ISERDAR International Science and Engineering Reviews: Development, Analysis and Research

Research Article

Evaluating Open-Pit Slope Stability Through Successive Modeling Stages

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ARTICLE INFO

Article history:

Received 27/11/2025
Received in revised form 17/12/2025
Accepted 27/04/2026
Available online 30/04/2026

Keywords:

Open-pit mining,
Slope stability,
Limit equilibrium method,
Factor of safety

Doi: 10.5281/zenodo.19929051

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ABSTRACT

Slope stability in open-pit mining is a critical factor influencing operational safety, production continuity, and overall economic performance. Conventional assessments typically employ two-dimensional limit equilibrium methods, which do not adequately represent the inherently three-dimensional nature of slope behavior. Even three-dimensional analyses may remain insufficient when geological conditions are oversimplified or model inputs are limited. In this study, open-pit slope stability was assessed using the three-dimensional limit equilibrium approach implemented in PLAXIS 3D LE. A simplified geological model was first created based on commonly accepted rock mass parameters from the literature, excluding groundwater, structural features, and dynamic loads. The analysis was then refined through a stepwise modeling strategy that sequentially incorporated site-specific geological units, rock mass properties derived from field and laboratory studies, identified fault zones, groundwater conditions, and pseudo-static seismic loading. Safety factors were calculated and compared using Bishop, Janbu, Generalized Limit Equilibrium, and Spencer methods. The results demonstrate a consistent reduction in safety factors as more realistic geological, hydrogeological, and structural conditions are integrated into the model. These findings emphasize the limitations of simplified analysis approaches commonly used in industry and highlight the importance of comprehensive geotechnical characterization for achieving reliable and realistic slope stability evaluations.

1. Introduction

Slope stability in open-pit mining is a critical parameter that directly influences personnel safety, equipment integrity, and operational efficiency. The continuity of production is closely linked to preventing sudden mass movements that may occur within the pit. Therefore, slope stability assessments are not only a component of engineering design but also a fundamental element of mine planning and risk management. Instability events can result in substantial production losses, environmental impacts, and, in severe cases, loss of life.

The reliability of engineering approaches adopted during slope design is thus of major importance. However, many commonly used analysis techniques still rely on idealized and two-dimensional geometries. Such simplifications create significant limitations, particularly in open pits characterized by complex geological settings and irregular slope geometries. Because the governing mechanisms of slope behavior in real field conditions are inherently three-dimensional, stability assessments must also consider this dimensionality. The engineering design process should therefore extend beyond geometric parameters such as slope angle, bench height, or bench configuration, and incorporate groundwater conditions, the orientation and characteristics of discontinuities, rock mass mechanical properties, and structural weakness zones. Without integrating these factors, computed safety factor values cannot adequately represent actual field stability conditions.

Previous studies in quarries and tunneling projects emphasize the importance of reliable rock mass characterization for accurate design. Geotechnical assessments in limestone quarries have been performed using point load index, Schmidt hammer measurements, and GSI values [1], while UCS estimation from Schmidt hammer results has also been applied in clay quarry conditions [2]. In addition, various rock mass classification systems have been successfully used in tunnel projects [3]. These studies collectively highlight the necessity of incorporating rock mechanics parameters when evaluating slope stability.

Recent research has underlined the need to advance beyond traditional two-dimensional approaches to obtain more realistic stability evaluations. Three-dimensional modeling has been shown to provide more realistic safety factor estimates compared to two-dimensional analyses [4]. Furthermore, probabilistic slope stability approaches combined with three-dimensional modeling have been used to investigate open-pit–underground excavation interactions, identifying the Geological Strength Index as a critical parameter influencing stability outcomes [5].

In light of these considerations, the present study addresses common limitations encountered in slope stability modeling for open pits and proposes a stepwise analysis framework aimed at achieving more reliable results. Using PLAXIS 3D LE, which enables three-dimensional limit equilibrium analysis, slope stability was evaluated under five progressively refined scenarios. These scenarios range from simplified geological assumptions to advanced representations that integrate field-derived geotechnical data and external loading conditions. This study distinguishes itself by the cumulative integration of geological, hydrogeological, structural, and seismic factors into a single three-dimensional model using site-specific field data.

2. Study area and general geology

The study area is located in the Marmara Region of northwestern Türkiye and is geologically associated with the Alpine Orogenic Belt. Previous investigations have shown that the Biga Peninsula lies within the Pontide tectonic domain, characterized by a complex geological evolution. The peninsula is composed predominantly of high-grade metamorphic rocks exposed around the Kaz Mountains and adjacent areas. From bottom to top, the metamorphic sequence includes amphibole-bearing gneisses interlayered with marble bands, meta-ophiolitic units, and quartz-feldspathic gneisses.

During the Tertiary period, from the Paleocene–Eocene to the end of the Miocene, the region underwent extensive magmatic activity. Numerous granodioritic plutons intruded the basement rocks, while volcanic units of andesitic, dacitic, rhyodacitic, and rhyolitic composition either cut through or unconformably overlapped the preexisting lithologies. This magmatic activity was commonly accompanied by synchronous sedimentation, resulting in widespread volcanic–sedimentary successions across the Biga Peninsula [6].

The lithological units observed in and around the investigation site belong to the Bilaller Member of the Şahinli Formation. This member consists of tuff, volcanic clastics, volcanic and sedimentary breccias, mica schists, and basaltic dikes. Drilling studies conducted within the operational area revealed that the upper portions of the sequence are dominated by tuff, while volcanic clastic units occur at greater depths. These clastic units comprise locally turbiditic deposits, as well as andesitic to basaltic lava flows affected by tectonic deformation. The formation is crosscut by numerous basaltic dikes of varying thickness.

The Bilaller Member specifically includes volcanic clastics of the Şahinli Formation, locally interbedded turbidites, and basaltic to basaltic-andesitic lava flows that are often difficult to distinguish from one another in the field. Overall, Miocene-aged volcanic and sedimentary units are widely distributed throughout the study area and its surroundings.

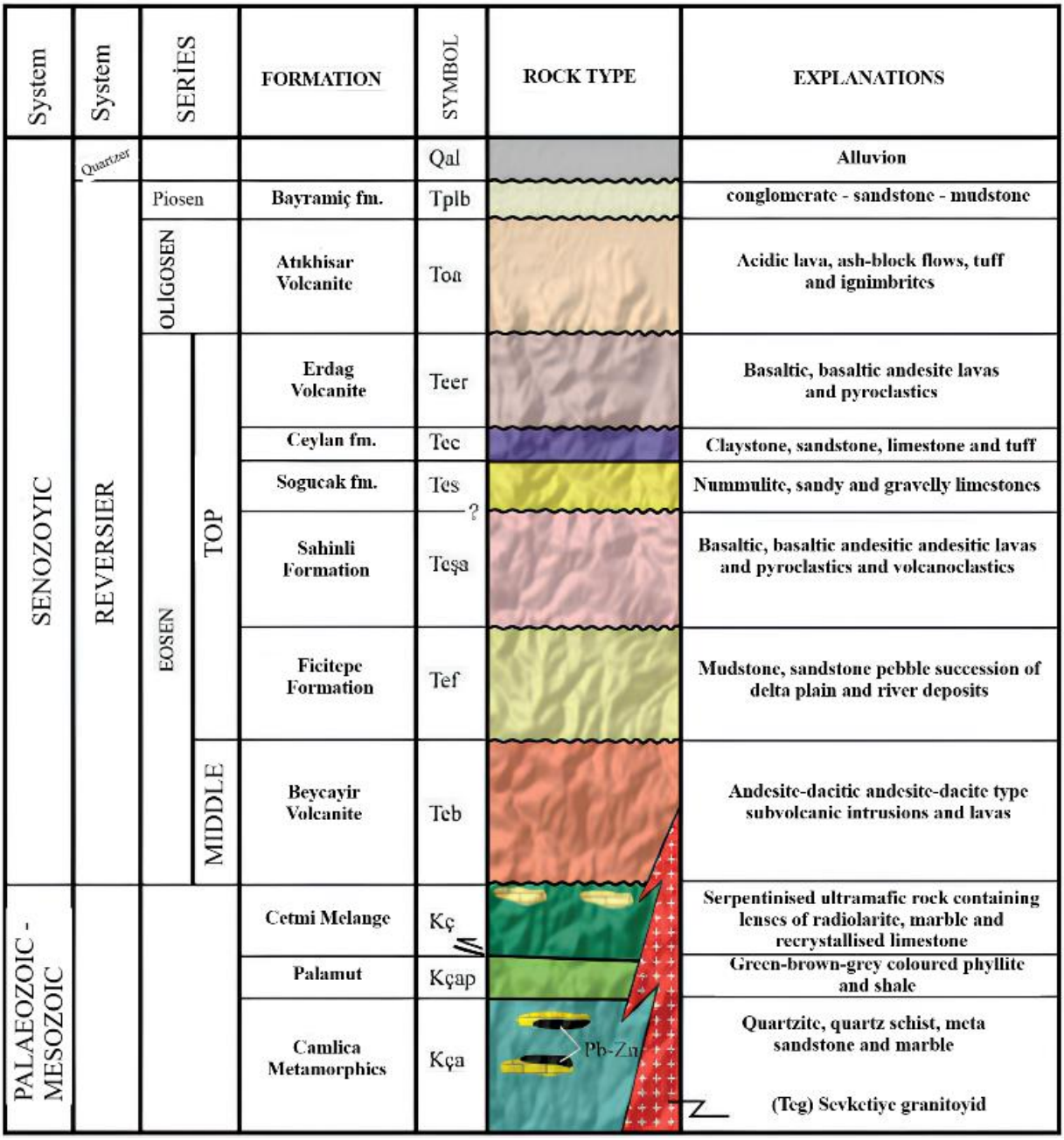

Figure 1. Generalized stratigraphic column of the study area and its surroundings.

3. Material and method

In this study, the three-dimensional stability of an open-pit slope was evaluated using the PLAXIS 3D LE software package [7]. PLAXIS 3D LE performs limit equilibrium analyses by identifying potential failure surfaces within a three-dimensional geometry and computing corresponding safety factors. Six different limit equilibrium formulations were applied: Bishop, Janbu, Spencer, Morgenstern–Price, Generalized Limit Equilibrium (GLE), and the Ordinary Method of Slices (OMS) [8–13].

The numerical model was developed based on the final pit design of the study area, representing bench geometry, slope angles, and pit boundaries in full three-dimensional detail. Geological units were assigned according to lithological logs and geotechnical drilling data, and each formation was attributed its own strength and deformation parameters. Structural discontinuities identified through

geological mapping and previous site investigations were modeled as weak zones to assess their influence on slope stability.

Slope stability analyses were conducted along ten critical cross-sections selected according to geological complexity, geotechnical characteristics, and the spatial orientation of the pit slopes. These cross-sections were selected based on objective criteria, including areas with the highest overall slope angles, sections intersecting multiple lithological units, and zones influenced by mapped fault structures. In addition, the sections were distributed across the entire pit to ensure that all regions of the excavation were represented in the analysis. The same stepwise analysis framework was applied to all sections. A three-dimensional slope-search algorithm was used to detect potential failure surfaces and to identify the most critical geometries. An overview of the ten modeled cross-sections is shown in Fig. 2.

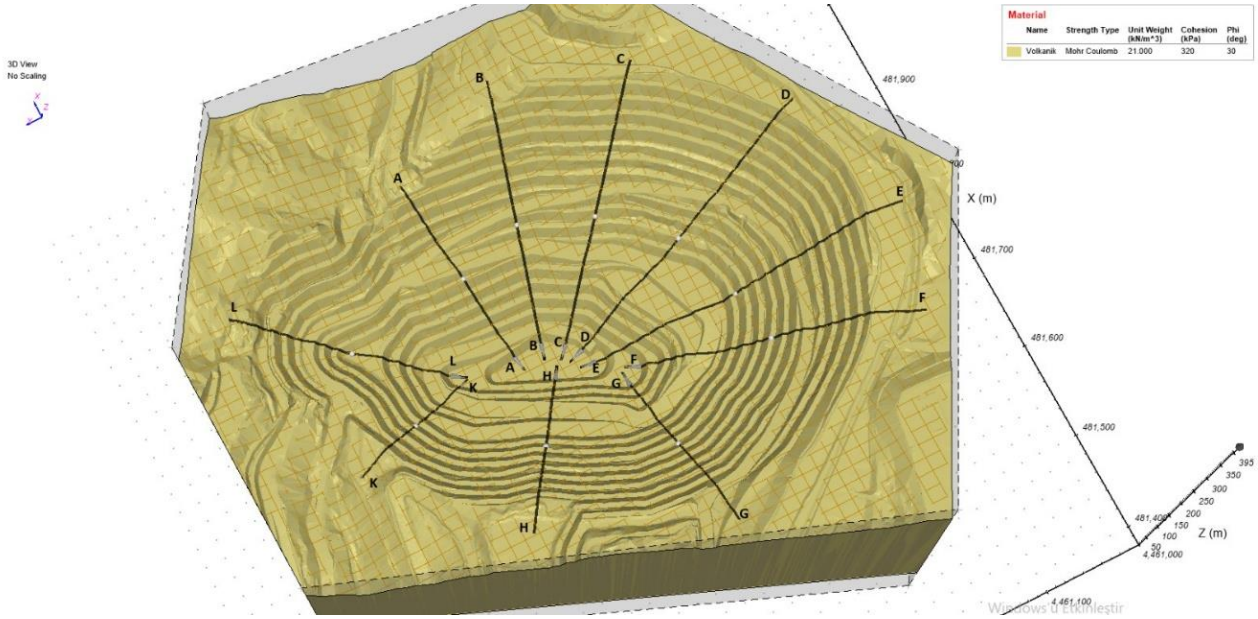

Figure 2. Locations of the ten critical cross-sections defined within the final open-pit model.

Limit equilibrium methods evaluate the stability of a slope by examining the balance of resisting and driving forces along a defined slip surface. The Factor of Safety (FS) is expressed as:

$$FS = \frac{\text{Available Shear Strength}}{\text{Driving Forces}}$$

In the simplified Bishop method, rotational moment equilibrium is ensured for each slice, while interslice shear forces are neglected. Vertical and horizontal force components are considered to compute the safety factor. The forces acting on slices in the Bishop method are illustrated in Fig. 3.

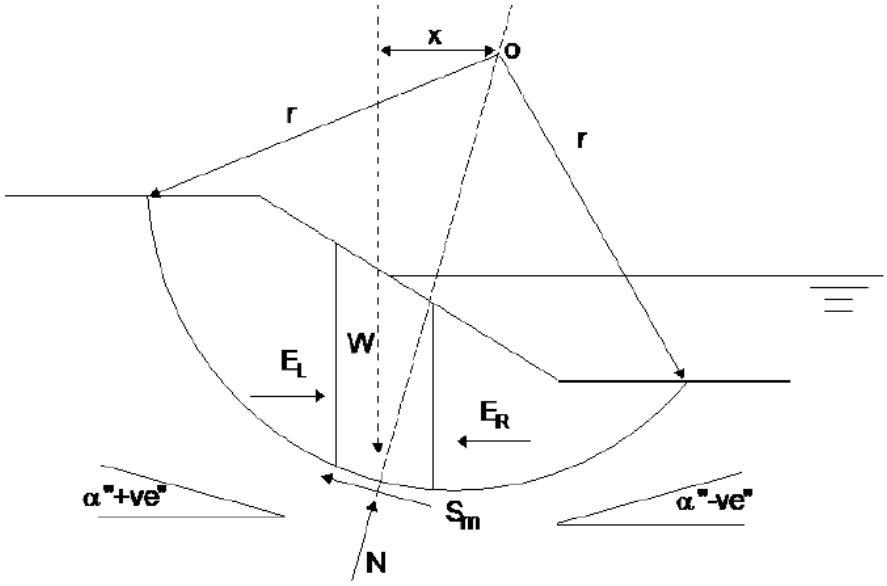

Figure 3. Forces considered in the simplified Bishop slice method (adapted from Bentley Systems, 2021).

In the simplified Bishop method, rotational moment equilibrium is ensured for each slice, while interslice shear forces are neglected. Vertical and horizontal force components are considered to compute the safety factor. The forces acting on slices in the Bishop method are illustrated in Fig. 3.

In general, limit equilibrium formulations divide the potential sliding mass into vertical slices and evaluate the following relationship:

$$FS = \frac{\sum(c' \cdot b + (\sigma_n - u)\tan\phi')}{\sum(W\sin\alpha)}$$

where:
c′ = effective cohesion
σ□ = normal stress
u = pore-water pressure
φ′ = effective friction angle
W = slice weight
α = base inclination of the slice

Using multiple limit equilibrium formulations enables evaluation of the sensitivity of FS to assumptions related to force distribution and interslice interaction. In this study, both model inputs and analysis methods were varied in a controlled manner to better represent actual field conditions. Accordingly, the modeling process was structured around five cumulative scenarios, each integrating an additional factor influencing slope behavior.

3.1. Successive modeling stages

A successive modeling approach was adopted to evaluate the influence of geotechnical, hydrogeological, and structural parameters on slope stability. Five cumulative stages were defined, each incorporating new data or loading conditions. All analyses were conducted across the ten critical sections, and safety factors were computed using all six limit equilibrium methods.

The stepwise modeling framework consisted of five cumulative stages designed to progressively integrate realistic geological, hydrogeological, and structural conditions into the slope stability analysis. The baseline stage involved developing a simplified and homogeneous model using rock mass parameters commonly cited in the literature, excluding groundwater, fault zones, and formation-specific characteristics; the resulting safety factors served as reference values for later comparisons. In the second stage, site-specific geotechnical properties were introduced by classifying units into

schist and volcanic formations based on drilling and field observations, and evaluating rock mass quality through the Geological Strength Index, which produced GSI values of 38 and 56, respectively; these were converted into Hoek–Brown parameters using RocLab and subsequently transformed into Mohr–Coulomb strength parameters for analysis. The third stage incorporated groundwater by defining a constant water table at an elevation of 175 m, modeling the unsaturated zone using the "Constant Above Maximum" approach and applying hydrostatic pore pressures below the water table. The groundwater table was assumed as a constant level due to limited hydrogeological data available for the site, which should be considered as a potential limitation of the study. In the fourth stage, structural complexity was added by integrating fault zones identified through geophysical surveys and geological logging; four discontinuity sets were recognized, two of which exhibited fault characteristics with orientations of 190/85 and 225/35, and were assigned low-strength parameters consistent with laboratory shear box tests before being modeled as three-dimensional discontinuity surfaces intersecting the pit slopes. The final stage introduced pseudo-static seismic loading using a horizontal seismic coefficient of kh = 0.15, while vertical seismic effects were neglected, enabling assessment of how geological, hydrogeological, structural, and dynamic factors interact to influence overall slope stability. The horizontal seismic coefficient was selected as a typical value commonly adopted in open-pit slope stability analyses in the literature. Vertical seismic effects were neglected, as they are generally considered to have a limited influence on slope stability compared to horizontal loading.

The engineering parameters assigned to the geological formations and fault zones were derived from field observations, laboratory testing, and GSI-based Hoek–Brown to Mohr–Coulomb conversions. The final parameters used in numerical modeling are summarized in Table 1.

Table 1. Final geotechnical parameters assigned to the units defined in the open-pit model

Unit	Unit weight (kN/m³)	Cohesion c (kPa)	Friction angle φ (°)
Volcanic	23.8	200	23
Schist	25.2	150	21
Fault_1	22.0	20	16
Fault_2	22.5	30	22

4. Results and interpretation of the stepwise stability analyses

The slope stability analyses conducted within the five-stage modeling framework clearly demonstrated the sensitivity of the Factor of Safety (FoS) to progressively refined geotechnical, hydrogeological, and structural inputs. In the baseline stage, where idealized and homogeneous parameters were assigned, the computed FoS values were relatively high, giving an artificially stable impression of the slope. As the model was gradually updated to reflect actual field conditions, notable reductions in FoS were observed. The most significant decrease occurred in Stage 2, in which site-specific geotechnical parameters were introduced; across the evaluated cross-sections, FoS values dropped by approximately 30–40%, highlighting the critical importance of using field- and laboratory-derived rock mass properties rather than generalized literature values.

In Stage 3, incorporation of groundwater conditions resulted in additional FoS reductions, particularly in sections where the phreatic surface intersected structurally or geometrically critical parts of the slope. In some cases, decreases of up to 10% were observed, emphasizing the destabilizing role of pore-water pressures. The influence of structural features became more pronounced in Stage 4, where faults identified in geophysical and geological investigations were modeled as low-strength weakness zones. In cross-sections such as B–B, C–C, and D–D, FoS values fell below 1.0, indicating potentially unstable conditions. The orientation and depth extent of these faults played a decisive role

in governing failure mechanisms, demonstrating that slope stability cannot be reliably assessed without explicit structural characterization.

The final stage evaluated slope performance under pseudo-static seismic loading. Application of a horizontal seismic coefficient of kh = 0.15 further reduced stability, with FoS values decreasing to approximately 0.75–0.85 in the more critical sections, particularly those already affected by geological weaknesses. These findings underscore the combined destabilizing effects of adverse geology, groundwater, and seismic forces on open-pit slope behavior.

Notable variability was also observed among the limit equilibrium methods. Bishop and Morgenstern–Price produced relatively similar FoS values, whereas Janbu and OMS yielded more conservative results, especially in groundwater- and seismic-influenced scenarios. Spencer and GLE provided more balanced and consistent outputs across all stages, reinforcing their suitability for complex geometries and multi-factor loading conditions. These differences highlight the importance of applying multiple methods in engineering design to capture method-dependent sensitivity.

Overall, sections such as L–L and G–G exhibited comparatively stable behavior across all modeling stages, maintaining higher FoS values. Conversely, sections B–B, C–C, and D–D repeatedly emerged as critical zones due to combined geological and loading effects. The results confirm that reliable slope design requires detailed geotechnical characterization, explicit inclusion of groundwater and structural features, and consideration of dynamic loading conditions. Representative outcomes for each modeling stage, based on Bishop analyses, are shown in Figures 4–8, while Figure 9 illustrates the distribution of FoS values across stages through boxplots that reveal changes in median values, variability, and outlier behavior. The pronounced increase in variability during Stages 4 and 5 indicates escalating model uncertainty under structural control and seismic loading.

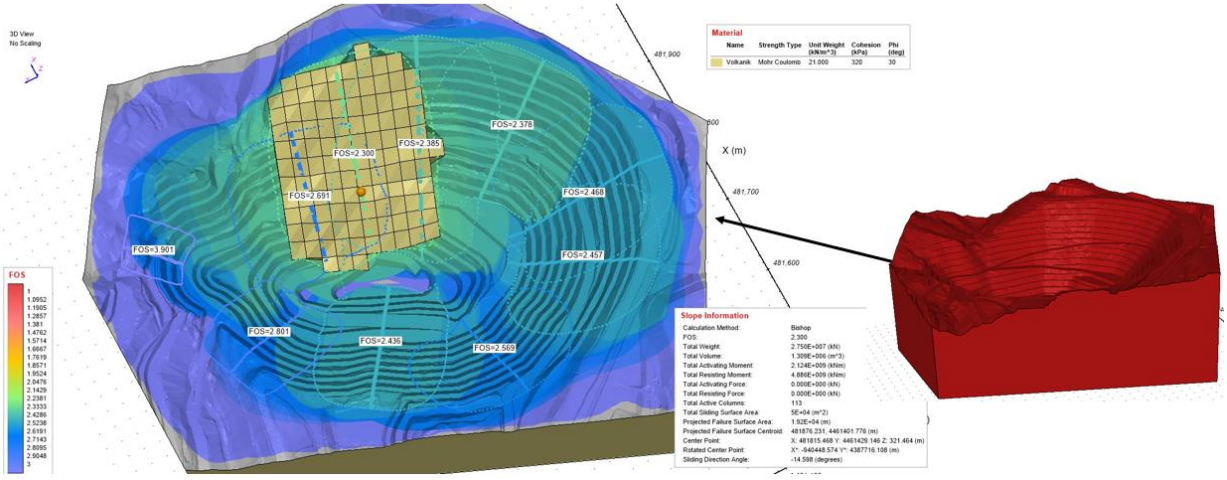

Figure 4. Slope stability distribution obtained for Stage 1 (baseline model)

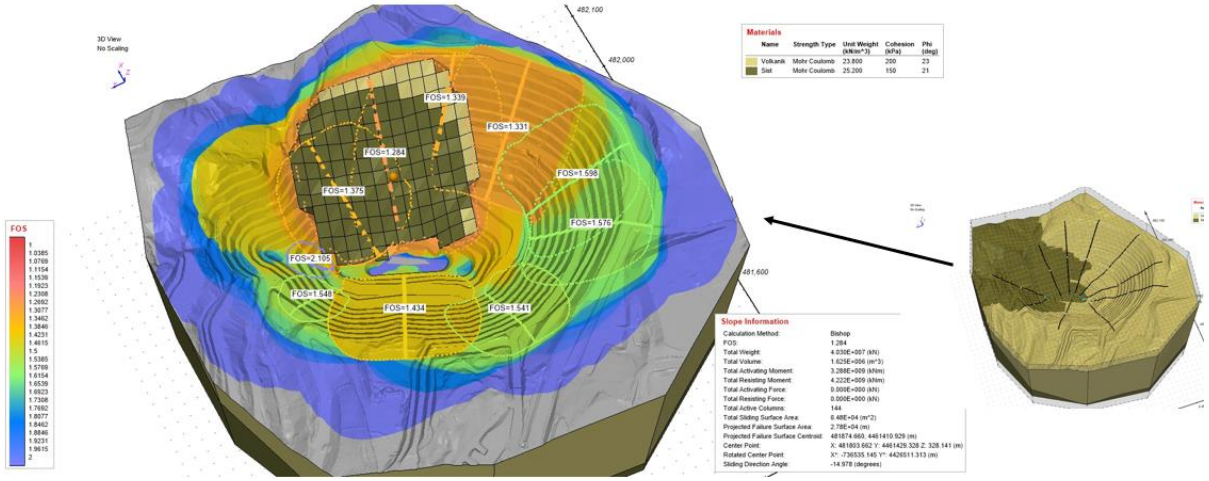

Figure 5. Slope stability analysis for Stage 2 (site-specific geotechnical parameters)

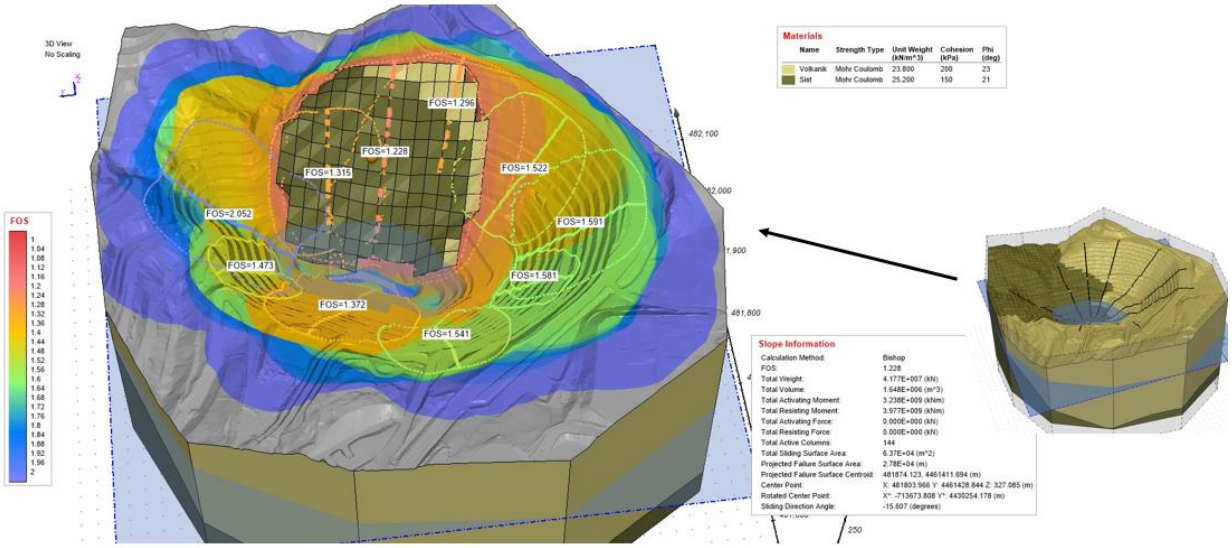

Figure 6. Slope stability analysis for Stage 3 (groundwater-included model)

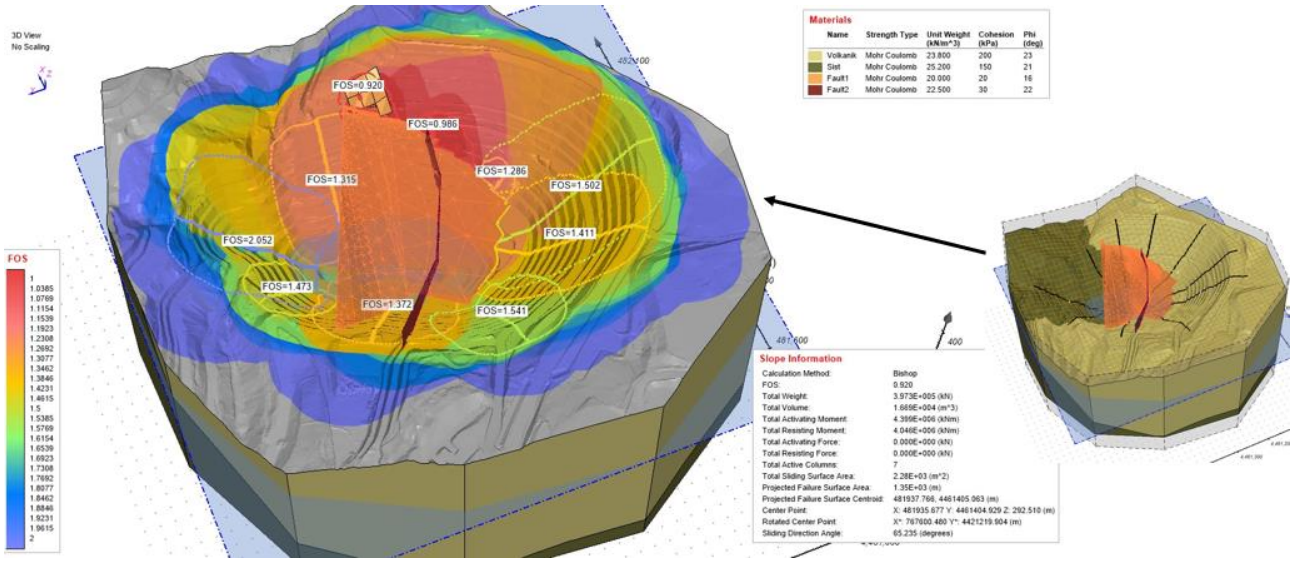

Figure 7. Slope stability analysis for Stage 4 (fault-inclusive model)

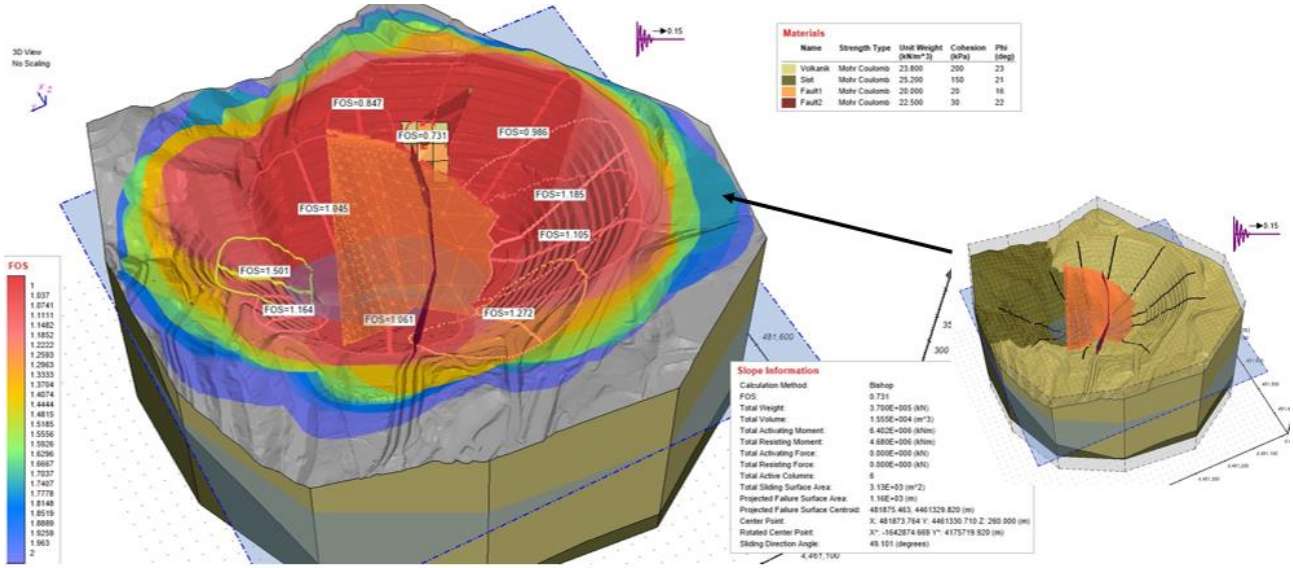

Figure 8. Slope stability distribution under seismic loading (Stage 5)

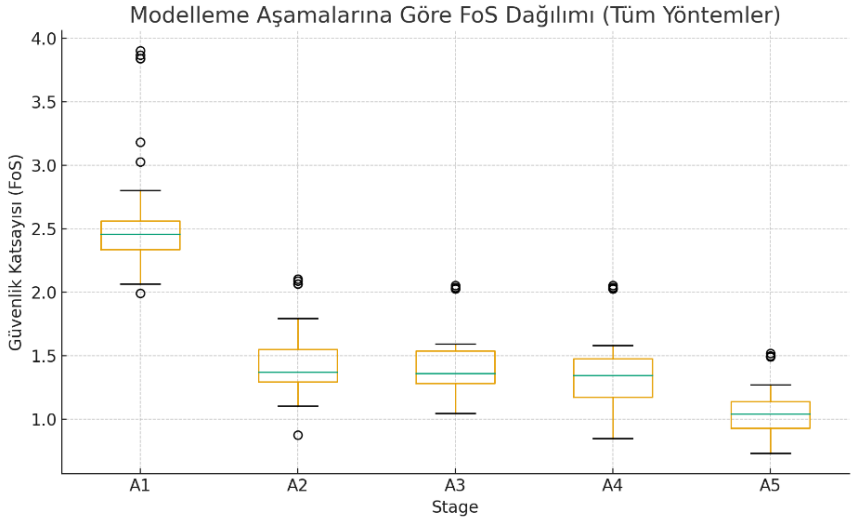

Figure 9. Boxplots showing the distribution of FoS values across the five modeling stages

5. Conclusions and recommendations

This study evaluated open-pit slope stability using a five-stage modeling framework and multiple limit equilibrium methods, demonstrating that the Factor of Safety (FoS) must be interpreted not merely as a numerical outcome, but within the broader geological, hydrogeological, and structural context of the site. The progressive incorporation of site-specific geotechnical properties, groundwater conditions, and structural features resulted in pronounced reductions in FoS, confirming that realistic slope behavior can only be represented when these critical inputs are explicitly included in the analysis. A three-dimensional surface plot summarizing the variation of mean FoS values across different modeling stages and analysis methods is shown in Fig. 10, illustrating the systematic decline in stability as additional complexities are integrated.

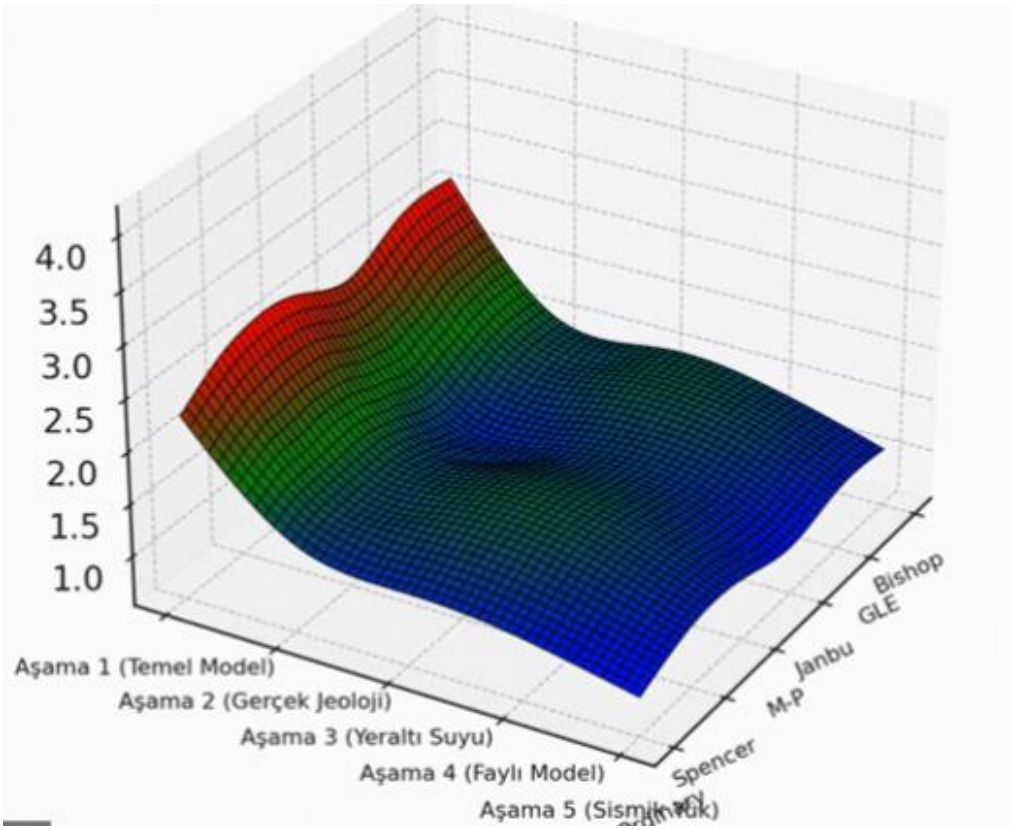

Figure 10. Three-dimensional surface plot illustrating changes in mean FoS across analysis methods and modeling stages

The integration of fault zones and seismic loading caused FoS values to fall below critical thresholds in several sections, emphasizing the need to account for structural and dynamic effects in engineering design. The observed discrepancies among analysis methods further highlight the importance of employing multiple approaches during stability evaluations, as reliance on a single method may lead to misleading or overly optimistic interpretations.

Findings from the literature reinforce these conclusions. Three-dimensional models have been shown to provide more reliable stability assessments than two-dimensional analyses by capturing edge effects and volumetric behaviors [14]. Similarly, comparisons between 2D and 3D analyses have reported substantial differences in FoS, attributed to the improved representation of stress redistribution and spatial variability in three-dimensional models [15]. These studies collectively support the premise that realistic slope stability assessment requires three-dimensional characterization and modeling.

Furthermore, improving the spatial resolution of slope assessment by increasing the number of analyzed cross-sections would enable more accurate identification of local stability variations. Complementing numerical findings with geotechnical monitoring techniques—such as ground-

penetrating radar, microseismic monitoring, or deformation measurement systems—can facilitate early detection of potential failure zones and strengthen the reliability of design decisions. Regular monitoring, model updating, and revision of site-specific geotechnical data should be considered essential engineering practices for ensuring operational sustainability and long-term slope performance.

Overall, while the progressive decline in FoS across successive stages is consistent with engineering expectations, the key message of this study is the inadequacy of simplified analyses that remain common in industry practice. Evaluations based solely on limited cross-sections or generalized parameters fail to capture the true behavior of open-pit slopes. Instead, a comprehensive approach that incorporates detailed geological, hydrogeological, and structural data is essential for producing reliable and defensible slope stability assessments.

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