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Slope Stability Analysis of Pit X on Nickel Mining Based on Comparison between Design and Actual Mining Condition

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Abstract

The nickel laterite mining on the slopes of pit X uses the open-cast mining method with material strength conditions similar to soil. Slope stability considerations under temporary conditions such as earthquakes and increased groundwater levels due to rain need to be reviewed as a precaution against landslides. Limonite and saprolite materials have varying cohesion and phi values that affect the safety factor value. The probability function describes the distribution of a random variable to estimate the probability value of a parameter. The limit equilibrium method can indicate the probability of failure. The pit X slope is designed with a bench height of 10 meters, a bench width of 7 meters, and a single slope inclination of 45°, but after mining, the slope geometry and material distribution conditions change. Stability analysis of the pit X by comparing design and actual conditions after mining is conducted to determine the safety factor comparison under various soil conditions in both design and actual states. The analysis is performed using the Unified Soil Classification System (USCS) classification method and the Morgenstern-Price (MP) limit equilibrium method. All sections meet the slope stability criteria based on the minimum safety factor standards of 1.30 for static conditions, 1.10 for dynamic conditions, 1.0 for saturated soil conditions, and a probability of failure of <5%. However, based on the results of physical property tests, slope stability needs to be reviewed periodically due to the potential for landslides. Sections A-A' and D-D' have steeper overall slopes in the actual condition, resulting in lower safety factors than in the design condition. Sections B-B' and C-C' have gentler overall slopes in the actual condition, resulting in higher safety factors than in the design condition.

Keywords: Slope stability, landslide, limit equilibrium method, safety factor, overall slope

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1. Introduction

Nickel laterite is a high-value economic mineral material. The distribution of nickel ore and differences in the characteristics of soil and rock masses affect slope geometry, which impacts safety factors. Lateritic nickel deposits are mined while considering slope stability to ensure the ore extraction process follows mining engineering principles. Slope stability is a consideration in mining activities. Inappropriate pit slope geometry can cause slope failures. The potential impact of slope failures depends greatly on the type of soil and rock mass and the formed slope geometry [1].

Slope stability is a crucial concept in geotechnical engineering regarding the stability of natural and artificial slopes. Slope stability analysis involves calculating safety factors and is followed by the development of geotechnical computations. Various parameters such as slope geometry, physical data of geological materials, and shear strength factors, as well as pore water pressure, play significant roles in slope stability evaluation. Slope stability is also characterized by numerous uncertainties such as soil properties, loads, and water pressure [2]. The basic characteristics of soil determine the type of structure to be built, and external actions must be taken to ensure that the structure withstands earthquakes, water seepage, and other external factors [3].

The open-pit mining system uses the open-cast mining method, by cutting the side of the hill from the top downwards following its contour lines with shallow excavation depth. Stripping is done in a stepped form. There are three materials: limonite, saprolite, and bedrock. Limonite and saprolite are materials containing nickel ore with strengths almost approaching soil, while bedrock is a very hard base rock [4].

Nickel laterite mining on the slopes of Pit X uses the open-cast mining method with material strength conditions similar to soil. Slope stability considerations under temporary conditions, such as earthquakes and increased groundwater levels due to rain, need to be reviewed as a precaution against potential landslides. The physical properties of the soil significantly impact slope stability, but no previous studies have compared slope stability analysis with soil physical properties. Limonite and saprolite materials have varying cohesion and phi values influencing the resulting safety factor value. The

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higher the cohesion and internal friction angle value, the greater the safety factor. The probability distribution function describes the spread of a random variable to estimate the probability value of a parameter. The limit equilibrium method can indicate the probability of failure. The pit slope design includes a bench height of 10 meters, a bench width of 7 meters, and a single slope inclination 45˚. The slope of pit X in the actual mining condition experienced geometry changes due to mining activities. After mining, no analysis was done on the actual conditions.

Limit Equilibrium Analysis is a modern method widely used for slope stability analysis, utilizing the static equilibrium concept and disregarding the slope's stress-strain relationship. It analyzes the comparison between driving forces and resisting forces on the slope. The Morgenstern-Price method is one of the analysis methods based on the limit equilibrium principle, where the analysis process results from the equilibrium of each normal force and moment acting on every slice of the slope's slip surface. The equilibrium conditions that must be met include vertical and horizontal force equilibrium, as well as moment equilibrium. The factor of safety (FoS) provides information on whether the slope is stable or unstable [5]. The Monte Carlo simulation is a flexible method in probabilistic analysis that incorporates significant distribution variations without interpretation and easily models correlations between variables. In the Limit Equilibrium Method, where the FoS is the ratio of resisting forces to driving forces, each parameter is a random variable with uncertainty and a specific probability distribution. Therefore, Monte Carlo simulation is suitable for determining the probability of failure (PoF) from the limit equilibrium analysis [6].

Responding to issues both from plan design and actual conditions of pit slope X, it is considered necessary to conduct further analysis of slope stability. Therefore, a study entitled "Analysis of Slope Stability of Pit X on Nickel Mining Based on Comparison Between Design and Actual Mining Conditions" was conducted to avoid potential hazards that may occur.

2. Literatur Review

Slopes are portions of the Earth's surface that form a certain angle with the horizontal plane. Slopes can be formed naturally or by human activities. Naturally formed slopes include hillsides and riverbanks, while human-made slopes include excavations, embankments, levees, canal banks, and open-pit mine slopes [7].

The possibility of landslides occurring always exists on all types of slopes. Landslides occur when driving forces exceed resisting forces originating from the shear strength of the soil along the failure plane. Technically, it can be said that landslides occur when safety factors do not meet the criteria for each slope [8].

Table 1. The values of the safety factor and the probability of landslide in mining slope

Landslide type	Severity of Landslide	Acceptable Criteria		
		Static Safety Factor	Dynamic Safety Factor	Probability of Failure
Bench	Low	1.1	None	25 – 50%
	High			
Interramp	Low	1.15 – 1.2	1	25%
	Moderate	1.2	1	20%
	High	1.2 – 1.3	1.1	10%
Overall	Low	1.2 – 1.3	1	15 – 20%
	Moderate	1.3	1.05	5 -10%
	High	1.3 – 1.5	1.1	<5%

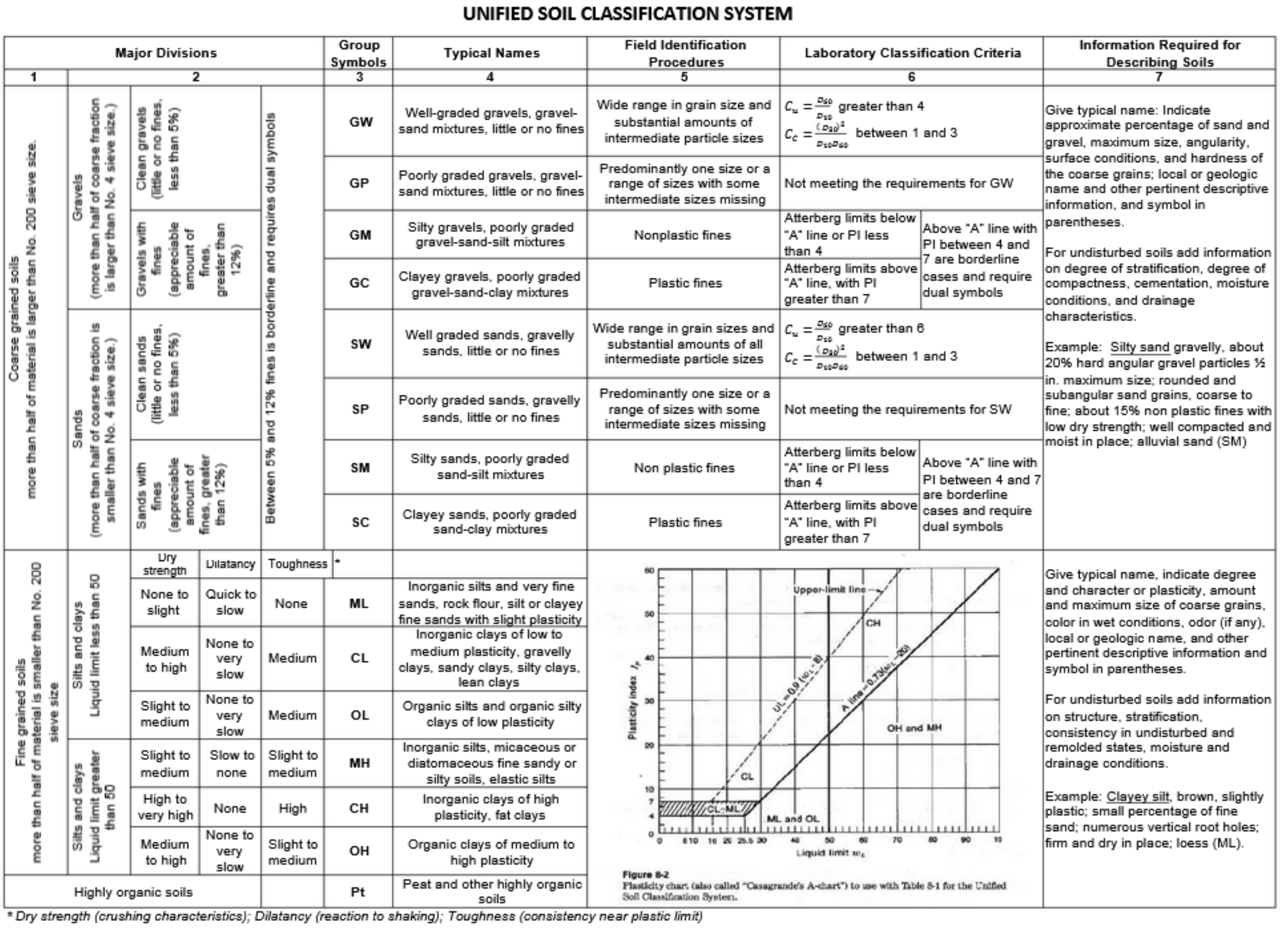
If the value of the safety factor (FK) for a slope is > 1.0 (resisting force > driving force), the slope is considered stable. However, if the value of FK < 1.0 (resisting force < driving force), the slope is considered unstable [6]. The design criteria for determining the stability condition of slopes using Ministry of Energy and Mineral Resources Regulation Number 1827 of 2018 can be seen in Table 1.

Natural and artificial slope failures occur due to changes in topography, seismic activity, groundwater flow, loss of strength, stress changes, seasons, climate, and weather. External forces acting on the materials forming the slope cause them to tend to slide. The tendency to slide can be resisted by the shear strength of the materials. A slope that has been stable for a long time can become unstable due to several factors such as the type and condition of the soil or rock layers forming the slope, slope geometry, increased water content in the soil (such as seepage or rainfall infiltration), weight and distribution of loads, and vibrations or earthquakes. Factors influencing slope stability can result in shear stress throughout the soil mass, and slope movement will occur unless the shear resistance on every potential failure surface exceeds the shear stress [9].

The Unified Soil Classification System (USCS), as shown in Fig. 1, first proposed by Casagrande and later developed by the United States Bureau of Reclamation (USBR), the United States Army Corps of Engineers (USACE), and subsequently the American Standard Testing of Materials (ASTM), has been adopted as the standard method for classifying soils. In the USCS soil classification system, soils are categorized into two main groups [3]:

1. Coarse-grained soils, consisting of gravel and sand, with less than 50% of the soil passing through a No. 200 sieve (F200 < 50). The group symbol begins with G for gravel or gravelly soil, or S for sand or sandy soil.
2. Fine-grained soils, with more than 50% of the soil passing through a No. 200 sieve (F200 ≥ 50).

The Limit Equilibrium method is highly popular in slope stability analysis. It is also known as the slice method because the failure surface of the slope is divided into several slices. The Limit Equilibrium method is expressed through equilibrium equations of one or several assumed undistorted blocks, which balance unknown forces (reactions from the stable rock mass or inter-block forces), particularly shear forces acting on the selected failure surface. These shear forces represent the entire section where shear strength is assumed to act. The stability condition of slopes using this method is expressed in terms of safety factor indices [1]



UNIFIED SOIL CLASSIFICATION SYSTEM

Major Divisions					Group Symbols	Typical Names	Field Identification Procedures	Laboratory Classification Criteria		Information Required for Describing Soils
1	2				3	4	5	6		7
Coarse grained soils more than half of material is larger than No. 200 sieve size.	Gravels (more than half of coarse fraction is larger than No. 4 sieve size.)	Clean gravels (little or no fines, less than 5%)		Between 5% and 12% fines is borderline and requires dual symbols	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Wide range in grain size and substantial amounts of intermediate particle sizes	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4 $C_c = \frac{(D_{30})^2}{D_{10}D_{60}}$ between 1 and 3		Give typical name: Indicate approximate percentage of sand and gravel, maximum size, angularity, surface conditions, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information, and symbol in parentheses. For undisturbed soils add information on degree of stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics. Example: Silty sand gravelly, about 20% hard angular gravel particles ½ in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% non plastic fines with low dry strength; well compacted and moist in place; alluvial sand (SM)
					GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing	Not meeting the requirements for GW		
		Gravels with fines (appreciable amount of fines, greater than 12%)			GM	Silty gravels, poorly graded gravel-sand-silt mixtures	Nonplastic fines	Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases and require dual symbols	
					GC	Clayey gravels, poorly graded gravel-sand-clay mixtures	Plastic fines	Atterberg limits above "A" line, with PI greater than 7		
	Sands (more than half of coarse fraction is smaller than No. 4 sieve size.)	Clean sands (little or no fines, less than 5%)			SW	Well graded sands, gravelly sands, little or no fines	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	$C_u = \frac{D_{60}}{D_{10}}$ greater than 6 $C_c = \frac{(D_{30})^2}{D_{10}D_{60}}$ between 1 and 3		
					SP	Poorly graded sands, gravelly sands, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing	Not meeting the requirements for SW		
		Sands with fines (appreciable amount of fines, greater than 12%)			SM	Silty sands, poorly graded sand-silt mixtures	Non plastic fines	Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases and require dual symbols	
					SC	Clayey sands, poorly graded sand-clay mixtures	Plastic fines	Atterberg limits above "A" line, with PI greater than 7		
Fine grained soils more than half of material is smaller than No. 200 sieve size	Silts and clays Liquid limit less than 50	Dry strength	Dilatancy	Toughness *			Figure 8-2 Plasticity chart (also called "Casagrande's A-chart") to use with Table 8-1 for the Unified Soil Classification System.			Give typical name, indicate degree and character or plasticity, amount and maximum size of coarse grains, color in wet conditions, odor (if any), local or geologic name, and other pertinent descriptive information and symbol in parentheses. For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. Example: Clayey silt, brown, slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess (ML).
		None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silt or clayey fine sands with slight plasticity				
		Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays				
		Slight to medium	None to very slow	Medium	OL	Organic silts and organic silty clays of low plasticity				
	Silts and clays Liquid limit greater than 50	Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts				
		High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays				
		Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity				
Highly organic soils					Pt	Peat and other highly organic soils				

** Dry strength (crushing characteristics); Dilatancy (reaction to shaking); Toughness (consistency near plastic limit)*

Figure 1. The unified soil classification system [3]

The Limit Equilibrium method calculates the safety factor by comparing the shear strength along the failure surface to the required force that can support the slope's equilibrium inclination. Shear failure can be expressed as a Mohr-Coulomb function with shear strength expressed as cohesion and friction angle [10]. Static equilibrium can be achieved in two ways. The first approach involves considering the equilibrium of the entire soil mass and then solving it for only the free body. The second approach divides the soil into many parts, and then each slice must satisfy the equilibrium condition for all forces [11].

The higher the values of cohesion and internal friction angle, the greater the factor of safety, as described in the Mohr-Coulomb equation, both in static and dynamic conditions. The shear strength of the material, which resists the material from causing a slope failure, is expressed in the Mohr-Coulomb failure criterion as follows [12]:

$$\tau = c' + (\sigma_n - u) \tan \emptyset \qquad (1)$$

where:

τ = Shear strength
c' = Effective cohesion
ϕ' = Effective friction angle
σ_n = Total normal stress
u = Pore water pressure

The probability distribution function describes the distribution of a random variable used to estimate the probability of occurrence of a parameter. The Limit Equilibrium method can indicate the Probability of Failure (PoF) value. The probability of a landslide can be defined as the ratio between the number of analyzed slope failures (FK < 1) and the total number of analyses (simulation samples), expressed as a percentage. The equation for the PoF function is [13]:

$$PoF = \frac{n\ FK{<}1}{n\ FK\ total}\, x\ 100 \qquad (2)$$

Monte Carlo simulation is a flexible method in probabilistic analysis that combines a significant distribution variation without interpretation and the ability to easily model correlations between variables. The Limit Equilibrium Method, where the value of FK represents the ratio of resisting forces to driving forces, each parameter being an uncertain random variable with a specific probability distribution. Therefore, the use of Monte Carlo simulation is suitable for determining the PoF value from Limit Equilibrium Analysis [6].

3. Research Method

The data collection technique for this research involves gathering topographic data, which is used to draw several sections or cross-sections of the pit under study. Material data composing the slope, physical property test data, and groundwater table data are also collected. Groundwater table data, based on drilling data, indicate a reference point of 12.5 meters for the initial placement of the groundwater table from the top of the limonite. However, several considerations need to be taken into account, such as the distance from the bedrock and the angle of the formed groundwater table. Data processing includes CU+PWP test results and physical property data such as moisture content, specific gravity, sieve analysis, Atterberg limits, and hydrometer test results. Vulcan software is utilized to process material distribution data, while Geostudio SLOPE/W is used to analyze slope stability.

The soil samples collected are obtained from drilling samples. Soil samples for physical property testing in the laboratory are obtained using Standard Penetration Test samples. Sample preparation is adjusted according to the equipment standards and testing protocols of ASTM system. The moisture content test determines the soil's water content percentage. Moisture content is the ratio of the weight of water in the soil to the total weight of the soil. The specific gravity test is performed to determine the soil's density that passes through a No. 10 sieve using a pycnometer. Soil-specific gravity is the ratio of the weight of soil grains to the weight of distilled water in the air with the same volume at a certain temperature. Sieve analysis and hydrometer tests are conducted to determine the particle size distribution of the soil for soil grain size distribution and classification. Particle size distribution larger than 0.075 mm is determined by sieve analysis, while particle size distribution smaller than 0.075 mm is determined by hydrometer analysis. The purpose of these tests is to determine the values of the liquid limit, plastic limit, and plasticity index in determining the consistency limits of the soil.

The slope stability analysis uses the Morgenstern-Price Limit Equilibrium Method in 2D using the Geostudio SLOPE/W software. The Morgenstern-Price method is chosen because it employs varied assumptions to calculate the resultant forces between slices. The analysis is performed by extracting section designs from the Vulcan software. These designs contain information about the slope geometry, including the slope height based on the Actual topography, overall slope, and individual slopes. The determination of the groundwater level angle based on the overall slope formed is made by calculating the angle from

The initial point at the top of the slope to the toe of the saprolite. The determining the water table. Here is a general approach based on such a reference:

$$a = tan^{-1}(0.65\ tan\ b) \tag{3}$$

where:

a = Water table slope angle (˚)
b = Overall slope angle (˚)

4. Results and Discussion

4.1. The Result of laboratory test data processing

4.1.1. The results of the physical properties test

The data from the physical property tests include moisture content, specific gravity, sieve analysis, Atterberg limits, and hydrometer test, as shown in Table 2.

Table 2. The results of the physical properties test

Height (m)	*Liquid Limit* (%)	*Plastic Limit* (%)	*Indeks Plastic* (%)	*Water content* (%)	*Sand* (%)	*Silt* (%)	*Clay* (%)	*Specific Gravity* (Mg/m^3)
1.55-2	63.19	46.17	17.02	81.40	1.00	88.00	11.00	3.51
3.55-4	84.04	65.16	18.88	69.47	5.90	77.00	17.10	2.80
6-6.45	74.37	51.34	23.03	44.49	2.10	81.40	16.50	3.29
8-8.45	89.67	64.48	25.19	74.83	1.30	87.50	11.20	3.36
11-11.45	75.86	63.36	12.50	75.17	6.30	77.80	15.80	2.62
13-13.45	84.69	57.91	26.78	95.01	1.50	96.00	2.50	3.24
15-15.45	77.84	70.57	7.27	84.68	2.40	86.30	11.30	3.24
17-17.45	63.52	47.43	16.09	80.92	4.20	88.20	7.60	3.22
19-19.45	81.75	59.85	21.90	77.99	1.30	96.20	2.50	3.19
21-21.45	90.80	74.99	15.81	88.32	3.30	86.00	10.70	2.55
23-23.45	119.92	75.31	44.61	85.26	2.80	96.50	0.70	3.12
27-27.45	73.25	42.13	31.12	53.56	6.10	85.00	8.90	3.40

Based on the results of the physical properties test for the soil type, which is silt, the average moisture content is 75.93%, indicating that the moisture content at Pit X is high. This suggests that during rainfall, water will overflow, and there is potential for landslides. The reason is that as the moisture content in the soil increases, the driving force of the soil also becomes stronger. The liquid limit test results show that the soil has high plasticity. High moisture content can cause an increase in pore pressure, a decrease in shear strength, a high swelling factor, and the formation of an interface zone.

The physical properties test data should be considered for slope monitoring because there is still potential for landslides at Pit X. Heavy rainfall causes the soil to absorb water, reducing cohesion and increasing the total weight of the soil mass. This condition makes the soil more prone to landslides. Water infiltrating the soil will increase pore water pressure, reducing the effective strength of the soil and making it more likely to collapse. Slopes exposed to continuous rainfall may deform or crack, potentially triggering larger landslides.

4.1.2. The results of the mechanical properties test

The soil mechanical properties data for slope stability analysis in Geostudio SLOPE/W software refers to the Final Geotechnical Report Engineering for Slope Geometry Based on Updated Parameters at Pit X. This includes the results of the CU+PWP triaxial test, which consists of values for cohesion, phi (friction angle), and unit weight obtained from undisturbed samples, as shown in Table 3.

Table 3. The results of the mechanical properties test

Material	Material Model	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction angle (^{0})
Limonite	Mohr-Coulomb	16.00	10.00	35.00
Saprolite	Mohr-Coulomb	17.00	15.00	35.00
Peridotite	High strength	22.00	-	-

Table 4. Input standard deviation value

Input Material	Standard Deviation	Minimum	Maximum	Mean
Limonite friction angle	1.78	30.99	40.08	35
Limonite cohesion	2.53	10	15	10
Saprolite friction angle	4.71	20.91	40.55	35
Saprolite Cohesi	12.26	7.56	18.52	15

4.2. The results of slope stability

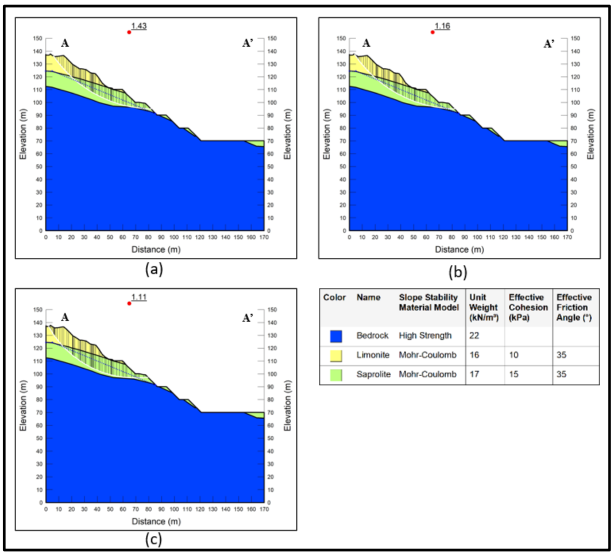
The slope stability analysis of pit X is conducted by comparing the planned design slope condition to the condition after mining activities in 4 sections for each condition based on reference safety factor values and landslide probability. The safety factor values used are a minimum of 1.30 for static conditions, 1.10 for dynamic conditions, and a maximum landslide probability of 5%, referring to the Ministry of Energy and Mineral Resources Regulation Number 1827 of 2018, as shown in Table 1. A safety factor of 1.0 for saturated soil conditions refers to the safety factor value set by pit X.

4.2.1. The results of plan design slope stability analysis

The input analysis used refers to the material data composing the slope and groundwater table. For dynamic conditions, a value of 0.2g is used based on the maximum hazard value for bedrock movement from the Indonesian earthquake hazard map 2017, with a return period of 50 years. For saturated soil conditions, a value of Ru 0.2 is used, derived from the average value observed at the research site. The landslide probability analysis utilizes the standard deviation from 2,000 data points, which were then statistically analyzed by pit X. The used standard deviation values can be seen in Table 4.

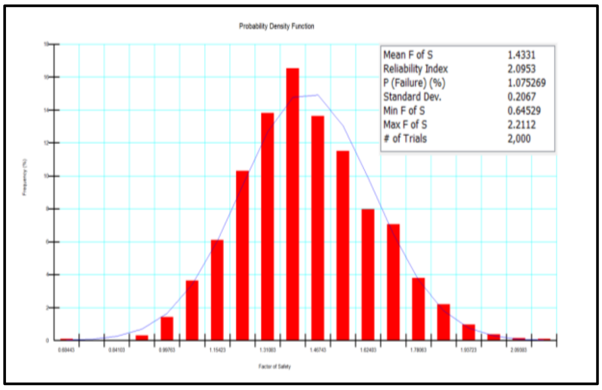
1. Section A-A’

The results of the slope stability analysis in the design condition of section A-A' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 2. Based on the simulation results for various soil conditions with an overall slope of 31.19˚, forming a water table angle of 21.48˚ from Eq. 3, it is obtained that section A-A' has a safety factor value for the static condition of 1.43, for the dynamic condition of 1.16, and for the saturated condition of 1.11. Based on the results of 2,000 simulation safety factors, the landslide probability value yields a PoF value of 1.07%, meaning there is a 1.07% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 3.



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟦	Bedrock	High Strength	22		
🟨	Limonite	Mohr-Coulomb	16	10	35
🟩	Saprolite	Mohr-Coulomb	17	15	35

Figure 2. Safety factor for section A-A' design: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition



Mean F of S	1.4331
Reliability Index	2.0953
P (Failure) (%)	1.075269
Standard Dev.	0.2067
Min F of S	0.64529
Max F of S	2.2112
# of Trials	2,000

Figure 3. Probability density function section A-A’ design

All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

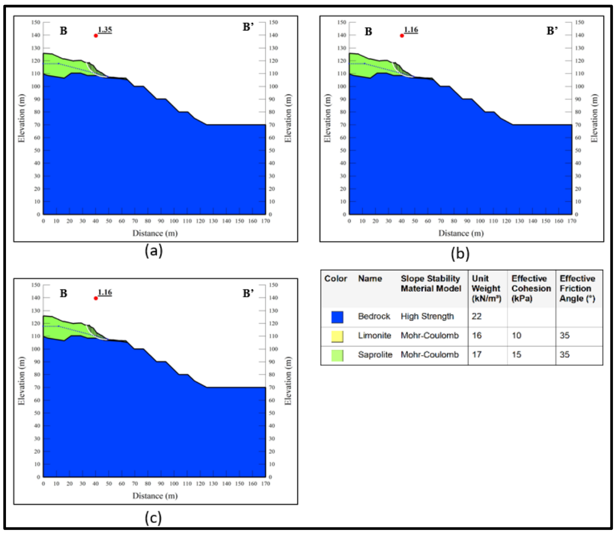
2. Section B-B’

The results of the slope stability analysis in the design condition of sections B-B' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 4.

Based on the simulation results for various soil conditions with an overall slope of 37.74˚, forming a water table angle of 26.71˚ from Equation 3, it is obtained that section B-B' has a safety factor value for the static condition of 1.35 for the dynamic condition of 1.16, and for the saturated condition of 1.16. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 2.7%, meaning there is a 2.7% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 5. All analysis results meet the slope stability criteria. Still, based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

3. Section C-C’

The results of the slope stability analysis in the design condition of section C-C' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 6.



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟦	Bedrock	High Strength	22		
🟨	Limonite	Mohr-Coulomb	16	10	35
🟩	Saprolite	Mohr-Coulomb	17	15	35

Figure 4. Safety factors for section B-B' design: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

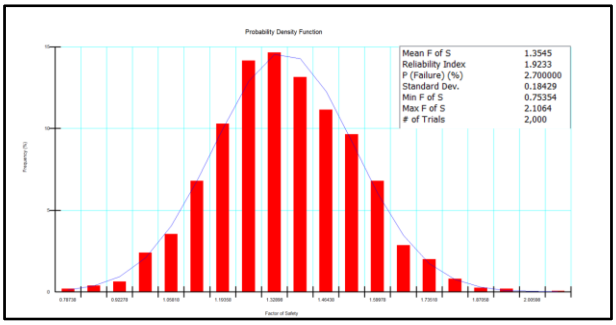
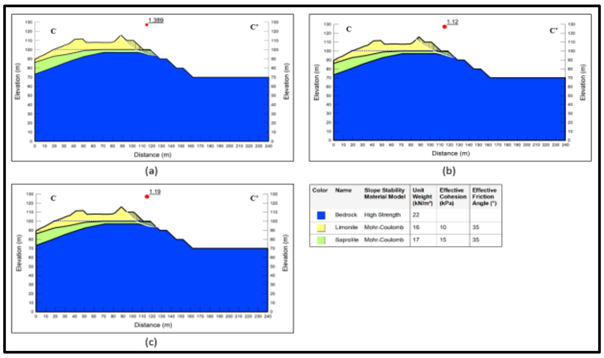


Figure 5. Probability density function section B-B’ design



(a)

(b)

(c)

Figure 6. Safety factor for section C-C' design: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

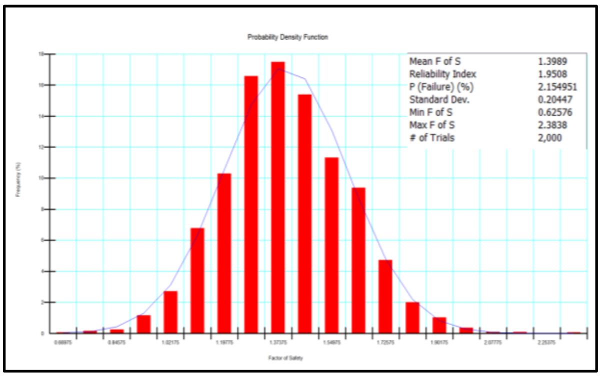
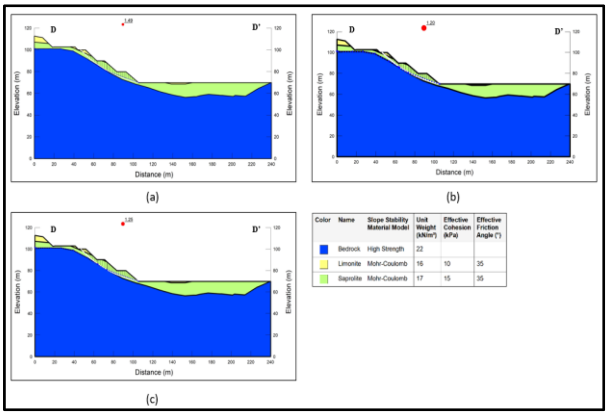


Figure 7. Probability density function section C-C’ design

Based on the simulation results for various soil conditions with an overall slope of 32.03˚, forming a water table angle of 22.12˚ from Equation 3, it is obtained that section C-C' has a safety factor value for the static condition of 1.389 for the dynamic condition of 1.12, and for the saturated condition of 1.19. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 2.15%, meaning there is a 2.15% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 7. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

4. Section D-D’

The results of the slope stability analysis in the design condition of sections D-D' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 8.



(a)

(b)

(c)

Figure 8. Safety factors for section D-D' design: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

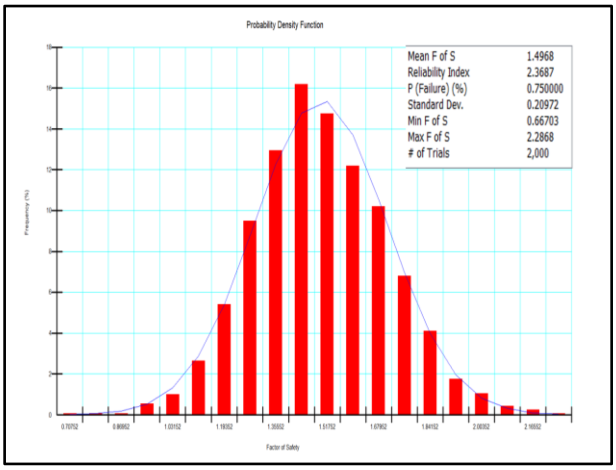


Figure 9. The probability density function section D-D’ design

Based on the simulation results for various soil conditions with an overall slope of 27.04˚, forming a water table angle of 18.35˚ from Equation 3, it is obtained that section D-D' has a safety factor value for the static condition of 1.49 for the dynamic condition of 1.20, and for the saturated condition of 1.25. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 0.75%, meaning there is a 0.75% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 9. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

4.2.2 The results of actual slope stability analysis

The actual condition of slope pit X has undergone changes in slope geometry due to mining activities affecting the overall slope formed. The input analysis used refers to the material data composing the slope and groundwater table. For dynamic conditions, a value of 0.2g is used based on the maximum hazard value for bedrock movement from the Indonesian earthquake hazard map 2017 with a return period of 50 years. For saturated soil conditions, a value of Ru 0.2 is used, derived from the average value observed at the research site. The landslide probability analysis utilizes the standard deviation from 2,000 data points, which were then statistically analyzed by pit X. The standard deviation values used for analysis can be seen in Table 4.

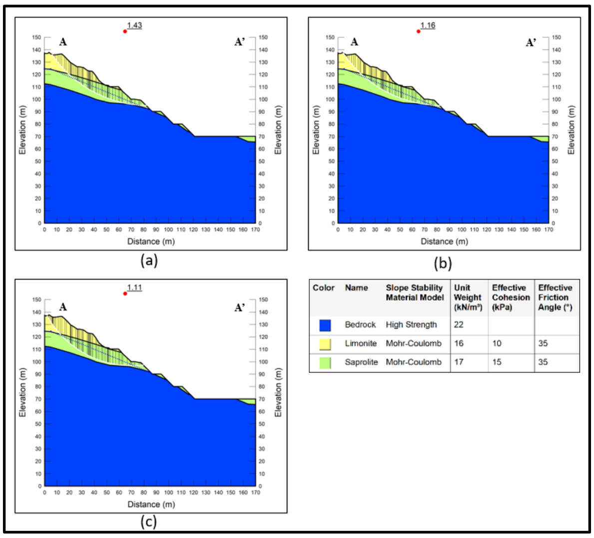
1. Section A-A’

The results of the slope stability analysis in the actual condition of sections A-A' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 10.

Based on the simulation results for various soil conditions with an overall slope of 32.29˚, forming a water table angle of 22.33˚ from Equation 3, it is obtained that section A-A' has a safety factor value for the static condition of 1.36 for the dynamic condition of 1.10, and for the saturated condition of 1.03. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 2.47%, meaning there is a 2.47% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 11. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

2. Section B-B’

The results of the slope stability analysis in the actual condition of sections B-B' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 12.



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟦	Bedrock	High Strength	22		
🟨	Limonite	Mohr-Coulomb	16	10	35
🟩	Saprolite	Mohr-Coulomb	17	15	35

Figure 10. Safety factor for section A-A' actual: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

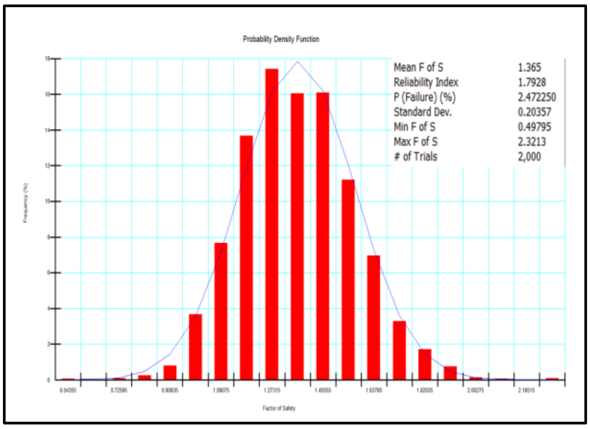
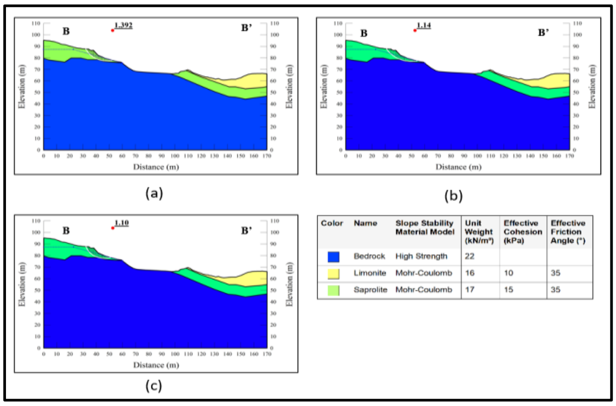


Figure 11. Probability density function section A-A’ actual



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟦	Bedrock	High Strength	22		
🟨	Limonite	Mohr-Coulomb	16	10	35
🟩	Saprolite	Mohr-Coulomb	17	15	35

Figure 12. Safety factor for section B-B' actual: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

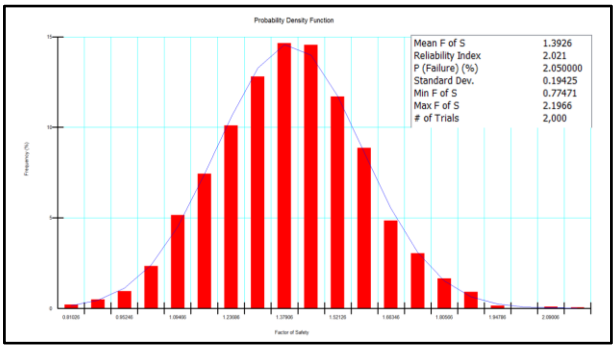
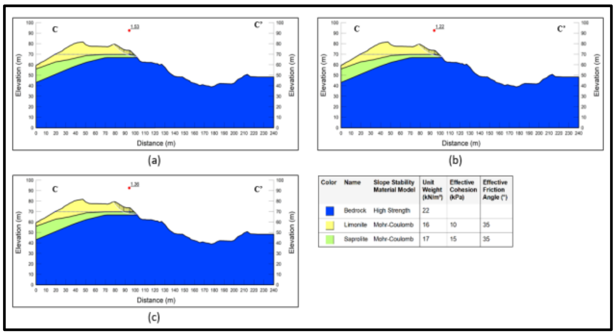


Figure 13. Probability density function section B-B’ actual

Based on the simulation results for various soil conditions with an overall slope of 26.47˚, forming a water table angle of 17.93˚ from Equation 3, it is obtained that section B-B' has a safety factor value for the static condition of 1.392 for the dynamic condition of 1.14, and for the saturated condition of 1.10. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 2.05%, meaning there is a 2.05% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 13. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

3. Section C-C’

The results of the slope stability analysis in the actual condition of section C-C' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 14.



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
🟦	Bedrock	High Strength	22		
🟨	Limonite	Mohr-Coulomb	16	10	35
🟩	Saprolite	Mohr-Coulomb	17	15	35

Figure 14. Safety factor for section C-C' actual: (a) Static condition, (b) Dinamic condition, and (c) Saturated condition

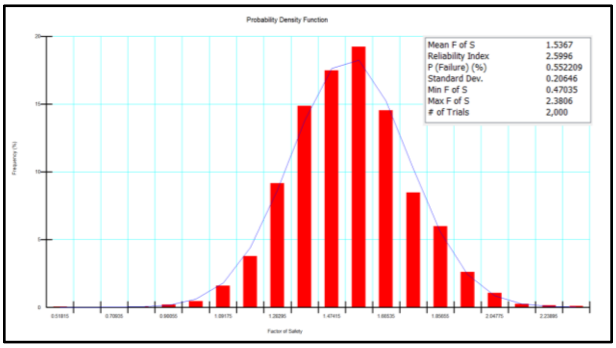


Figure 15. Probability density function section C-C’ actual

Based on the simulation results for various soil conditions with an overall slope of 29.34˚, forming a water table angle of 20.07˚ from Equation 3, it is obtained that section C-C' has a safety factor value for the static condition of 1.53, for dynamic condition of 1.22, and for the saturated condition of 1.36. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 0.55%, meaning there is a 0.55% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 15. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

4. Section D-D’

The results of the slope stability analysis in the design condition of sections D-D' using the Limit Equilibrium Method (LEM) based on Geostudio SLOPE/W can be seen in Fig. 16.

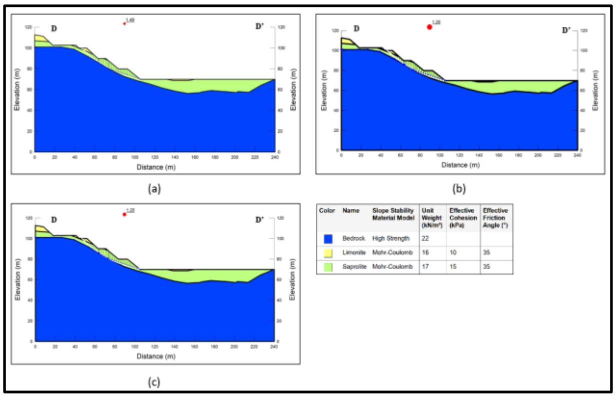


Figure 16. Safety factor for section D-D' actual: (a) Static condition, (b) Dynamic condition, and (c) Saturated condition

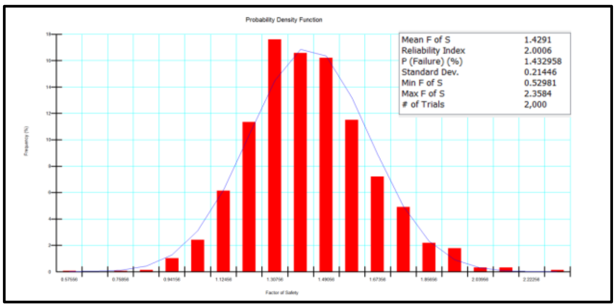


Figure 17. Probability density function section D-D’ actual

Table 5. Results of all slope stability analysis

Section	FK Static	FK PGA	FK Saturated	Probability of Failure (%)	Overall Slope (˚)
A - A’ Design	1.43	1.16	1.11	1.07	31.19
A - A’ Actual	1.36	1.10	1.03	2.47	32.29
B - B’ Design	1.35	1.16	1.16	2.7	37.74
B - B’ Actual	1.392	1.14	1.10	2.05	26.47
C - C’ Design	1.389	1.12	1.19	2.15	32.03
C - C’ Actual	1.53	1.22	1.36	0.55	29.34
D - D’ Design	1.49	1.20	1.25	0.75	27.04
D - D’ Actual	1.42	1.15	1.12	1.43	29.69

Based on the simulation results for various soil conditions with an overall slope of 29.69˚, forming a water table angle of 20.44˚ from Equation 3, it is obtained that section D-D' has a safety factor value for the static condition of 1.42, for dynamic the condition of 1.15, and for the saturated condition of 1.12. The landslide probability value based on the results of 2,000 simulation safety factors yields a PoF value of 1.43%, meaning there is a 1.43% probability of safety factors falling below 1 from the conducted simulations, as shown in Fig. 17. All analysis results meet the slope stability criteria, but based on the physical property data, slope stability needs to be monitored due to the potential for landslides.

Based on the results of the slope stability analysis for both design and actual conditions in Table 5, it can be observed that the factor of safety values is influenced by the overall slope formed at the same sections. The flatter the slope, the higher the factor of safety obtained, as the resisting forces are greater and the driving forces are smaller. Section A-A’ in the actual condition has a steeper overall slope compared to the design condition, resulting in a lower factor of safety. Section B-B’, on the other hand, has a flatter overall slope in the actual condition, leading to a higher factor of safety. Similarly, Section C-C’ also has a flatter overall slope in the actual condition, which results in a greater factor of safety. Conversely, Section D-D’ has a steeper overall slope in the actual condition, resulting in a lower factor of safety.

The probability of failure using Monte Carlo simulation is employed to determine the percentage likelihood of landslides based on unsafe conditions (SF < 1.0) against the overall factor of safety using the limit equilibrium method. The probability of landslide occurrence is inversely proportional to the factor of safety obtained; the higher the factor of safety, the lower the potential for landslides. Factors contributing to the slope becoming flatter or steeper in the actual condition include discrepancies in the block model compared to the actual conditions, the presence of high-grade ore in the actual final plan leading to overcutting, and planning priorities that affect the relocation of equipment.

Recommendations from the analysis for maintaining long-term slope stability include conducting routine monitoring of groundwater level changes, slope movements, and signs of deformation such as cracks or changes in soil structure. The importance of regular monitoring allows for early detection of changes in conditions that could lead to landslides, enabling mitigation measures to be implemented before significant failures occur, thus ensuring the safety of mining operations efficiently. Regular slope stability analyses should be conducted, considering weather conditions, changes in groundwater levels, and additional loads such as mining activities. The existing drainage systems should be properly maintained to ensure that rainwater can be efficiently diverted without causing water accumulation around the slope.

5. Conclusion

Based on the analysis results of pit X under actual mining conditions and design plan, it can be concluded that:

1. The slope stability analysis results under both design and actual conditions, considering various slope conditions using the limit equilibrium method, indicate that all sections meet the stability criteria based on the minimum safety factor standards for different slope conditions: 1.30 for static condition, 1.10 for dynamic condition, and 1.0 for saturated soil condition. However, regular monitoring of slope stability is necessary based on the results of physical property tests due to the presence of landslide potential.
2. The slope stability analysis results based on the probability of failure values under both design and actual conditions using the limit equilibrium method indicate that all sections meet the stability criteria based on the minimum probability of failure standard of less than 5%. Nevertheless, periodic review of slope stability is required based on the results of physical property tests due to the potential for landslides.
3. Comparison of the slope stability analysis results between the design and actual conditions shows that Sections A-A’ and D-D’ have a steeper overall slope in the actual condition, resulting in a lower factor of safety compared to the design condition. In contrast, Sections B-B’ and C-C’ have a flatter overall slope in the actual condition, leading to a higher factor of safety than in the design condition. The factors contributing to the slope becoming flatter or steeper in the actual condition include discrepancies in the block model compared to the actual conditions, the presence of high-grade ore in the actual final plan leading to overcutting, and planning priorities that affect the relocation of equipment.

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