under seismic conditions. Unlike the traditional models, which ignore time-history response of slopes in seismic events, FEA includes both explicit and implicit methods; therefore, it can depict the dynamic response [35]. This method is able to develop the mechanics of failure or trace the progression of instability caused by slope because of seismic activities forces.
FEA time-dependent analysis of a slope provides a more complete understanding of how seismic energy travels through a slope under stress accumulation, which may eventually cause failure. Another advanced FEA technique used to estimate the effect of ground motion on slopes is response spectrum analysis [36]. Hence, its knowledge is essential in designing measures to prevent landslides. Frequent use of constitutive models for soils in software tools such as PLAXIS and “GeoStudio” in seismic slope stability studies has also become a widespread feature. Many recent case studies indicate that FEA models, both 2D and 3D, are more efficient than the traditional pseudo static methods, which rely on even more drastic simplifications [37].

1.5Challenges and Limitations

Despite all its merits, FEA is still plagued by quite a number of challenges and shortcomings that must be recognized. Chief among these challenges is the cost in computation associated with FEA, particularly for large scale three dimensional models with difficult boundary conditions [38-40]. Simulations that are high fidelity demand significant computational resources and hence, solution times would be pretty large due to the large number of degrees of freedom. FEA is generally expensive and might well be too pricey for any project requiring detailed, large-scale simulations.
Another equally crucial challenge in FEA is calibration of the model. In FEA, the quality of input data used will typically be affecting the accuracy of the results since models require input data, such as material properties and boundary conditions, to be very accurate. Any inaccuracy in the input data might make the analysis inefficient by returning unreliable results. More complex constitutive models, for instance, Mohr-Coulomb and Hardening Soil models, may improve it to a great extent, but that kind of data is not commonly available [41-44]. Another significant factor that causes FEA not to be perfectly accurate is mesh quality. A bad mesh construction or large size of the elements tends to cause either convergence failures or spurious solutions. At the same time, although it performs better at higher accuracy in finer meshes, computation requirements shoot up with finer meshes and rather negate practical applications in most real scenarios.

FEA also fails in the task of modelling complex dynamic behaviour, especially under high frequency loading conditions. Explicit time-integration techniques are widely used in the analysis of dynamics. Unfortunately, explicit schemes require very small time steps to maintain numerical stability; this certainly leads to increased computational activities. Additionally, contact problems with large deformation and plasticity are

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tricky cases to model accurately using nonlinear analysis methods, and as a rule, lead to divergence [45]. Finally, FEA models usually make some assumptions, which could be miles from reality: such assumptions as linear elasticity, isotropy, and small deformations. These assumptions cause a conflict between the computed values and actual material response, particularly in viscoelastic or liquefaction phenomena during earthquakes [46-47].

1.6 Emerging Trends and Future Scope in Finite Element Analysis

Emerging trends in FEA are the movement towards overcoming these limitations by incorporating new technologies into FEA. Some emerging trend is the incorporation of advanced technologies into FEA, such as the application of machine learning techniques [48]. Specifically, the recent advancement made in machine learning models, especially those drawn from neural networks, has created the possibility of approximating how inputs translate to outputs from FEA models with minimal computational latency and even without the full-scale FEA simulation. This means that it can do structural responses very fast by relating inputs to outputs in models, thereby reducing computational costs and allowing real-time analysis, thus making FEA more practicable for large-scale engineering projects [49].

Another significant stride forward is the concept of digital twins. Digital twins are the virtual models representing how the physical assets behave in real-time, thus allowing for constant monitoring and management of slope stability. Integrating real-time sensor data with FEA models puts digital twins in a position to make proactive slope management that predicts potential failures before their occurrence [50-54]. That is particularly very helpful where there are significant landslide-prone or earthquake-prone regions, where for very timely interventions can help prevent catastrophic failures [55-57]. Digital twins in geotechnical engineering will herald an efficient step forward in the management of infrastructure approaches that are more intelligent and resilient. This integration of machine learning and digital twin technologies with FEA shall automate model calibration and sensitivity analysis, enhance accuracy, and save time [58]. All these emerging trends have great potential in making FEA able to use modern advances of computation, increasing efficiency, and real-time accuracy solutions compared with the traditionally complex and time-consuming challenge of engineering[59-62].

Motivations behind the conducting of this specific study include introducing a method that might be employed to identify the role of computational modeling and finite element analysis in evaluating and validating slope stability [63-64].Surely, one among the utmost focuses in geotechnical engineering is dealing with the impact as it directly affects infrastructure safety and sustainability of the environment [65-66].Traditional methods, including the Limit Equilibrium Method, are common for stability analysis but severely limited in real-world applications, especially for complex geometry or variation of soil properties under dynamic loading conditions [67-68].However, FEA forms a more general framework to model the behavior of soil and understand the mechanisms of failure under various types of loading [69].This systematic review will synthesize recent findings about how FEA has been applied to analyze slope stability by commenting on its benefits over traditional methods and clarifying current shortcomings for future work. However, one can see that trend-emerging trends, especially those combining machine learning into FEA and creating digital twins, are envisioned to cut down the computational time while ensuring greater accuracy [70].It summarises the current state of research and strives to provide an overall understanding of the capabilities and future potential of FEA in geotechnical applications, contributing thus to safer and more sustainable engineering practice [71].

2. Literature Review Methodology

The literature review would therefore cover the study and forecasting of slope stability applying FEA techniques to geotechnical projects. The concept behind this is the enhancement of safety and reliability by use of journal articles in Scopus, covering the period of 2018 to 2024. Data collection guided accordingly and filtered thereafter as required by specific criteria will be conducted. The greater objective is to gain more profound insights into the efficiency and applicability of FEA methods in predicting slope stability, which contributes to a betterment of the practice in engineering, where risks are lessened and infrastructure develops.

Table 1: Searching Keywords

Databases	Keywords Used
Scopus	TITLE-ABS-KEY ("Slope stability" OR "Slope failure" OR "Slope assessment") AND TITLE-ABS-KEY ("Finite Element Analysis" OR "Computational Modeling" OR "Safety factor" OR "Limit Equilibrium")

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2.1 Inclusion and Exclusion Criteria

The literature search was conducted by applying specific inclusion and exclusion criteria to ensure that the selected studies were directly relevant to computational modeling and FEA in slope stability. The criteria are shown in Table 2 below.

Table 2

Criterion	Inclusion	Exclusion
Keywords	Records addressing the relationship between slope stability, FEA, and safety assessments	Records not directly related to these topics
Type of Literature	Articles, conference papers, book chapters, reviews	Retracted publications
Language	English	Non-English publications
Timeframe	2018-2024	Studies published before 2018
Publication Stage	Final publications	In press or under review
Access	Open Access	Paid access without institutional subscription

PRISMA- Model

The review utilized the PRISMA framework to allow for an appropriate systematic and transparent process. The methodology also attempted to ensure directing to massive identification, screening, and selection of pertinent studies. Data extraction started with an extensive search identifying relevant research articles via keywords before a detailed scrutiny of irrelevant records could be carried out.Therefore, a total number of 200 records were identified from the SCOPUS database. At the screening stage, there were records of 50 that were excluded after looking at the title and abstract for relevance on the research topic. This will leave 150 records and then go into a full-text review. A total of 10 records were excluded because of unsuitable document types. Other records were excluded since they were still in press or incomplete; still, others were excluded because of language restrictions, after the content was manually reviewed, an extra 20 records.

Figure 2: A PRISMA-based flowchart for systematic reviews of publications found in databases.

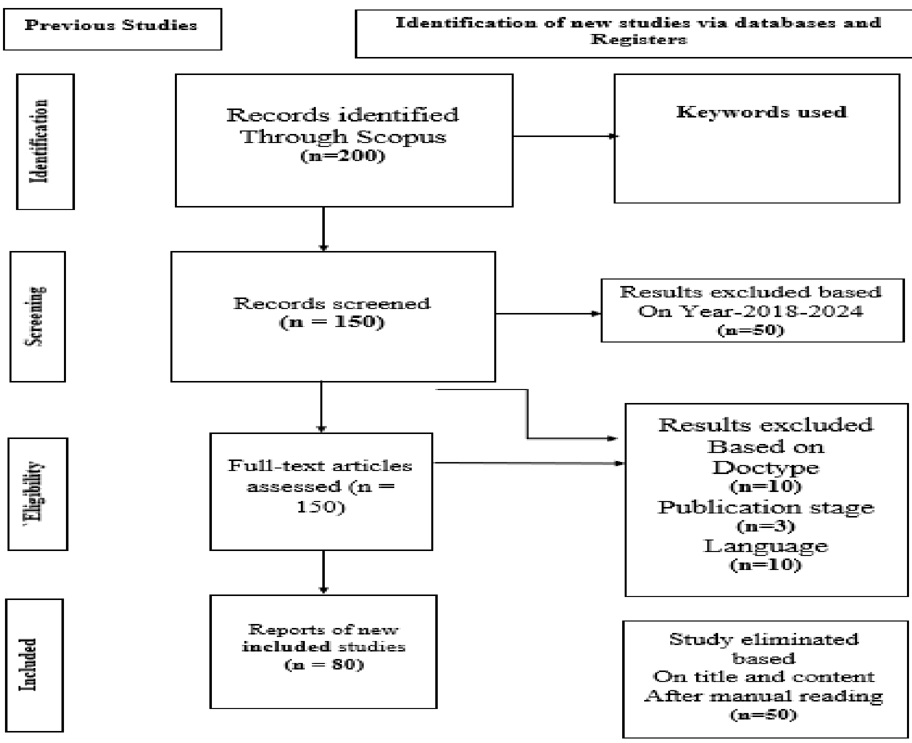

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Figure 3 demonstrates the top 5 areas that were most extensively studied based on specific criteria. The figure shows that Geotechnical Engineering has the most published articles, i.e.,
60, followed by Civil Engineering, which has 55 published articles. In Computational Modeling and Simulation, there were 45 articles, followed by Environmental Science and Mining Engineering, which have 35 and 25 published articles, respectively.

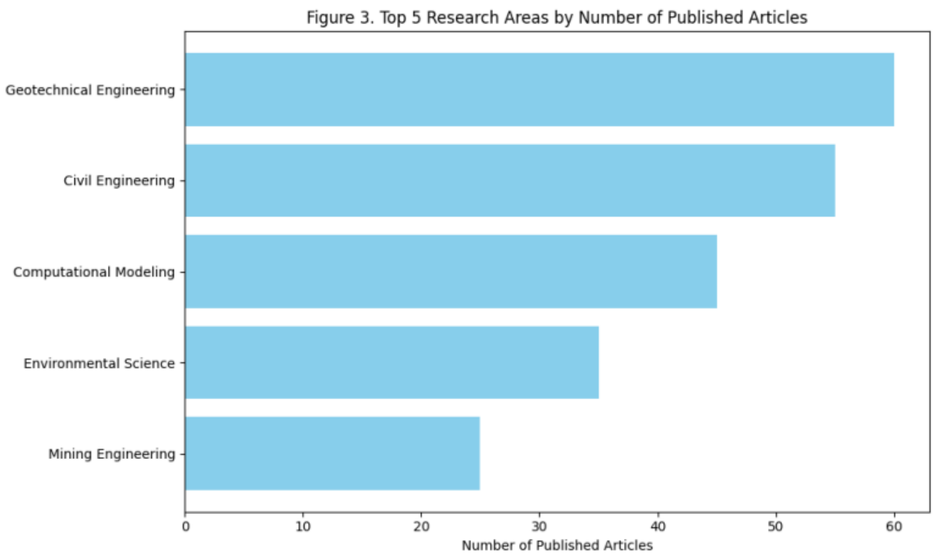

Figure 4: The findings highlight that the following keywords are significant during a literature review on slope stability analysis: While out of 88 papers, it was seen that a large number of papers focus on the stability evaluation of varying slope configurations. Machine learning (ML) techniques have been widely used; of 53 papers, discussions were found regarding the application of ML in predicting the slope stability, which reflects a rise in dependence on ML models for values prediction. An equally important factor is the factor of safety, or FoS" , which has 56 and 28 papers, respectively, relating to its determination, testifying to the role that Additionally, 25 papers focus on overall stability analysis, showing that there are considerable researches oriented to develop a method that enhances the level of safety and reliability in slope assessments. These trends depict improvements in the slope stability evaluation system by integration of advanced predictive models, such as ML, which will result in better outcomes of safety and sustainability. The approach here is methodology-based, using ML-based models and integrating safety-related parameters, congruent with the trend established and set to further elevate the reliability of slope stability prediction.

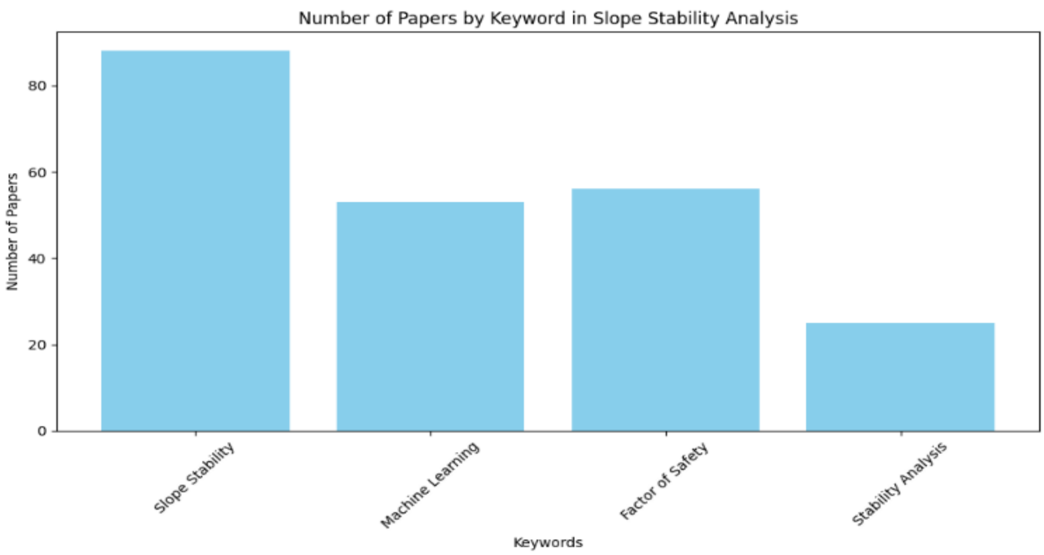

Figure 4:

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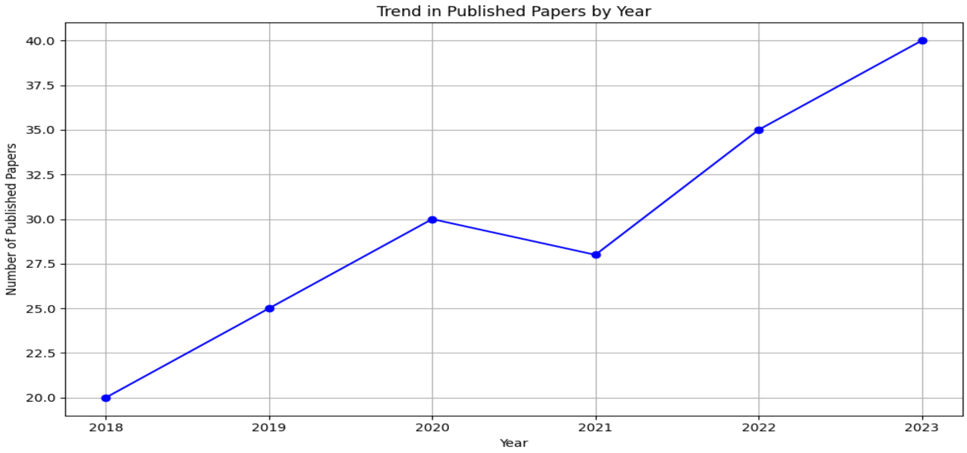
Figure 5: Represents the timeline of research publications on finite element analysis (FEA) in validating slope stability. In conducting the literature review, we were careful about our choice of keywords that would lead us to the publication on computational modeling and how FEA could support geotechnical engineering, especially in assessing soil and rock slope stability under diverse conditions.

Figure 5:



3. Literature Review

This literature review discusses state-of-the-art FEA techniques in predicting slope stability of geotechnical engineering projects. The objective is to better safety and reliability aspects as the analysis will be carried out based on journal articles published between 2018 and 2024 sourced from Scopus. After screening various data sets based on specific criteria, a final comprehensive understanding of how effective FEA methods are for the prediction of slope stability is achieved. The ultimate goal for this study would be contribution toward better engineering practices in risk reduction and the enhancement of resilience in infrastructures.

- **FOS prediction for slope stability analysis through FEA**

FEA has been effective for improving slope stability analysis and to support risk management. Wei et al. (2024) have recently proposed a micro-structure tensor enhanced elasto-plastic finite element method in order to address the complexities related to strength anisotropy. Various slope geometries such as straight, convex and concave slopes have been analysed through the Gravity Increase Method (GIM) to improve the predictions concerning stability for such slopes. Jia et al. (2024) also put forward a GPU-accelerated explicit smoothed particle finite element method ("eSPFEM"), which integrates the strength of high-performance computing into the investigation of big deformation slopes. In this respect, such a method has been used for simulating several landslide initiation stages, sliding, and accumulation conditions, which can provide more valuable slop stability insight.

Other research works point out those FEA methodologies could be effectively applied to enhance slope stability analysis in different cases. Jiang et al. (2024) presented stochastic finite element methods of quantitative slope reliability and risk assessment by emphasizing the spatial variability of geomaterials in the influencing patterns of failure modes and risk levels. Zhou and Qin (2023) used the finite-element lower-bound (FELB) and upper-bound (FEUB) approaches with pseudo-dynamics in the seismic slope stability analysis, which made an emphasis on the role of soft bands in safety factors. Kadlíček and Mašín (2023) proposed a surface layer method to stabilize the numerical model while analyzing strength reduction, especially in 3D environments with complex surface morphologies.

Liu et al. (2020) recommended a finite element limit equilibrium method for time-efficient analysis of various slope types that do not require iterative strength reduction. Moreover, Chen et al. (2019) utilized the finite element method of Coupled Eulerian-Lagrangian to eliminate the mesh distortion problems usually inherent in the traditional Lagrangian methods to obtain a more reliable Factor of Safety prediction. Oberhollenzer et al. (2018) compared the strength reduction finite element analysis with a finite element limit analysis. This paper has especially emphasized the role played by adaptive mesh refinement in improving safety factor estimations. These together prove that conventional geotechnical practices shall be put together with the methodologies of FEA to enhance slope stability analysis and thus make better risk management strategies in geotechnical engineering.

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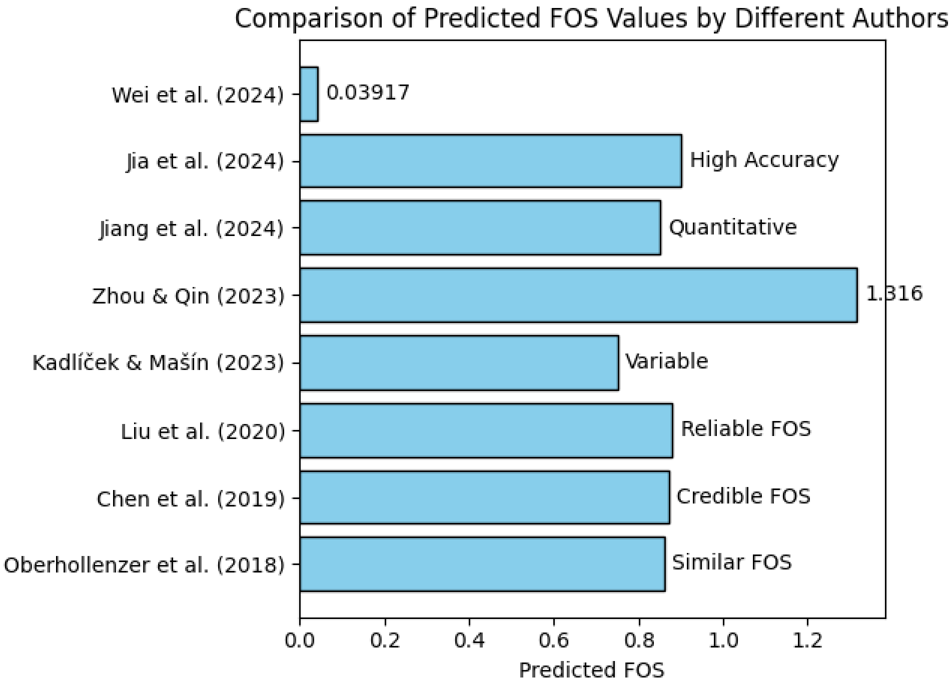
Table 3: Literature review shows the comparative analysis of several studies applied for FOS prediction

Author	Year	Method to Obtain FOS	FEA Method/Technique Used	Input Variables	Predicted FOS
Wei et al.	2024	GIM	Micro-structure Tensor Enhanced FE	ρ, c, φ, β, H, ru	0.03917
Jia et al.	2024	Strength Reduction	GPU-Accelerated eSPFEM	Cohesive properties, slope moisture level	High Accuracy
Jiang et al.	2024	Stochastic Analyss	Stochastic Finite Element Method	Geomaterial variability, slope geometry	Quantitative
Zhou & Qin	2023	Seismic Analysis	FELB and FEUB	φ, c, seismic inputs	1.316
Kadlíček & Mašín	2023	Surface Layer Method	Surface Layer Method	Surface irregularities, slip surface	Variable
Liu et al.	2020	Limit Equilibrium	FELEM	2D and 3D elastic stress fields	Reliable FOS
Chen et al.	2019	Coupled Eulerian-Lagrangian (CEL) FE	Coupled Eulerian-Lagrangian (CEL)	Homogeneous and layered slopes	Credible FOS
Oberhollenzer et al.	2018	Strength Reduction	SRFEA vs FELA	High friction angles, non-associated flow	Similar FOS

Figure 6: illustrates the findings presented by the authors for FOS prediction



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- **Limit Equilibrium Method vs. Finite Element Method**

The slope stability will be analyzed, so the literature review will refer to the Limit Equilibrium Method (LEM) and Finite Element Method (FEM). In essence, this will be mainly to assess and compare the effectiveness of the methods towards this problem, and also find any gaps in current knowledge. The supporting data are journal articles from SCOPUS, which fall within the range of 2012 to 2024. Analyzing the said studies critically, this section would explain the limitations and strengths of LEM and FEM in predicting slope stability, which would eventually help improve geotechnical engineering practices. Liu et al. (2015) conducted a comparative study of the safety factors FoS and critical slip surfaces generated through LEM, ELSM, and SRM. The analysis of several two-dimensional slope examples revealed that usually LEM generates a larger value of FoS than FEM-based methods but gives a much more realistic representation of the failure surface. Burman et al. (2015) reported the application of SRT in the FEM for evaluating the FoS. Although SRT enables high accuracy, their extensive computational activity restricts its present use to only routine slope stability analysis. Khabbaz et al. (2012) reviewed the application of both LEM and FEM methods in slope stability analysis in the context of the SLOPE/W and PLAXIS software programs. Khabbaz et al. opine that the primary difference between the LEM and the FEM method lies in the fact that LEM involves simpler computations but deepens the understanding of the distribution of stresses and deformation behavior.

Rawat and Gupta (2016) have analyzed the failure of a nailed soil slope using LEM and FEM. The authors conclude that LEM generally computes higher values of FoS with the nail forces build-up with increasing slope angles, as can be seen from the FEM results. There is a large difference in the predicted failure surfaces based on these two methods. It is particularly remarkable for the reinforced slopes. A new method for shear strength reduction in FEM was proposed by Wei et al. (2010) to determine the FoS with better accuracy. The examination of yield elements within finite element results provides the possibility of more accurate failure predictions as compared to the conventional methods. Ayob et al. (2019) carried out a case study on the evaluation of slope stability at a landslide-prone location in Malaysia using both LEM and FEM.

The study results indicate that FEM is able to predict the mechanism of slope failure accurately, while LEM overestimates the FoS. Yang et al. (2015) suggested an integrated approach that has been developed based on the principles of LEM and FEM to compute critical slip surfaces and minimum safety factors. The method mainly reduces the search space for computing the critical slip surface, thus improving efficiency in the slope stability analysis. Tan and Sarma have used finite element analysis to verify a new procedure for slope stability analysis applied to homogeneous and non-homogeneous slopes.

They concluded that their FEM results are in close agreement with the new procedure on critical acceleration, slip surfaces, and stress distribution. Recently, Li et al. (2016) compared LEM and FEM in the probabilistic approach to predict the probabilities of slope failure. According to their study, though less computationally intensive, LEM has some limitations, and FEM can give more realistic representation of the failure mechanisms in complex geometries. Aa complex slope composed by alternate layers of sandstone and marl, LEM and FEM have been adopted by Khadija et al. (2012). When compared with each other, it was seen that though the stabilization of analysis was quite good for such complex geometries through FEM, for the true failure mechanism, LEM was not successful in capturing.According to the comparison analysis, although LEM is mostly employed due to the complexity and lower computational cost, FEM is still the most accurate in explaining stability in slope cases, especially in detailed configurations, and especially when conditions are reinforced. In Table 2, the studies consulted have been summarized based on the method used to arrive at the findings:

Table: 4

Author	Year	Method to Obtain "FoS"	Technique/Approach Used	Input Variables	Key Findings
Liu et al.	2015	Limit Equilibrium, FEM	ELSM, SRM	c, φ, H, γ	LEM tends to overestimate FoS
Burman et al.	2015	Strength Reduction	FEM	c, φ, pore water pressure	Limited adoption in practice
Khabbaz et al.	2012	LEM, FEM	SLOPE/W, PLAXIS	Slope geometry, soil strength,	Specific advantages for each method

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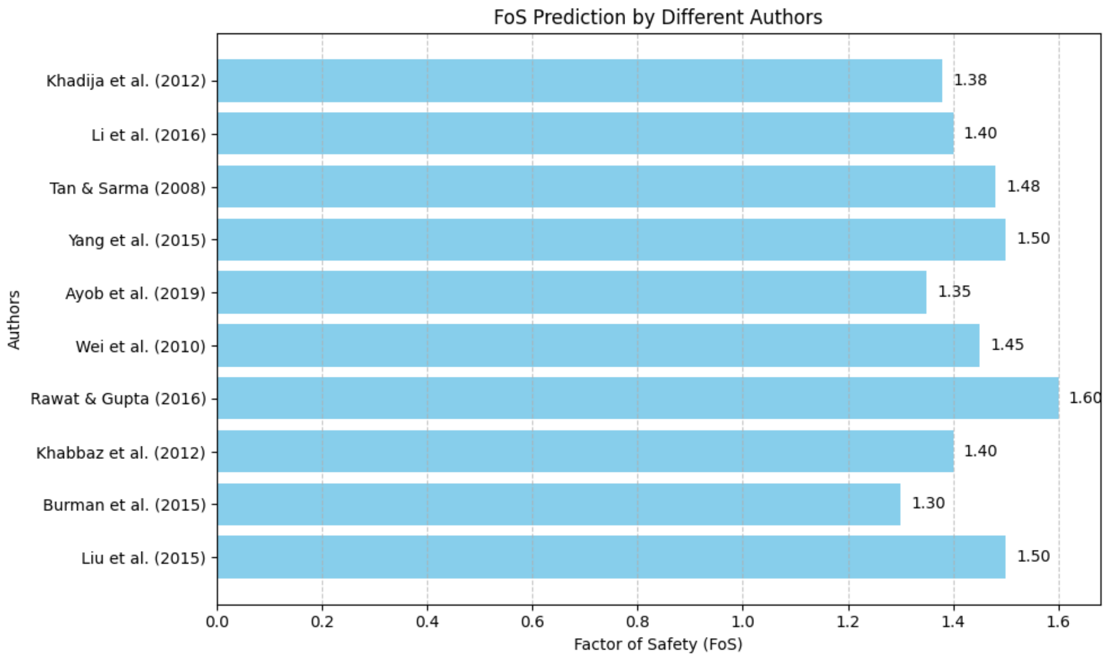
				groundwater	
Rawat & Gupta	2016	LEM, FEM	Nailed slope analysis	Nail length, nail inclination, c, φ	LEM yields higher FoS
Wei et al.	2010	Shear Strength Reduction	FEM	Shear strength, slope geometry, γ	Enhanced failure prediction accuracy
Ayob et al.	2019	Case Study	SLOPE/W, PLAXIS	Soil properties, slope geometry, groundwater	FEM is more accurate for landslide-prone slopes
Yang et al.	2015	Integrated LEM & FEM	Critical Slip Surface	c, φ, slope geometry	Improved efficiency in calculations
Tan & Sarma	2008	FEM Validation	Homogeneous, Non-homogeneous	c, φ, slope geometry	Good agreement with new procedure
Li et al.	2016	Probabilistic Analysis	LEM, FEM	c, φ, slope geometry, material variability	FEM better for complex geometries
Khadija et al.	2012	LEM, FEM	Complex Slope Analysis	Soil stratification, c, φ, slope geometry	FEM better manages complex geometries

Figure 7: illustrates the findings presented by the authors for FOS prediction



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- **Application of FEA to Slope Stability Analysis**

FEA has been found to be a potent tool toward enhancing the analysis related to slope stability and to help manage the risks associated with geotechnical projects. Kardani et al. in their work presented a hybrid stacking ensemble method combining an artificial bee colony optimization algorithm with several machine learning models together with FEA to create a synthetic database. Results showed improved prediction accuracy higher than individual machine learning models and traditional ensemble methods.Qi and Tang (2018) performed a comparative study of hybrid integrated techniques in artificial intelligence. In this, machine learning has been combined with firefly algorithm optimization for the hyperparameter. It identified cohesion as the key variable responsible for slope stability. Hybrid models used metaheuristic optimizations along with machine learning models, bringing accuracy into prediction stability. Wang et al. (2020) added a method of reliability analysis, based on XGBoost, considering the spatial variability of soil properties. Their approach emphasized the effect of soil heterogeneity on stability of slopes and greatly improved the failure probability prediction by employing auto-correlation functions. The latest advancement by Nie et al. (2019) was about designing a convergent SRM technique, and they put special focus on stable slope analysis with constant boundary elements. This approach, therefore, is likely to exhibit higher convergence rates than the limit equilibrium techniques and would also be able to accurately predict stability. Bao et al. (2022) used the extended finite element method (XFEM) to investigate the impact of crown cracks on soil slopes. They showed that crown cracks are metastability indicators and successfully modeled slip surface formation and tensile behavior in cohesive soil slopes. Wang et al. (2019) used the Eulerian-based finite element modeling technique to investigate the large deformation of earthquake-induced landslides. This approach solved some of the problems in the traditional Lagrangean models, including the dynamic behavior and failure surfaces that occurred during earthquakes; therefore, it represented one of the helpful tools for the analysis of slope stability under seismic conditions. Kumar et al. (2024) connected the topic of rock slope stability analysis to sustainable development goals (SDGs). The work was framed around the need for holistic assessment frameworks that integrate climate action, water resource management, and ecological considerations to advance a sustainability approach in geotechnical engineering. Gurruchaga and Viscarra (2020) applied FEA for slope stability in La Paz, Bolivia, and suggested various stabilization practices, which stretched from simple remediation measures to complex stabilization works. Their study showed that numerical techniques are more conservative than the limit equilibrium methods.

Literature Key Findings

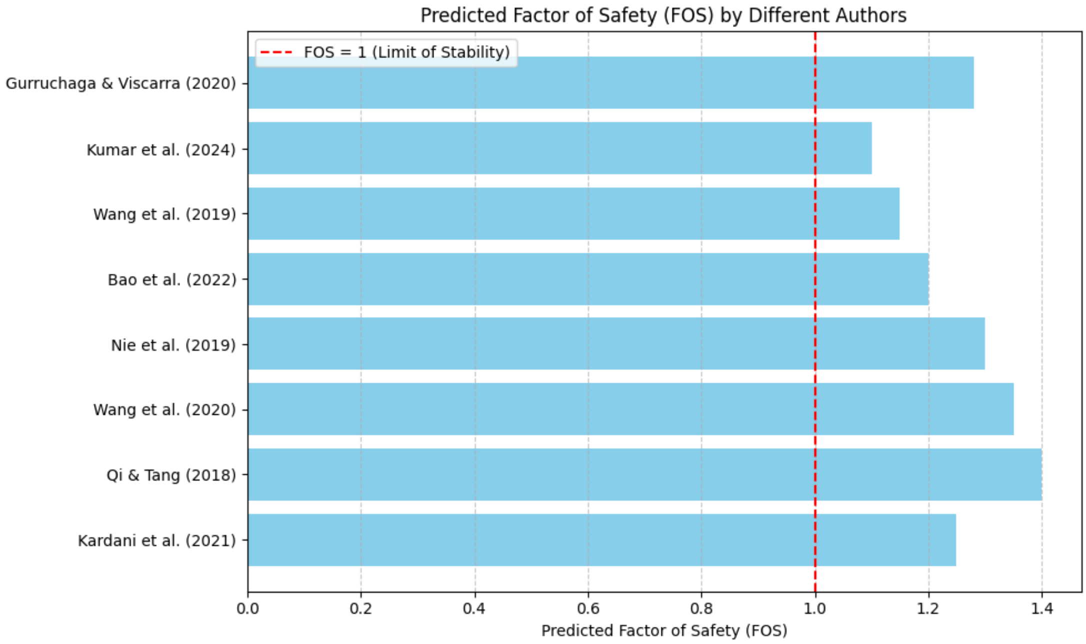
The key findings of the studied literature emphasize the capabilities of the effective integration of advanced modeling techniques with FEA to yield improved stability prediction in slopes and significant insight into related risks in geotechnical engineering.

Table 5: Literature Review on FEA Applications for Slope Stability

Author	Year	Method to Obtain FOS	FEA Method/Technique Used	Input Variables	Predicted FOS
Kardani et al.	2021	Hybrid Stacking Ensemble A	Artificial Bee Colony and Machine Learning Models	Synthetic Data	Improved Accuracy
Qi & Tang	2018	Integrated AI Approach	Firefly Algorithm and Machine Learning	Cohesion, Slope Geometry	(0.967)
Wang et al.	2020	Reliability Analysis	XGBoost-based FEA	Spatial Variability of Soil	Reliable Failure Probability
Nie et al.	2019	Strength Reduction	Convergent SRM	Boundary Elements	Enhanced Convergence

Bao et al.	2022	Crown Crack Analysis	XFEM	Tensile Behavior, Slip Surface	Indicators of Metastability
Wang et al.	2019	Seismic Analysis	Eulerian FEM	Earthquake Loading	Accurate Dynamic Behavior
Kumar et al.	2024	Sustainability Review	Sustainability Review Holistic Models	Climate, Water Resources	Need for Holistic Approaches
Gurruchaga & Viscarra	2020	Stabilization Techniques	FEA	Slope Geometry	Conservative Estimates

Figure 8: illustrates the findings presented by the authors for FOS prediction.



4. Discussion

This review goes on to detail how FEA has been used in slope stability analysis. It discusses a few methods that are used in estimating the Factor of Safety (FOS), a common geotechnical design parameter. These include: LEM, FEA, and newer computational approaches, such as digital twins, and machine learning-enhanced FEA. Most of these models consider factors including soil density, cohesion, angle of friction, height of slope, angle of slope, and groundwater conditions, among others. The performance measures considered here are accuracy in prediction, efficiency in computations, and the capability to deal with complexities in slope behaviours. The interesting and promising direction is that advanced FEA integrated with machine learning (ML) and digital twins may further enhance the quality of prediction in slope stability. For example, the application of GPUaccelerated FEA and stochastic analysis by Wei et al. (2024) and Jia et al. (2024) demonstrated better accuracy and faster computation, especially for complex or dynamic slopes. Emerging trends such as ML-based FEA and digital twin technology introduce great improvements in terms of prediction accuracy and real-time monitoring. Digital twins, therefore, bring proactive tools in the form of prediction of probable slope failures integrating real-time sensor inputs with computational models that enhance safety and reliability in engineering projects. Other methods, for example surface layer by Kadlíček and Mašín (2023) or Chen et al. approach in 2019 with the aid of coupled Eulerian-Lagrangian method will help specifically overcome the problem of quality meshes or simple surfaces complexity, hence improving the stability prediction.

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5. Conclusion

There is ample evidence that reveals FEA as a more powerful tool in improving analysis and understanding especially when set in comparison to the traditional slope stability assessment methods, such as the Limit Equilibrium Method. Advanced computational techniques, ranging from digital twins and enhanced FEA through machine learning, have led to better predictions and increased efficiency over complex boundary conditions and real-time monitoring. These methods enable more reliable and practical solutions of geotechnical engineering complexities, especially for dynamic loading, such as in seismic events.Integration of FEA with machine learning models and introduction of digital twin technology might lead to a great way forward in the very near future. They can facilitate real-time proactive monitoring with respect to timely interventions to prevent any failures. Again, they significantly reduce computational times for more accurate models in support of safer and more sustainable infrastructure development.

6. Future Scope

Future research scope would focus on integrating machine learning models with FEA further towards improving the effectiveness of predictions and reducing the computing burden. Real-time data through digital twin systems would most probably play a significant role in improving proactive safety measures and real-time decision-making for slope stability. Handling the challenges of high computational costs, improved accuracy in model calibration and better mesh quality will only make FEA accessible and practical to apply in large-scale geotechnical projects. Research on better algorithms, advanced constitutive models, and combinations of ML with traditional techniques for FEA will continue pushing boundaries for slope stability analysis so that further enhanced resilient, sustainable, and increasingly competent infrastructure solutions are achieved.

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