STABILITY ANALYSIS OF EMBANKMENT SLOPE USING BISHOP METHOD IN LUBE MODULE AREA PT. X

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ABSTRACT

The stability of embankment slopes in open-pit mining areas is a crucial factor in ensuring work safety and continuity of mine operations. This study aims to analyze the stability of embankment slopes in the Lube Module area of PT X using the simple Bishop method. The analysis was conducted by modeling the slope geometry and considering soil mechanics parameters, such as cohesion, inner shear angle, and material specific gravity. Simulations were conducted under two main conditions, namely dry conditions and conditions saturated with pore water pressure and seismic loads. The analysis showed that under dry conditions, the factor of safety (FS) of the slope was 2.45, indicating a stable condition. However, under saturated conditions with a pore water pressure of 0.2 and a seismic load of 0.2, the FS decreased to 1.1, indicating a critical condition. This study confirms that pore water pressure and seismic loads have a significant effect on slope stability. Therefore, mitigation in the form of drainage management and optimal slope geometry design is necessary to reduce the risk of landslides.

Keywords: Bishop's method; safety factor; slope stability

Introduction

Indonesia is one of the countries with abundant mineral resources, including gold, which is spread in various regions.[1] Gold mining activities have a strategic role in supporting economic development, especially in areas that have abundant mineral potential.[2] One of the mining companies in Indonesia that is known for its gold and copper potential is PT. X. The mine is managed with an open-pit mining system, which is a method of excavation that involves removing layers of soil or overburden to obtain the desired minerals.[3,4] The main activities of this mine include stripping the overburden, drilling and blasting to unload the rock from its host rock, loading, and transporting the ore to the stockpile or crusher, and disposing of the waste material to the waste dump area. One of the waste material disposal methods used by PT X is the in-pit dump, where materials are stockpiled in the mine-out area.[5]

Material disposal activities in the waste dump area require special attention, especially regarding slope stability. Unstable slopes can increase the risk of landslides, which not only jeopardize work safety but can also disrupt mine operations and potentially pollute the surrounding environment.[6] Avalanches on embankment slopes generally occur when the factor of safety (FS) is less than 1, indicating that the driving force is greater than the restraining force.[7] Therefore, an in-depth understanding of the factors that affect slope stability is required, such as slope geometry design, the presence of weak planes at the base of the waste dump, the nature of the materials that make up the slope, pore water pressure, and the additional load due to the accumulation of materials above the weak plane.[8,9] One of the most important aspects of open-pit mine design is establishing the optimal mine opening slope angle, which not only allows the mining process to proceed effectively but also ensures the long-term stability of the slope.[10]

In general, slopes formed in mining activities can be categorized into three main

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types, namely natural slopes, excavation slopes, and embankment slopes.[7] Natural slopes have usually been stable for a long time, but can experience landslides due to environmental changes, such as erosion, changes in groundwater conditions, earthquakes, or weathering.[9] Meanwhile, excavation and embankment slopes are artificial slopes formed by mining activities. Excavation slopes are formed from cutting soil or rock with a certain slope, while embankment slopes result from dumping excavated material into a certain area.[7,11] Compared to natural and excavated slopes, embankment slopes have their own challenges as the materials used generally consist of loose soil or non-coherent materials such as sand, gravel and silt. Therefore, the stability analysis of embankment slopes focuses more on parameters such as deep shear angle, specific gravity of the material, pore water pressure, and embankment geometry, which includes the height and angle of the slope.[9]

To analyze slope stability, one of the commonly used methods is the equilibrium method. This method is based on the principle of equilibrium of forces and moments in the slope system to determine the probability of collapse or landslide.[12] One frequently used variant of the boundary equilibrium method is the simple Bishop method, which assumes that the potential slip plane is circular. In this approach, the slope is divided into several vertical slices, and the balance of normal forces, friction forces, and moments is calculated for each slice to determine the factor of safety (FS). The simple Bishop method has the advantage of being relatively simpler to calculate than other boundary equilibrium methods, while still providing fairly accurate results in most cases. The factor of safety is calculated as the ratio between the restraining force and the driving force, where FS > 1 indicates that the slope is stable, while FS < 1 indicates that the slope is at risk of landslide.[13,14]

Based on previous studies, most slope stability analyses focus on mining areas in general without emphasizing the influence of pore water pressure and seismic loads on slopes made of heterogeneous waste materials. Recent research highlights that seismic load intensity and subsurface heterogeneity significantly alter slope safety factors, especially in open-pit mining environments. He et al.[15] reported that increased earthquake acceleration exponentially reduces slope stability, while Kumar et al.[16] confirmed that the simple Bishop method provides reliable results for assessing slope behavior under dynamic conditions. Therefore, this study fills this research gap by specifically analyzing the stability of the embankment slope in the Lube Module area of PT X in both dry and saturated conditions. This analysis aims to determine the influence of pore water pressure and earthquake loads on slope safety factors, as well as to propose an optimal slope design that improves both safety and environmental sustainability.

Methods

This research was conducted at the PT X mine site, focusing on the lube module area of the embankment slope. The research location map can be seen in Figure 1.

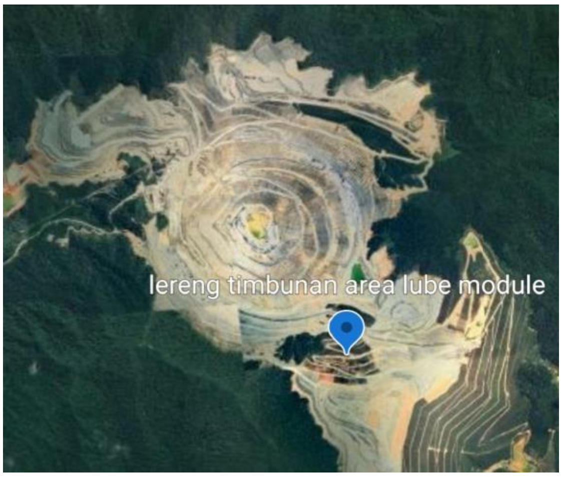

Figure 1. Research the location map of PT. X lube module stockpile slope

The data used in this study are data on soil mechanics parameters, such as cohesion (c), material content weight (γ), and inner shear angle (φ) for each soil layer. The data were obtained from geotechnical measurements by PT X. Furthermore, the soil parameters were

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processed using Surface software for slope cross-section design and Slide2 for slope stability analysis. The equation used in the manual calculation is the simple Bishop equation, written in Equation (1).

$$FS = \frac{\sum_{n=1}^{7} cl_n + \tan\varphi\, W_n \cos\alpha_n}{\sum_{n=1}^{7} W_n \sin\alpha_n} \quad (1)$$

Equation (1) is the slope safety factor equation using the Bishop method that ignores pore water stress, while the slope safety factor equation that does not ignore pore water stress is written in Equation (2).[17]

$$FS = \frac{\sum_{n=1}^{7} cl_n + \tan\varphi\, W_n \cos\alpha_n}{\sum_{n=1}^{7} W_n \sin\alpha_n} \quad (2)$$

Where, c = cohesion (kPa), l = wedge arc length (m), W = wedge weight (kN), μ = pore water pressure (kPa), φ = inner friction angle (°), α = wedge angle (°).

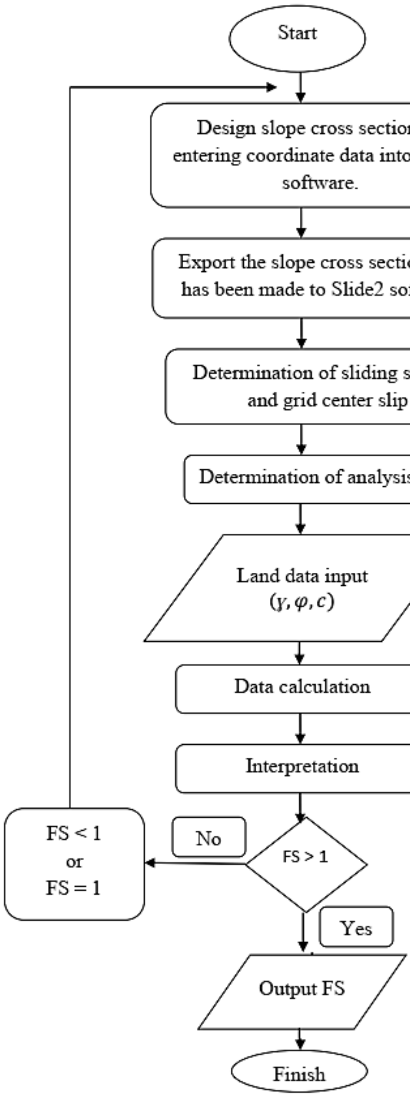

Figure 2. Flowchart of Data Analysis

In the analysis flow (Figure 2), if FS > 1, the slope is considered stable. If FS approaches 1, the slope is in a critical condition and needs to be reanalyzed by entering new parameters (e.g., slope angle, cohesion, or different pore water pressure). The results of this iteration are then tabulated to provide a more comprehensive variation of FS values.

The following are the soil mechanics parameters used in the data analysis.

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Table 1. Material types and soil mechanics parameters

Materials	Shear parameters		
	ɣ (kN/m^3)	c (kPa)	φ (°)
Waste Rock	22	0	34.5
Soil Foundation	18	10	30
Bedrock	27	220	45

The *ɣ* (kN/m^3) parameter is the specific gravity or bulk density of the soil, which indicates the weight of the material per unit volume. It is a measure of how dense and heavy the material is. A higher specific gravity indicates a denser material. Cohesion (c) is the component of shear strength that comes from the intermolecular forces between the particles in the material. It indicates the ability of the material to stick together and resist shear stress, and the inner friction angle (φ°) is a measure of the shear strength of the material caused by friction between particles.

Result and Discussion

a. Result

The stability of the Lube embankment slope is greatly influenced by the type of material used. The materials that form the embankment slope consist of waste rock, subsoil, and bedrock, each of which has different mechanical properties that affect the behavior of the slope. The values of the soil shear parameters are presented in Table 1.

To further understand the influence of slope geometry and soil properties on slope stability, several key parameters were changed, including slope angle (α), pore water pressure (Ru), and cohesion (c). The relationship between these parameters and the slope safety factor (FS) for each material layer is illustrated in the following figures.

- Waste Rock Layer

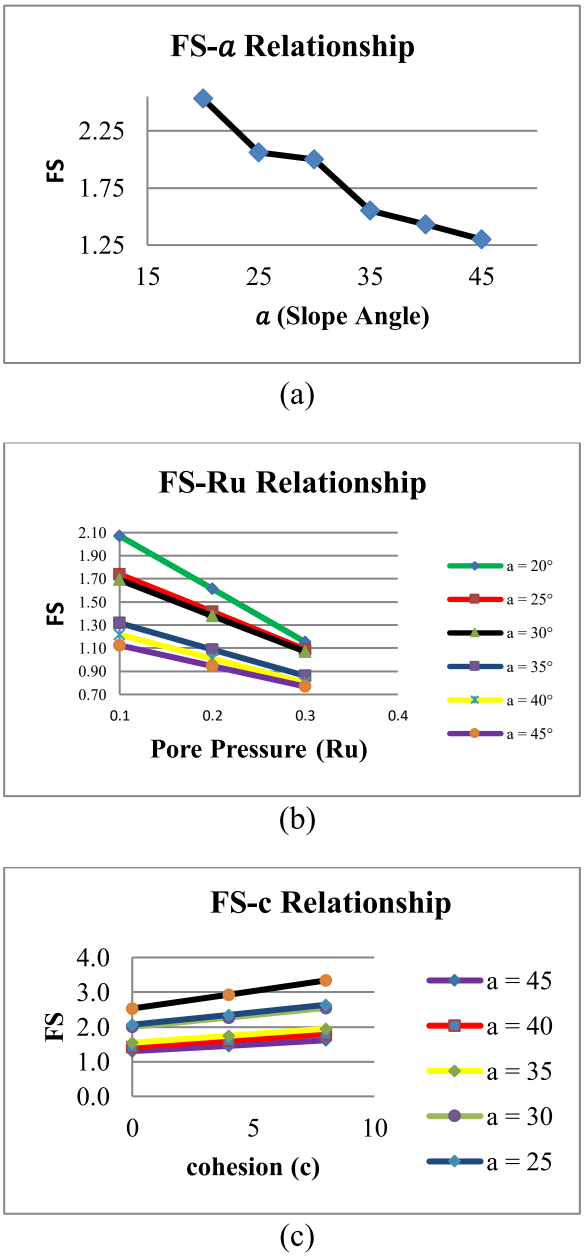

Figure 3. Relationship graphs of slope safety factor (FS) on waste rock layer:
(a) FS with slope angle (α), (b) FS with pore pressure (Ru), and (c) FS with cohesion (c).

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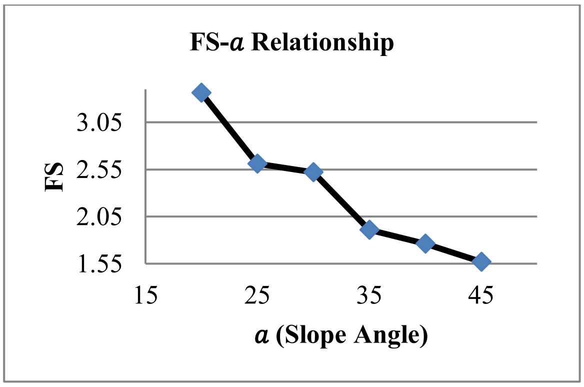
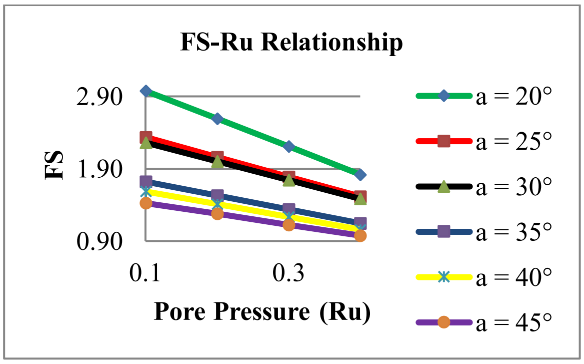
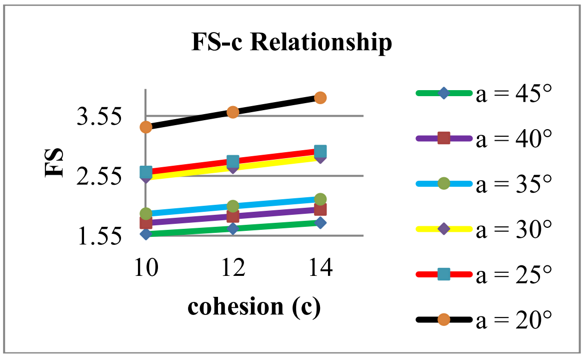
- Soil Fondation Layer



(a)



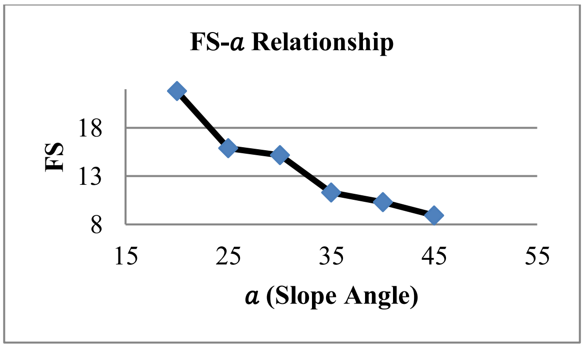
(b)



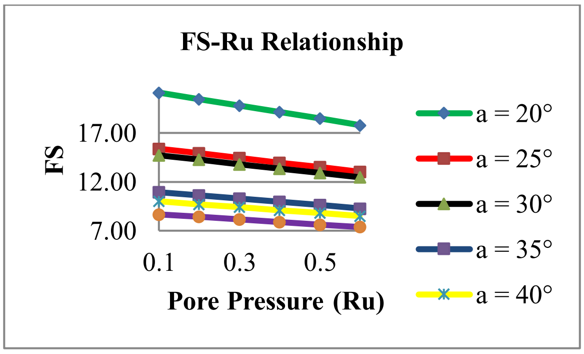
(c)

Figure 4. Relationship graphs of slope safety factor (FS) on soil foundation layer: (a) FS with slope angle (α), (b) FS with pore pressure (Ru), and (c) FS with cohesion (c).

- Bed Rock Layer



(a)



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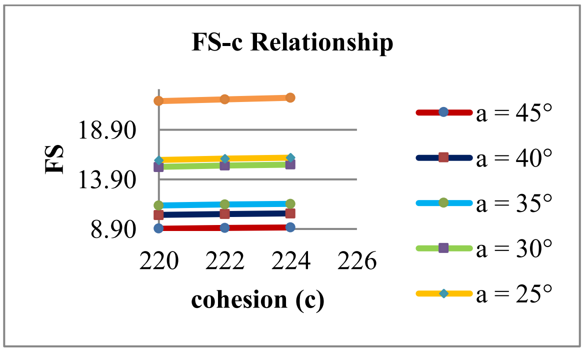

(c)

Figure 5. Relationship graphs of slope safety factor (FS) on bedrock layer: (a) FS with slope angle (α), (b) FS with pore pressure (Ru), and (c) FS with cohesion (c).

Table 2. Results of slope safety factor with varying values of pore water pressure and seismic loading

Ru Coefficient	FS	Ru + Seismic Load	FS
0.1	2.19	0.18	1.31
0.2	1.93	0.20	1.1
0.3	1.70	0.22	0.96
0.4	1.41	0.24	
0.5	1.15	0.26	

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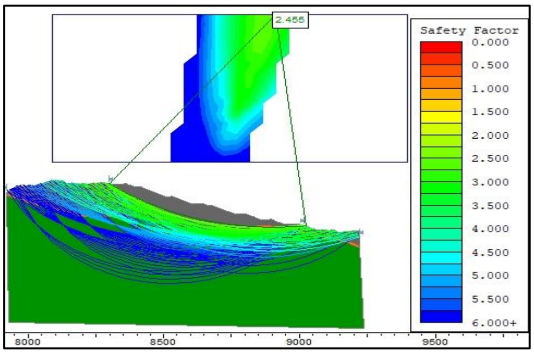
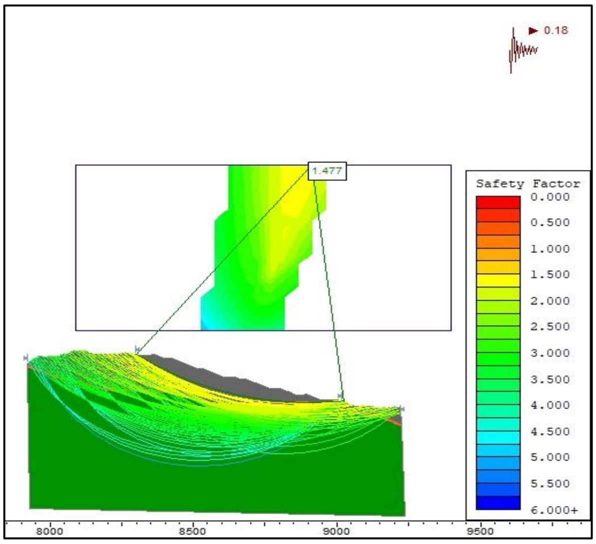
- Slope Analysis Under Dry Conditions



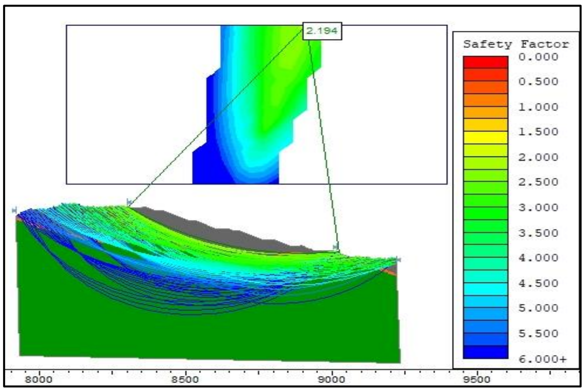
(a)



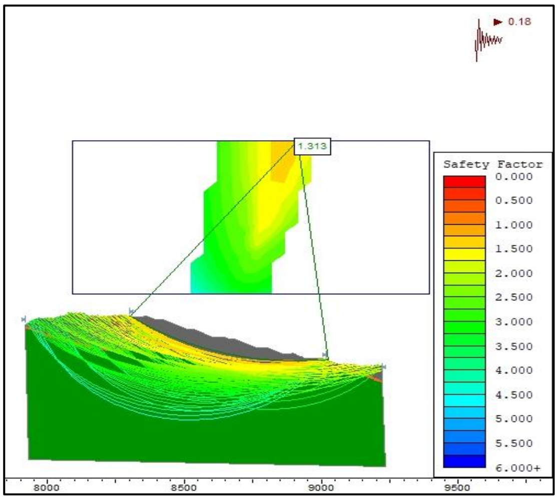
(b)

Figure 6. Simulation results of slope stability under various conditions: (a) Dry condition, (b) Dynamic state with seismic load 0.18, Slope Analysis Under Saturated Conditions

- Slope Analysis Under Saturated Conditions



(a)



(b)

Figure 7. Simulation results of slope stability under saturated conditions: (a) Saturated condition with pore pressure 0.1, (b) Saturated condition with pore pressure 0.1 and seismic load 0.18.

The simulation results show that pore water pressure and seismic load greatly affect the stability of the slope material. The factor of safety values obtained with the variation of Ru and seismic load until the slope gets critical and unstable factor of safety values are listed in Table 2.

b. Discussion

- Comparison of Slope Material Stability

The first layer, waste rock, is the material left over from the mining process that generally consists of various types of rocks that do not contain valuable minerals. Waste rock has a variety of strengths depending on its composition. The second layer, the soil foundation, is the layer of soil that supports the overlying structure. This soil can be clay, sand, silt, or a combination of several types of soil. The strength of the soil varies depending on the type. The third layer, the bedrock, is a layer of hard rock that lies beneath the ground or below the topsoil. This bedrock is generally very strong and stable. Compared to soil and waste rock, bedrock has much higher strength.

Based on the FS–α graph, it is known that the greater the slope design angle, the smaller the factor of safety. This study proves that the slope has an effect on the level of stability. In addition, based on the FS–Ru and FS–c

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relationship graphs, it was found that the larger the Ru coefficient value, the lower the factor of safety. This simulation shows that the saturated condition of the slope with high pore pressure will affect its stability. Meanwhile, the higher the cohesion value of the material layer, the more the slope stability increases. This proves that cohesion plays an important role in determining the stability of the material on the slope.

The analysis shows that the most stable material is bedrock, as it has high strength and cohesiveness. The intermediate stability is found in the soil foundation, while the most vulnerable material is the waste rock. Similar findings were reported by Moosavi et al.[18] who emphasized that pore water pressure exerts a substantial influence on the decrease of slope safety factor, particularly in areas with loose or mixed soil composition. Wu et al.[19] also demonstrated that the coupled hydro-mechanical interactions in saturated embankments significantly accelerate slope deformation and failure. Furthermore, Enkhbold et al.[20] found that combining Bishop and Janbu methods produces a more accurate estimation of safety factors for slopes composed of non-homogeneous materials. These results support the findings in this study, indicating that pore water pressure and seismic load are key parameters determining slope stability in mining environments.

- Overall Slope in Dry and Saturated Conditions

Based on the analysis results, the factor of safety (FS) value obtained for the slope in the dry state is 2.45, as shown in Figure 6 (a). This indicates that under actual conditions, the slope is in a stable and safe state. For slopes under dynamic conditions, the FS value obtained from the first simulation with a seismic load of 0.18 is 1.47, as shown in Figure 6 (b). This result confirms that seismic loading has a significant influence on slope stability, consistent with the findings of He et al.[15] who reported that increasing seismic acceleration reduces slope stability exponentially.

Meanwhile, the analysis of the slope under saturated conditions was carried out by considering the influence of pore water pressure as well as an additional dynamic scenario involving seismic loads. The results show that when the material is affected by pore water pressure (Ru) and seismic loads, the FS value varies depending on the magnitude of Ru and the applied seismic intensity. In the condition with Ru = 0.1, the FS value is 2.19 (Figure 7(a)), but when a seismic load of 0.18 is applied, the FS decreases to 1.31 (Figure 7(b)). These results align with Moosavi et al.[18] who found that pore water pressure has a strong inverse correlation with slope safety factor, and with Wu et al.[19] who demonstrated that coupled hydro-mechanical effects under saturated conditions accelerate slope deformation and instability. Thus, the simulation results in this study reaffirm that both pore water pressure and seismic loads are critical factors influencing the overall slope stability.

Based on the research conducted, it can be concluded that the most stable material layer is bedrock, intermediate stability is found in soil foundation, while the most vulnerable layer is waste rock. Under dry conditions, the slope safety factor value is 2.45, which indicates optimal conditions. However, under saturated conditions with a pore water pressure of 0.2 and a seismic load of 0.2, the factor of safety value decreases to 1.1, which is a critical condition for slope stability.

This study is limited to two-dimensional slope modeling and uses available geotechnical data without considering time-dependent effects, such as rainfall infiltration, weathering, or long-term loads. Further studies are recommended to incorporate three-dimensional numerical modeling, field monitoring of pore water pressure, and seismic response analysis to obtain more comprehensive results. In addition, slope stabilization strategies such as drainage improvements and reinforcement structures should be evaluated to improve safety and sustainability in mining operations.

Conclusion

Based on the research that has been done, it can be concluded that the most stable

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material layer is bedrock material, medium stability is soil foundation, and the most vulnerable is waste rock material. In dry conditions, the FK value of the slope is 2.45, which is the optimal condition of the slope, and in saturated conditions, the FS value of the slope is 1.1, which is the critical condition of the slope with a pore water pressure of 0.2 and with a seismic load of 0.2.

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