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SLOPE STABILITY ANALYSIS USING 3D LIMIT EQUILIBRIUM METHOD IN A FAULT CONTROLLED METAL MINE

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Abstract

The effective management of slope stability risks stands as a cornerstone in ensuring the secure and cost-efficient operation of open-pit mines. Over time, a plethora of analytical methodologies have been devised to enhance the handling of these risks. Presently, while the overarching goal remains the eradication of all potential instabilities through the reduction of slope angles, it's evident that such an approach is economically unfeasible. Within open-pit mining operations, meticulous attention is demanded during the planning and production phases. The primary objective revolves around maximizing ore extraction while minimizing waste removal. Consequently, the accurate determination of bench heights, bench widths, and slope angles holds paramount importance. This study undertakes slope stability analyses utilizing the multiple limit equilibrium method within a field characterized by the aforementioned parameters. Identifying the most critical slip surfaces with the lowest safety coefficients among the array of potential slip scenarios forms a focal point of the investigation. Throughout the study, the outcomes are scrutinized utilizing diverse calculation methodologies, notably the Generalized Limit Equilibrium (GLE) and Bishop methods. Analysis is conducted using the "Plaxis 3D LE" software, ensuring comprehensive evaluation and validation of the results.

Key words

Slope stability, limit equilibrium, gle, bishop, open-pit

1 Introduction

The management of personnel, equipment, and ongoing production risks associated with slope instability is a critical responsibility of geotechnical and mining engineers in open pit mining. The primary objective of slope stability studies is to achieve economically viable and safe outcomes in ground structures, excavations, and embankments. This process begins with a comprehensive analysis of geotechnical, material, environmental, and economic parameters. Subsequently, it is essential to examine the dimensions, structure, and potential causes of the slope to determine the most appropriate slope stability analysis. This aspect of the field typically necessitates extensive research encompassing technical geology as well as soil and rock mechanics. A realistic slope analysis must incorporate numerous factors, such as topography, geology, material properties, and loading conditions. The primary variables influencing the stability of open pit slopes include slope geometry, the geomechanical properties of the material, and the engineering characteristics of the rock mass, such as faults, fractures, stratification, folds, cracks, groundwater conditions, and seismic activity. The incorporation of all these variables into the evaluation renders slope stability analyses inherently complex.

Failures in rock slopes primarily result from discontinuities within the rock mass. Therefore, the occurrence of such failures is contingent upon the interplay between the location and characteristics of these discontinuities and the position of the slope surface. Fault zones, frequently encountered within open pits and among the largest geotechnical structures, play a crucial role in slope stability. While faults represent the most significant discontinuity structures, the material composition within fault zones, such as clay bands, also contributes to the formation of direct failure surfaces on slopes. Consequently, this complex scenario must be meticulously considered when analyzing the stability of open pits that contain faults. (Deliormanli and Ozdogan, 2023)

There are different methods used both in the evaluation of open pit slopes and in the evaluation of the stability of natural slopes. Among these methods, the most preferred methods are kinematic analysis, limit equilibrium analysis, numerical analysis and rock mass classification systems such as Slope Mass Rating (SMR) (Hoek and Bray, 1981; Hoek, 1999; Ulusay et al., 2001; Pantelidis, 2009; Alejano et al., 2011; Komurlu, 2022; Karaman, 2013).

In this study, 3D Limit-Balance Equation Slope Stability Analyses were performed according to the slope structure created by the company. Slope stability analyses were analyzed with the "Multiple Limit Equilibrium Method" calculated by Plaxis 3D LE program using analytical methods. In limit equilibrium methods, a slip surface is accepted and the equilibrium of the soil mass trying to slip is investigated and a safety coefficient is obtained. Among the slipping possibilities of the surfaces, the most critical slip surface that gives the lowest safety coefficient is found. During the study, two different calculation methods, GLE and Bishop, were used and the results were analyzed.

2 General Geology Of The Study Area

The pre-Tertiary rock assemblages of the Biga Peninsula are represented by Paleozoic aged Kazdağı metamorphics, Triassic aged Karakaya formation, Jurassic limestones and Upper Cretaceous aged ophiolitic melange. Tertiary rocks, which cover large areas in the region, begin with the Edincik and Beyçayır volcanites consisting of Middle Eocene aged andesitic lavas and pyroclastics. These two units are unconformably overlain by the Sahinli Formation consisting of basalt, basaltic andesite and associated volcaniclastics.

These units are unconformably overlain by the Fıçıtepe formation consisting of fine coal interbedded pebbles, sandstones and shales representing the delta plain and fluvial deposits. The Sahinli Formation and Fıçıtepe Formation are followed by the Soğucak Formation consisting of igneous limestone with a relationship that cannot be clearly traced. The Ceylan formation composed of turbiditic sediments and the Dededag volcanites were formed simultaneously with them in the region which started to deepen in the Upper Eocene. Dededag volcanites are divided into three members; Hacıbekirler member, Kazmalı tuff member and Korudere ignimbrite member. Ignimbirites, which constitute the dominant rock type, are widely distributed between Balıklıçeşme, Çan and Bayramiç districts of Çanakkale Province. Ignimbirites were developed as a product of submarine pyroclastic flows. Ignimbrites are overlain by the Beybaşlı Formation consisting of Upper Eocene aged sandstone, claystone and reefal limestone north of Beybaşlı village. The Beybaşlı formation is overlain by the Erdağ volcanite, which is thought to be Upper Eocene in age, with an abrupt contact. The Eocene volcano-sedimentary assemblages are unconformably overlain by Oligocene and Miocene aged andesitic, basaltic, rhyolitic and dacitic volcanites and lacustrine sediments in places. Following the Beyçayır volcanite of the Sahinli Formation, shallow marine sediments started to form in the region and this was accompanied by volcanism with a basic composition. Accordingly, volcaniclastic rocks were intensively deposited together with lavas. The unit presents a type section especially in the east of Lapseki district, around Şahinli village and was named Şahinli Formation.

The unit is cut by numerous basaltic dykes. Bilaller Member. The unit within the Sahinli Formation, consisting of volcanoclastics and turbiditic sediments in places and dominantly basalt and basaltic andesite composite lavas that cannot be separated from these sediments, is named as Bilaller Member. The rocks have hypocrystalline porphyritic texture and plagioclase and pyroxenes are the main phenocrysts. Plagioclases are semi-cored and polysynthetic twinned in places. Pyroxenes are in non-cored forms and are observed as bilaterally diluted. The paste consists of volcanic glass, plagioclase microliths, pyroxene minerals and disseminated opaque minerals. Volcanic glass is heavily clayified and chloritized. The voids in the rock are filled with chlorite.

3 Methods

3D Limit-Balance Equation Slope Stability Analyses were performed according to the slope structure created by the company. Slope stability analyses were performed with the "Multiple Limit Equilibrium Method" calculated by Plaxis 3D LE program using analytical methods using rock mass properties. In limit equilibrium methods, a slip surface is accepted and the equilibrium of the soil mass trying to slide is investigated and a safety coefficient is obtained. Among the slipping possibilities of the surfaces, the most critical slip surface that gives the lowest safety coefficient is found. During the study, two different calculation methods, GLE and Bishop, were used and the results were analyzed.

Bishop method: This method considers the horizontal and vertical force balance and neglects the shear force between the slices.

Generalized Limit Equilibrium method (GLE): In the GLE approach, the safety numbers of the cohesion and friction components that make up the strength of soils are the same. The safety number is the same for all slices forming the shear circle under investigation. The force balance safety number Fs is calculated from the sum of the horizontal forces acting on all slices.

The results obtained as a result of these calculation methods and analysis methods are given below. The rock parameters used in the numerical model are given in Table 1.

Table 6. Rock parameters used in the analysis

	Unit Volume Weight (kN/m^3)	**Cohesion (c) (kPa)**	**Internal Friction angle (^{0})**
Volcanic Rock	24.80	200	23
Fault 1	22	20	16
Fault 2	22.5	30	22

The digital elevation model of the open pit operation is given in Figure 1.

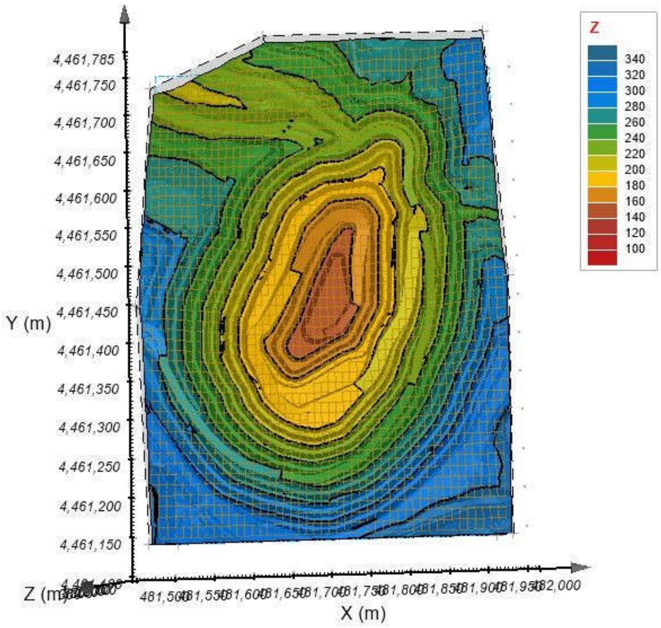


Figure 25. Digital elevation model of the open pit operation

The steps performed during the analysis phase are summarized below:

Using Plaxis Designer, the area to be studied on the hearth triangle model was determined and the volume definition process was performed. The quarry with the defined volume was transferred to Plaxis 3D LE application and material properties were defined for both the surface and the detected discontinuity elements. Contours were determined in the areas where we want to calculate the coefficient of safety FOS values on the quarry. For the determined contours, Bishop and GLE methods were examined and the solution process was started and took approximately 235 minutes.

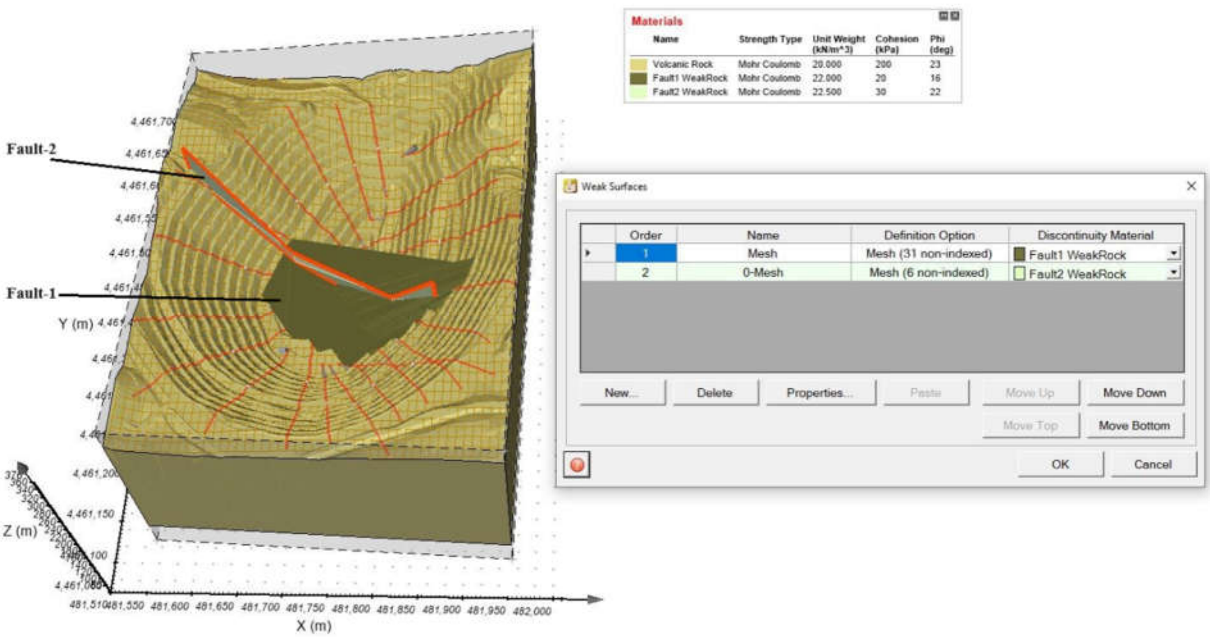


Figure 2. Contours determined on the quarry with defined faults and general view of the 3D design

In order to make a homogeneous analysis, contours (pink lines in Figure 2) were drawn at certain intervals throughout the quarry (22). Faults previously identified as a result of related studies on the quarry were defined as weak surface/discontinuity material on the program. For the area covered by each contour, coefficients of safety (CoS) were calculated using the limit-balance method, Bishop and

GLE approach. The results obtained for the open pit using these two calculation methods are given below.

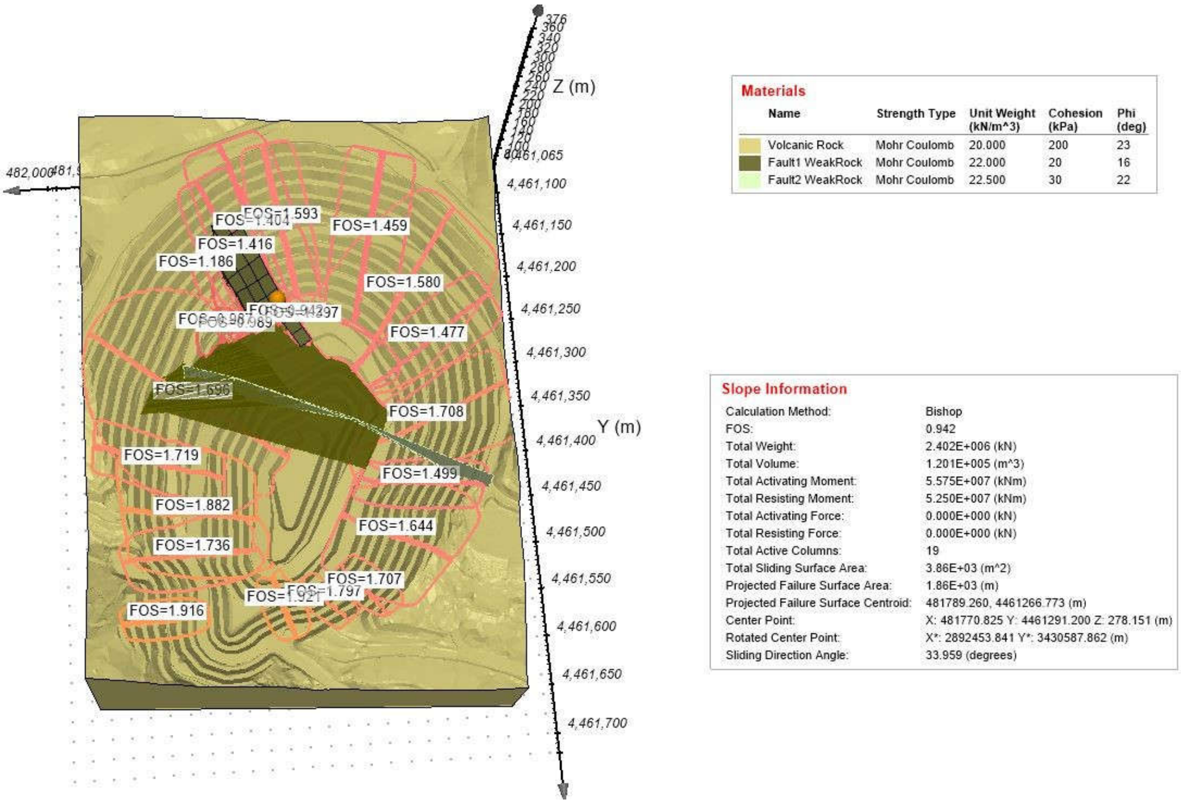


Figure 3. Safety factor values calculated by Bishop's method and the lowest safety factor (0.942)

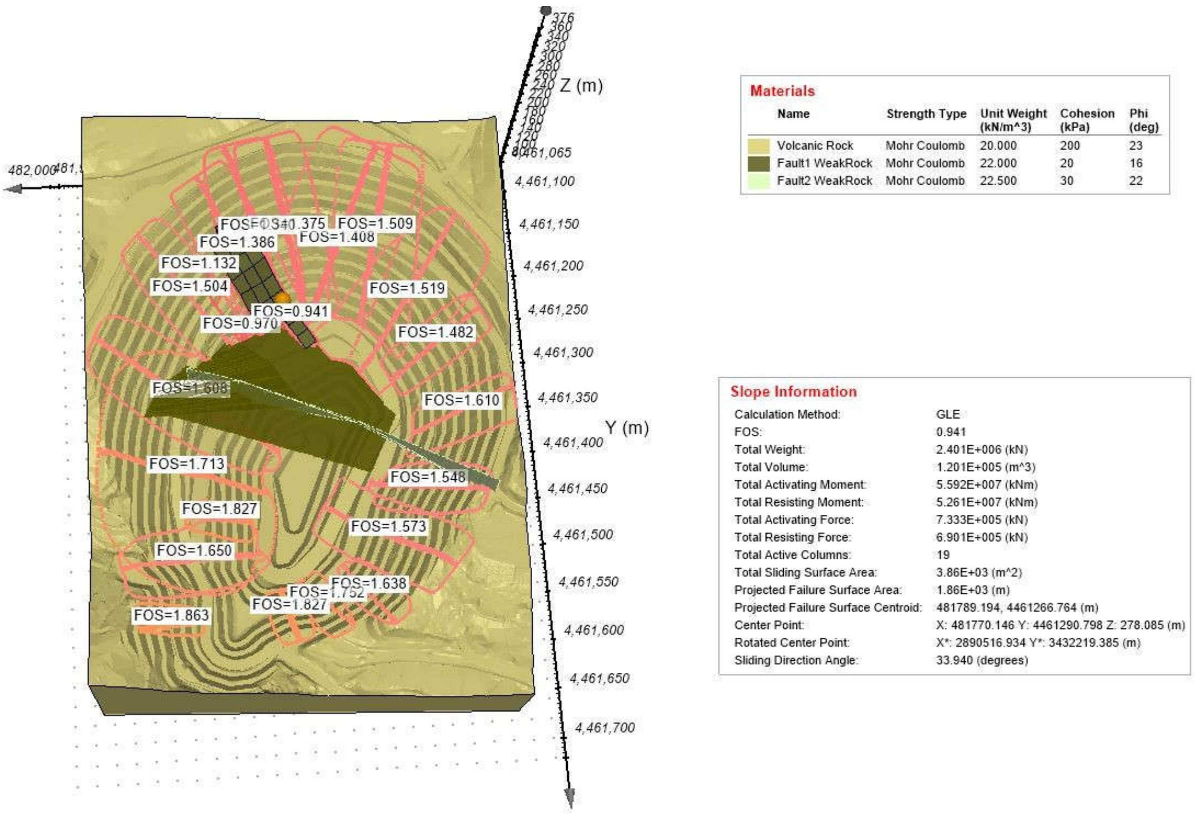


Figure 4. Safety factor values calculated by the GLE method and the lowest safety factor (0.941)

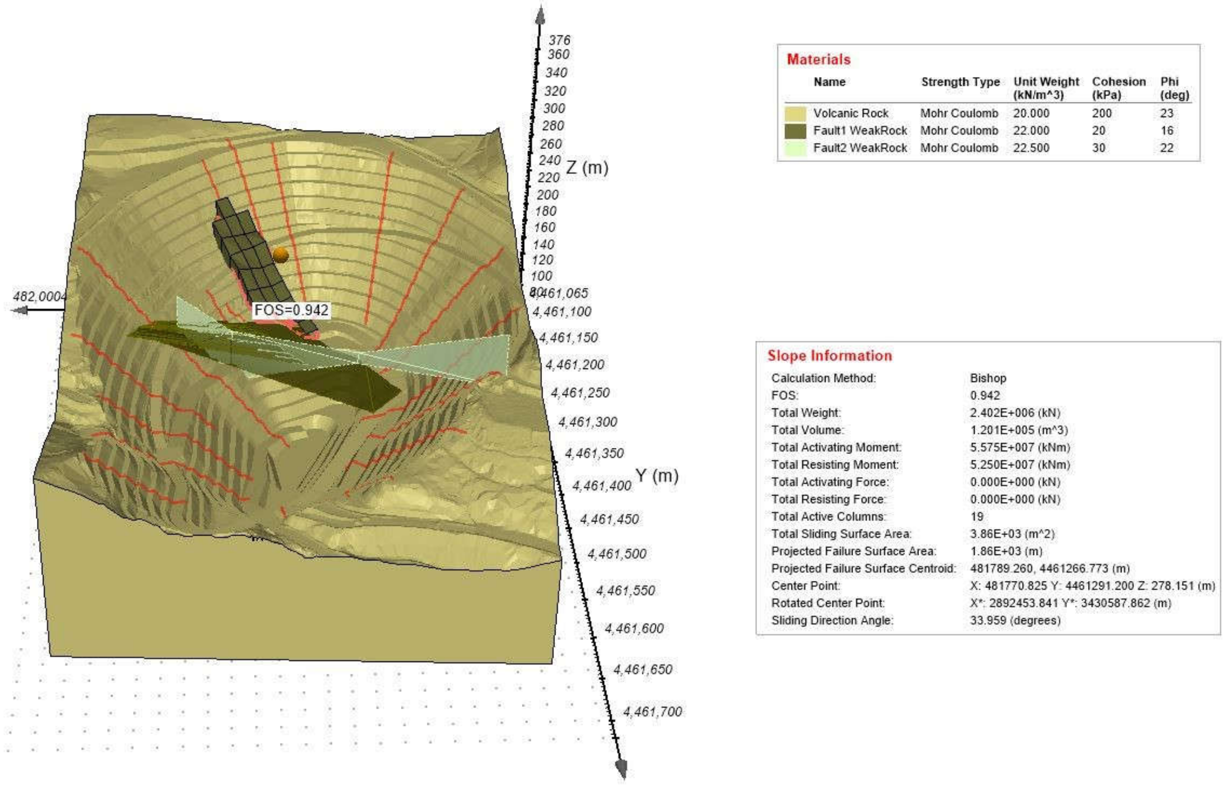


Figure 5. Critical slip surface resulting from Bishop's method analysis

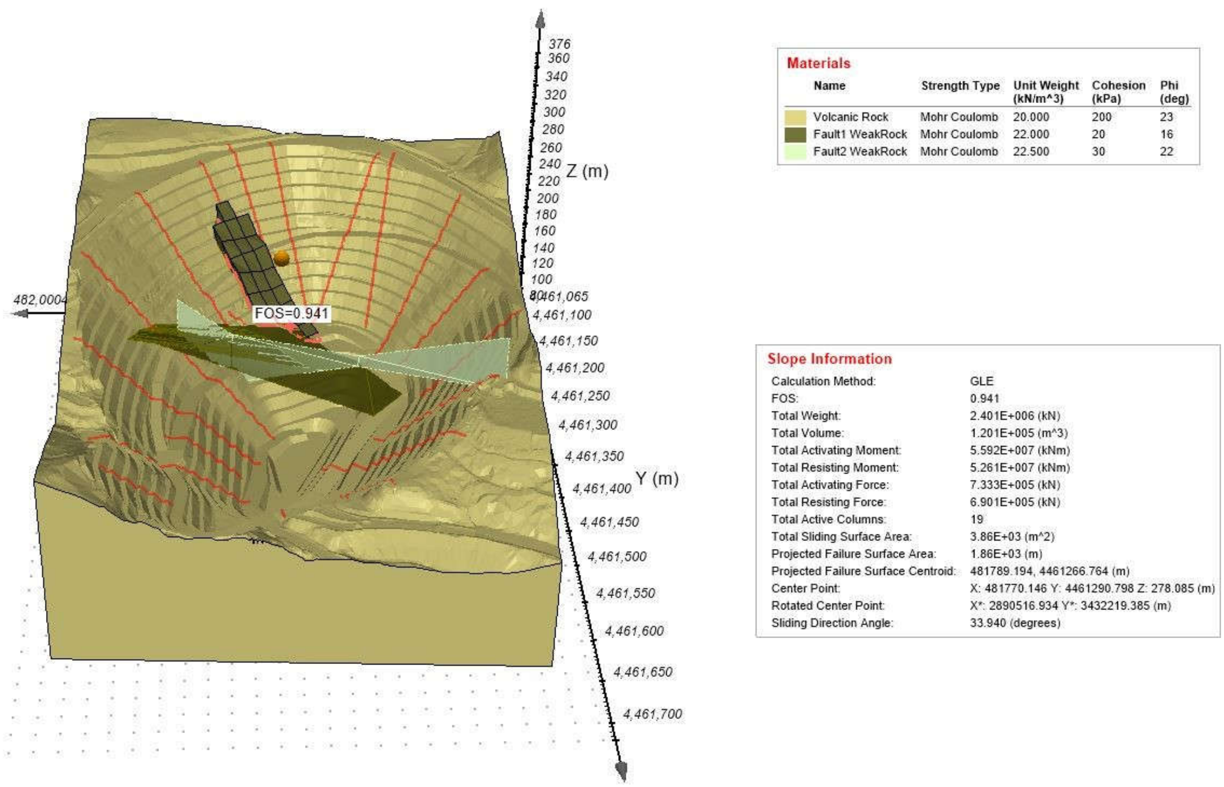


Figure 6. Critical slip surface resulting from GLE method analysis

Figures 5 and 6 show the critical slip surfaces determined by two different methods, bishop and gle. FOS values are written above the critical slip surfaces and highlighted with an orange dot.

4 Results

In this study, 3D Limit-Equilibrium Equation Slope Stability Analyses were performed according to the slope structure created by the company in order to evaluate the open pit slope stability. Slope stability analyses were analyzed with the "Multiple Limit Equilibrium Method" calculated by Plaxis 3D LE program using analytical methods.

In open pit slope stability analyses, the evaluation of faults together with rock mass properties provides more reliable and accurate results. The location, orientation, length and other geometric characteristics of faults can directly affect slope stability. Therefore, it is important to analyze faults in an integrated manner with rock mass properties. At this point, the fault surfaces that we directly identified were used in the analysis. It includes fault location, orientation, length and other geometric features.

In open pit slope stability analyses and analyses, it was seen that if the faults detected in the quarry are included in the analysis by determining the rock mass properties, the analysis gives much healthier results.

Within the scope of this study, Bishop and GLE methods were examined by using the 3D limit equilibrium method;

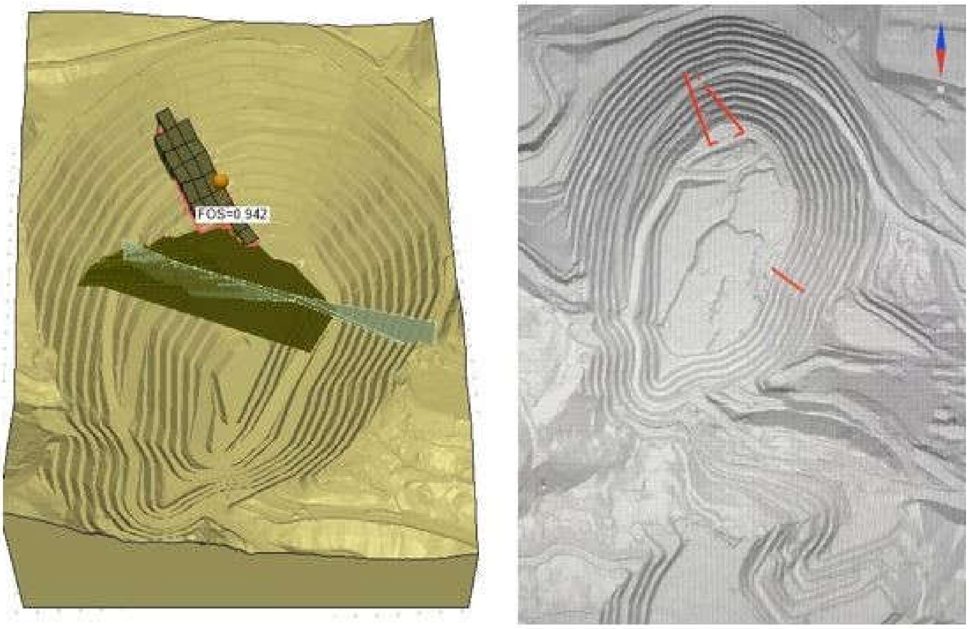
- The lowest safety factor value obtained using the Bishop method was calculated as 0.942.
- The lowest safety factor value obtained using the GLE method was calculated as 0.941.

The important point to be emphasized in this paper is that discontinuities and faults in the region should be included in the analysis of slope stability in open pit mining or in areas with any natural/artificial slope structure.

5 Conclusion

In the scenario where discontinuities and faults, which we define as weak surfaces, are not included in the analysis, it is observed that the average safety factor is around 1,400 - 1,700. This shows the importance of the fault plane in the quarry on the analysis in slope stability analysis in open pit mining.

In Figure 7, the slip surface detected by the program in the limit equilibrium analysis results is compared with the actual slip point detected in the quarry. The important factor here is that due to the heel left in front of the area where the wedging faults are located, the movement in this area was restricted and as a result, the forces accumulated here found their way from the heel edge area.
Figure 7.b is the visual sent by the company. The red lines indicated on the quarry surface are the areas of the quarry where slippage is currently observed. Comparing Figure 7, a and b proves that the results obtained from the analysis (critical slip surface) are in direct correspondence with the current situation.



(a) **(b)**

Figure 7. The slip surface detected by the program and the actual slip point detected in the quarry

References

Alejano, L.R., Ferrero, A.M., Oyanguren, P.R., Fernandes, M.I.A., 2011. Comparison of limit equilibrium, numerical and physical models of wall slope stability. International Journal of Rock Mechanics and Mining Sciences, 48, 16-26.

Deliormanli, A.H., Ozdogan, M.H., 2023. Stability Analysis in a Fault Controlled Open Pit, Journal of Underground Resources, MT Scientific, 23.

Hoek, E., Bray, J.W., 1981. Rock Slope Engineering. 3rd edition. London, Institute of Mining and Metallurgy. 385 p.

Hoek, E., 1999. Putting numbers to geology – an engineer's viewpoint. Quarterly Journal of Engineering Geology, 32, 1-19.

Karaman, K., 2013. Evaluation of Rock Slope Stability by Different Methods (Unye, Ordu) Journal of Geological Engineering 37 (1), 27-47.

Komurlu, E., 2022. Case studies on Q-slope method use for slope stability analyses. Studia Geo technica et Mechanica, 44, 190-197.

Pantalidis, L., 2009. Rock slope stability assesment through rock mass classification systems. International Journal of Rock Mechanics and Mining Sciences, 46, 315-325.

Ulusay, R., Gokceoglu, C., Sonmez, H., Tuncay, E., 2001. Causes, mechanism and environmental impacts of instabilities at Himmetoğlu coal mine and possible remedial measures, Environmen tal Geology, 40 (6), 769-786.