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SLOPE STABILITY ANALYSIS USING LIMIT EQUILIBRIUM AND FINITE ELEMENT METHODS: A CASE STUDY OF THE KHERRATA LANDSLIDE, ALGERIA

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ABSTRACT

Landslides are one of the biggest natural dangers around the world. They can cause serious damage to properties and infrastructure and even threaten people's lives. Therefore, researchers and engineers throughout the world have come up with many methodologies to evaluate slopes stability and to find ways to reduce these dangerous risks. Using both analytical and numerical methods, this study provides an analysis of landslide stability in Kherrata, located in the Wilaya of Bejaia, northeastern Algeria. Specifically, in this two-dimensional analysis, the Limit Equilibrium (LEM) methods were compared with the Finite Element Method (FEM) calculations performed in the PLAXIS 2D V8.2 software to evaluate the safety Factor (FoS). The results clearly show that the Factor of Safety values are significantly less than unity (FoS < 1.0), both the LEM and FEM analyses yield similar findings, confirming that the slope is in an unstable state.

KEYWORDS

Factor of Safety; Finite elements analysis; Limit equilibrium methods; Kherrata landslides stability.

1. INTRODUCTION

Landslides are gravity-driven mass movements that affect natural slopes and constructed embankments. They damage infrastructure and engineering works, create economic losses, and, in severe cases, human casualties (Haque et al., 2016; Kanungo et al., 2006; Pan et al., 2008; Petly, 2012; Shano et al., 2020; Shano et al., 2024; Wubalem and Maten, 2020; Zhang et al., 2015). Most slope failures occur due to natural triggers such that heavy rainfall, volcanic eruptions, river erosion, changes in topography, earthquakes, and similar environmental factors (Froud and Petly, 2018; Highland and Bobrowsky, 2008; Keefer, 2002; Kirschbaum et al., 2015). Human activities also cause slope failures - either suddenly or gradually - through construction excavations, deforestation, and other changes to land use that directly or indirectly influence landslide susceptibility (Ayalew et al., 2009; Erginal et al., 2008; Huang and Chan, 2004).

Studying landslides and reducing their risks requires knowledge from several fields: applied geology, geotechnical engineering, and soil mechanics. Mass movements vary widely both nature and scale. They include landslides, rockslides, debris flows, underground collapses, ground subsidence, and soil volume changes from swelling or shrinkage processes. Where these occur depends on topography, geomorphology, geology (lithology and structural discontinuities of bedrock formations), and groundwater conditions. Classification systems for mass movements are based on what material is moving, the shape of the failure surface, rupture depth, deformation characteristics, and moisture content of the displaced materials (Li and Mo, 2019).

Numerous computational methods for analyzing slope stability in two-dimensional (2D) and three-dimensional (3D) frameworks have been developed by researchers. Limit Equilibrium Methods (LEM) have been the standard approach for a several decades. Based on the rigid-plastic Mohr-Coulomb failure criterion, several LEM approaches have been developed and widely applied (Hammouri et al., 2008; Xiao and Chen, 2021).

The most popular techniques for determining the Factor of Safety (FoS) are the Fellenius method Bishop's simplified methods, which split the slope into vertical slices (Bishop, 1955; Fellenius, 1927). The results obtained from LEM analyses vary depending on the equilibrium conditions taken into consideration due to the assumptions posited regarding the distribution of internal forces.

In various fields, commercial software packages for numerical modeling are now widely adopted to solve complex engineering problems (Khadim and AL-Jassani, 2021; Zainy et al., 2025). Numerical analysis offers both a powerful tool and an efficient methodology for assessing slope stability, which in turn supports more comprehensive landslide investigations and enables the development of effective hazard moderation strategies.

Recent advances in Finite Element Method (FEM) analysis, particularly through strength reduction techniques, have provided effective means for evaluating slope stability (Cheng et al., 2007; Fawaz et al., 2014; Griffiths and Lane, 1999; Hammouri et al., 2008; Huang and Jia, 2009; Song et al., 2012). Extensive experience gained from both analytical and numerical methods has consistently demonstrated their reliability and accuracy in solving slope stability problems.

A comparative analysis of Factor of Safety (FoS) values obtained through analytical and numerical methods is presented for a landslide case study located near Kherrata city in northeastern Algeria, within the Wilaya of Bejaia. This mountainous area is characterised by a dense population, significant seismic activity, and steep slopes along major roads, yet previous landslide research in the region remains limited. The methodology employs two-dimensional limit equilibrium and finite element analyses to compare FoS results. Firstly, the Bishop simplified method and the Fellenius analytical method are compared for the reference case. Subsequently, analytical solutions are compared with numerical calculations obtained from PLAXIS 2D v8.2 software (Brinkgreve, 2008).

2. PRESENTATION OF THE CASE STUDY

Kherrata is a town located in the Wilaya of Bejaia, within the lower Kabylie region of northeastern Algeria. The local geology consists of a limestone stratigraphic sequence overlying clay deposits, a configuration that promotes both seismic instability and active landslide processes, as observed in the Tamaleht area. This study focuses on a landslide that damaged a section of the provincial road CW16 in the Ichhen locality of Ait Idriss, as shown in Figs. 1-2 (Sellami and Belamri, 2014).

Geologicaly, the Ait Idriss region is primarily distinguished by black schistose marl formations containing calcite veins, which are overlain by conchoidal marls interbedded with yellow limestone lenses. These formations date to the Senonian age. In addition, the region contains limestone breccias and colluvial deposits composed mainly of heavily cemented detritus originating from Liassic and Jurassic formations.

The geotechnical properties used in this analysis are derived from previous site investigations, with soil characteristics shown in Table 1.

3. LIMIT EQUILIBRIUM CALCULATION

Over many years, researchers have developed and established numerous limit equilibrium methods to analyze circular failure surfaces and determine the Factor of Safety (FoS)

(Hammouri et al., 2008). The Fellenius method of slices was one of the pioneer techniques used for stability analysis. This method divides the potentially unstable mass into series of vertical slices.

Fig. 1. Site photographs illustrating the geomorphological characteristics of the study area (Sellami and Belamri, 2014)

Fig. 2. Geographic location of the study area (google maps imagery) (Sellami and Belamri, 2014)

Table 1. Geotechnical properties of soil layers (Sellami and Belamri, 2014)

Depth (m)	proprieties	Nature of soil layers
0.00 to 5.00	γ = 19 kN/m^3, C = 5 kPa φ = 35°	Silty sandy clays Low mechanical characteristics
5.00 to 9.00	γ = 19 kN/m^3, C = 14 kPa φ = 20°	Silty clays Low mechanical characteristics
9.00 to 20.00	γ = 21 kN/m^3, C = 24 kpa φ = 25°	Marnes Good mechanical characteristics

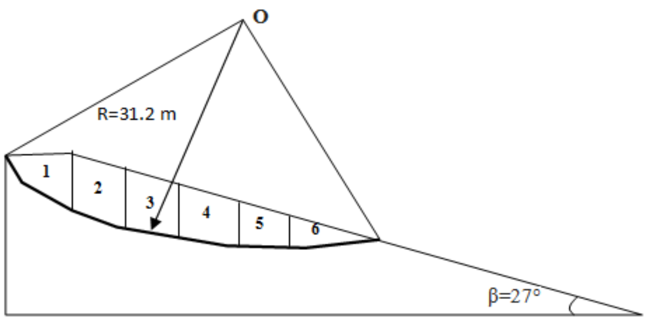

Fig. 3. The slope model divided into vertical slices, illustrating the circular failure surface used in limit equilibrium analysis

The calculation treats each slice as an independent rigid body at limit equilibrium along the failure surface.

Analytical slope stability calculations use an iterative trial-and-error approach to find the most critical failure surface by testing the slope's geometric, geotechnical, and hydraulic parameters. However, this approach limits the number of potential failure surfaces that can be examined.

In this study, three iterations were performed to determine the critical failure surface, resulting in the circular rupture surface depicted in Fig. 3. The circular failure surface that illustrated in Fig. 3 reveals the following geometric parameters: radius R = 31.2 m, center coordinates O (26.8, 720.83 m), and α = 36°. This failure surface closely approximates the observed natural landslide slip surface shown in Fig. 1. To achieve accurate calculations, engineering judgment was applied to define the slice configuration and discretization scheme presented in Fig. 3. According to the Fellenius approach, the Factor of Safety of about 0.78, confirming slope is unstable (FoS < 1.0).

Subsequently, the Factor of Safety was recalculated using Bishop's simplified method, while maintaining the identical geometric model and slice configuration previously employed in the Fellenius analysis which produced a Factor of Safety of 0.82 indicating that the Fellenius approach yields a more conservative (lower) safety factor for this particular slope configuration.

4. FINITE ELEMENT METHOD ANALYSIS

In this section, a numerical study was conducted to calculate the factor of safety using the Finite Element Method implemented in PLAXIS software. This software package is widely used for slope stability analysis and for solving other geotechnical problems. The main objective was to compare the numerical results with the analytical ones.

The landslide case study presented herein is relatively straightforward, and the well-established Mohr-Coulomb constitutive model was chosen for this analysis. PLAXIS 2D version 8.2 was employed, which provided satisfactory results (Alasadi and Mustafa, 2022; Alsamia and Koch, 2023; Djabri and Benmebarek, 2020; Khalid and Alshameri, 2021; Ngoc et al., 2020; Yang et al., 2019).

4.1. Reference model in PLAXIS 2D

The numerical analysis was performed on the reference model shown in Fig. 4. This model was previously calculated using analytical methods. The Mohr-Coulomb model was used for soil behavior, with input parameters identical to those in the analytical calculation, as summarized in Table 1.

4.2. Mesh and hydraulic conditions

The PLAXIS software enables visualization of the model geometry discretized into a regular 6-node triangular finite element mesh Fig. 5. The selection of a regular mesh was justified by the simplicity of the model studied and the absence of soil-structure interaction elements.

Initially, the generate option must be accessed to define the water level (hydraulic conditions). In the present study, the soil was assumed to be drained, and the piezometric level was located below the failure surface Fig. 6.

This study compares the LEM and FEM approaches to assess the slope instability. Under these conditions, long-term drained calculations were used following the landslide occurrence. In-situ investigations revealed that the major factor contributing to instability was earthquakes of low intensity during dry periods. After generating the initial conditions, the effective stresses in the model can be visualized Fig. 7.

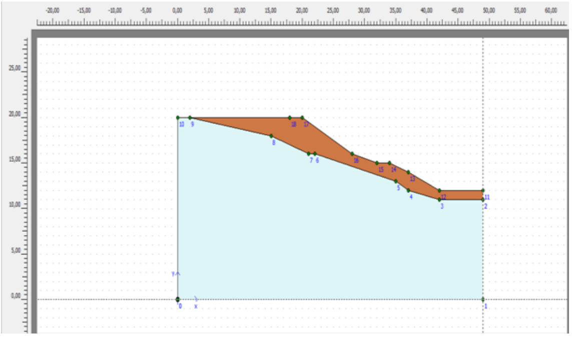

Fig. 4. Reference model geometry in PLAXIS 2D

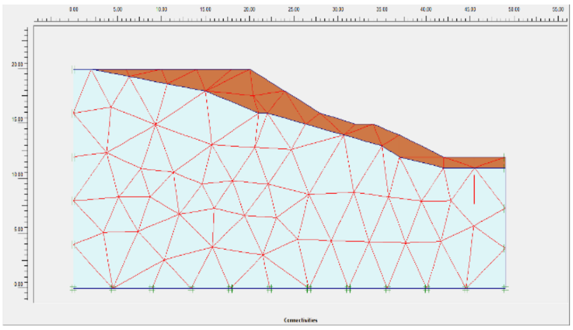

Fig. 5. Finite element mesh of the reference model

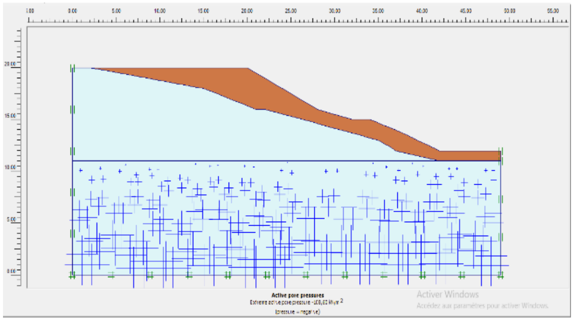

Fig. 6. Force distribution and piezometric level in the reference model

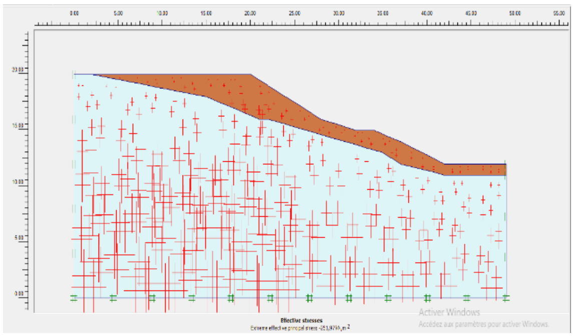

Fig. 7. Effective stress distribution

4.3. Numerical calculation phases

The PLAXIS software enables the performance of analyses using several available methods. The "Phi/C reduction" approach is employed for safety factor calculations where the soil shear parameters, namely cohesion and friction angle, are predominant. Using this approach adopted in this study, slope safety analysis is performed by successively reducing the strength parameters of the soil until slope collapse occurs (Hammouri et al., 2008).

During the calculation processes, the total multiplier is defined as the ratio of the strength parameters entered as input values to the reduced ones. The total multiplier is initially set to 1 to establish all material strengths at their unreduced values. In the Phi/C reduction approach, the strength parameters are successively reduced until the collapse of the slope occurs. The strength parameters of the soil are automatically reduced step by step with an increment set by default to 0.1 and the factor of safety (FoS) is given by the ratio of the available strength over the strength until failure (Brinkgreve, 2008; Fawaz et al., 2014).

Two calculation phases are performed in sequence: slope construction of the; followed by calculating the factor of safety.

4.4. Numerical results and discussion

Two criteria were selected to evaluate slope stability: soil displacement and factor of safety. The total displacement is shown in Fig. 8, where the maximum value reached is 17.4 cm.

The total displacement contours in Fig. 8 show progressive deformation of the slope model, with a characteristic failure pattern that confirms the computational predictions obtained from both analytical methods.

The displacement field shows a distinctive spatial distribution. Maximum deformations appear in the upper slope (red/orange contours), transitioning through intermediate displacement zones (yellow/green) to minimal deformation at the toe (blue contours). This progressive pattern strongly suggests a deep-seated rotational failure mechanism. The contour gradients effectively outline the slip surface geometry and identify stress concentration zones where failure most likely to initiate.

This displacement visualization demonstrates that advanced numerical modeling captures nonlinear soil behavior, progressive failure mechanisms, and stress redistribution better than traditional limit equilibrium methods. The analysis provides engineers the quantitative data for slope monitoring, remedial measures design, and makes informed decisions regarding slope stability management in critical infrastructure.

The Factor of Safety (FoS) is determined by the ratio of the available strength to the strength at failure. It is equal to the value of total multiplier ΣM_{sf} defined by Eq.1:

$$\Sigma Msf = \frac{tg\varphi_{input}}{tg\varphi_{reduced}} = \frac{C_{input}}{C_{reduced}} \tag{1}$$

Fig. 9 presents the calculation procedure performed by PLAXIS, with a factor of safety equals 0.72. The FoS obtained from numerical analysis is more conservative (lower) than the LEM results. This difference occurs because FEM captures more complex failure modes and stress concentrations that LEM simplifies. In addition, LEM methods assume a predetermined failure surface, which introduces uncertainty to the calculations.

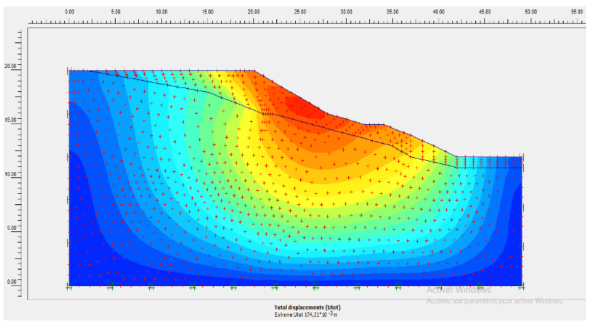

Fig. 8. Total displacement contours of the slope model

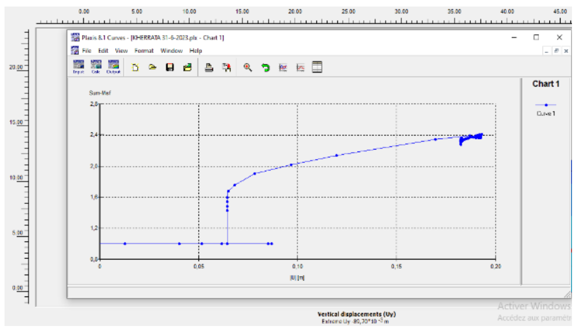

Fig. 9. Load-displacement curve and factor of safety calculation

5. COMPARATIVE DISCUSSION

5.1. Failure surface

Fig. 10 shows a comparison of the FEM-predicted failure surface's geometry and location with the circular arc assumed in the LEM approaches. It was found that both analyses yielded failure surfaces that were identical.

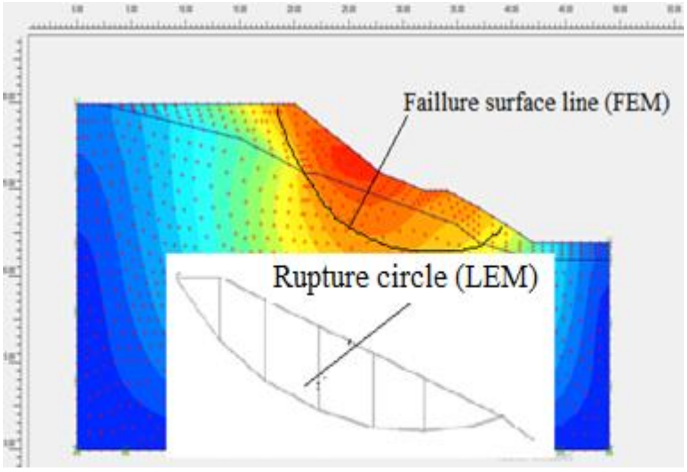

Fig. 10. Comparison of failure surfaces between LEM and FEM analyses

The displacement contour analysis confirms these predictions through a clear view of the deformation field. It shows progressive failure development with highest displacements concentrated in the upper slope and characteristic bulging patterns indicating deep-seated rotational failure.

More significantly, comparing the failure surface geometry of the two methods reveals fundamental differences in failure mechanism prediction. The classical circular rupture surface assumption contrasts with the complex, noncircular geometry from advanced FEM constitutive modeling, which more accurately reflects stress-strain behavior and progressive failure development.

This convergent evidence from several computational approaches—factor of safety, displacement field, and failure surface geometry-strongly validates our slope instability assessment. Additionally, It shows that finite element methods have superior predictive capability. FEM excels at capturing nonlinear soil behavior, stress redistribution, and progressive failure mechanisms, which is essential for informed engineering decisions in critical infrastructure where stability evaluation directly affects safety.

5.2. Factor of safety

Based on the comparative analysis presented in Fig. 11, the evaluation of factors of safety through different methods reveals critical insights for geotechnical engineering applications. The comparison between the Bishop method (FoS = 0.85), Fellenius method (FoS = 0.78), and finite element method (FoS = 0.71) shows significant variation between methods, though all indicate unstable conditions below the conventional safety threshold of 1.0.

The progressively lower values from limit equilibrium methods to finite element analysis suggest that FEM provides a more realistic representation of soil behavior through improved constitutive modeling and stress-strain relationships.

The instability assessment is consistent across all methods, which strengthens confidence in our slope stability evaluation. It also highlights the value of using multiple computational approaches for critical geotechnical assessments. The observed variations underscore the necessity for conservative design approaches and risk management strategies when dealing with marginal stability conditions, particularly in projects where failure consequences could be severe.

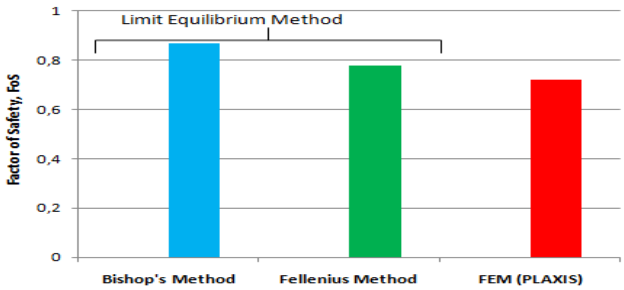

Fig. 11. Comparison of factors of safety between LE and FE Methods

6. CONCLUSION

Analyzing slope stability is a challenging due to many factors, especially uncertainty in geotechnical parameters. The failure mechanism is complex and is inadequately described by conventional slope stability calculation methods that employ simplified approaches.

Limit Equilibrium Methods (LEM) are the most widely used approaches in soil mechanics. However, they require identifying the surface failure beforehand and then dividing the soil into slices.

In contrast, the Finite Element Method (FEM) determines the most probable failure surface by analyzing stress and strain states, nevertheless it requires detailed knowledge of material characteristics and resistance parameters.

Within this context, this investigation assessed the stability of a slope by analyzing the Kherrata embankment at "Ichhen" located near the CW 16 road (Wilaya of Bejaia, northeast Algeria). Specifically, this stability was evaluated by calculating the factor of safety using both analytical and numerical approaches.

The main findings are summarized as follows:

1-The results obtained by the Fellenius and Bishop's Limit Equilibrium Methods, despite using fundamentally different principles, give reasonably comparable results.

2-The slope stability analysis using LEM showed that the Fellenius approach underestimates the factor of safety by 5% compared to Bishop's method.

3-The displacement magnitudes and failure mechanism provide quantitative validation, with the extensive deformation field particularly supporting the finite element prediction of the lowest factor of safety.

4-The factors of safety and failure surfaces determined by analytical calculation and FEM analysis are in good agreement. The difference in the FoS between both analyses is approximately 20%.

5-Both methods can be used depending on available conditions (data availability, time constraints, required precision, etc.).

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and interpretations. Data collection and numerical analysis were performed by M.D. The first draft of the manuscript was written by M.D., R.B and A.G. All authors commented, supervised, read and approved the final manuscript.

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COMPETING INTERESTS

The authors have no relevant financial or nonfinancial interests to disclose.

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