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Slope Stability Analysis Using the Probability of Failure Approach at PT. Kencana Bumi Mineral Nickle Mine in Morowali Regency Central Sulawesi Province

Hamka Jaya[1], Sriyati Ramdhani[2], Astri Rahayu[3]
*[*1]Department of Civil Engineering, Tadulako University, Central Sulawesi, Indonesia*
[2]Department of Civil Engineering, Tadulako University, Central Sulawesi, Indonesia
[3]Department of Civil Engineering, Tadulako University, Central Sulawesi, Indonesia
Corresponding Author: Hamka Jaya

Abstract
Nickel laterite deposits are economically valuable and widely distributed in eastern Indonesia. The latest Ministerial Decree number 1827.K/30/MEM/2018, requires IUP holders to conduct geotechnical studies in support of the planning and implementation of mining activities to be carried out, including slope stability analysis that refers to the safety factor and probability of failure. PT Kencana Bumi Mineral is one of the Nickel commodity IUP holders located in Bahodopi District, Morowali Regency, Central Sulawesi Province.
The purpose of this thesis is to determine the characteristics of nickel deposits, analyze the planned slope geometry and redesign the optimum slope geometry at PT Kencana Bumi Mineral. Soil material data were obtained from laboratory tests. Data analysis used the limit equilibrium method with the software Slide6.0 and probability analysis using the Monte Carlo method and adjusted to the new regulation of the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018.
The results of this thesis show that the characteristics of nickel deposits in the study area are the result of weathering of Ultramafic rocks with nickel ore content varied from 0.67-1.27% for limonite zone while variations in nickel ore content for the saprolite zone are 1.07% - 2.37% . The results of the analysis in the existing state obtained unsafe slopes in the overall slope and single slope analysis both static and dynamic conditions. The factor of safety value was obtained <1 and the probability of failure reached 100%. So that the slope geometry redesign is needed. The redesign was made by changing the overall slope angle to20o, the single slope angle to 30^o and 40^o, and the bench width to 6 m. The results of the redesign analysis showed that the slope was safe in the overall slope and single slope analysis in both static and dynamic conditions characterized by a safety factor value >1.1 and the largest probability of failure was only 23.50%.
Keywords: *Factor of Safety, Probability of Failure, PT Kencana Bumi Mineral, Limit Equilibrium Method, Monte Carlo Method.*

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I. INTRODUCTION

Lateritic nickel deposits are economically valuable and widely distributed in eastern Indonesia. As a non-renewable resource, the enormous potential of nickel will one day run out. Therefore, the management of nickel resources must be carried out through the application of good mining principles to obtain the most optimal benefits for the advancement of development and the welfare of the Indonesian people. The Ministry of Energy and Mineral Resources issued Ministerial Decree number 1827.K/30/MEM/2018 concerning Guidelines for the Implementation of Good Mining Engineering Rules. This Ministerial Decree issued in 2018 is a technical guideline guided by the government in carrying out guidance and supervision activities on mining business activities carried out by Mining Business License (IUP) owners, as well as guidelines for Mining Business License (IUP) owners in carrying out mining business activities in accordance with the principles of good mining management. Ministerial Decree number 1827.K/30/MEM/2018 replaces Minister of Mining and Energy Decree number 555.K/26/M.PE/1995.

The latest Ministerial Decree number 1827.K/30/MEM/2018, requires IUP holders to conduct geotechnical studies to support the planning and implementation of mining activities. The study must contain a slope stability analysis that must refer to the safety factor and landslide probability of the mine slope [5]. This is different from the provisions stipulated in the previous Ministerial Decree, namely the Decree of the Minister of Mining and Energy number 555.K/26/M.PE/1995 where the provisions related to slope stability only refer to the safety factor of mining slopes.

PT Kencana Bumi Mineral is one of the Nickel Mining Company located in Bahodopi District, Morowali Regency, Central Sulawesi Province with an area of 2,549 Ha. In addition to being granted a license to carry out nickel mining activities, PT Kencana Bumi Mineral is of course also obliged to implement good mining practices as mandated by the applicable laws and regulations.

The slope stability analysis that has been carried out previously by PT Kencana Bumi Mineral still refers to the old regulations, which uses the Safety Factor in determining whether the slope is safe or not. Meanwhile, according to the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018, the determination of whether a slope is safe or not is based on the Factor of Safety (FS) and Probability of Failure (PoF). Therefore, it is necessary to recalculate and re-analyze the geometry of the planned slope.

1.1 Regional Geology

The Regional Geology of the study area is included in the Bungku Sheet Geology divided into five units, namely mountainous morphology, midland morphology, lowland morphology, undulating hilly morphology and karst morphology [6]. Mountain morphology occupies almost half of the sheet area, namely the mountains around the ridge of Bulu Karoni water separator which is northwest - southeast, and the ridge of Wawoombu water separator which is southwest - northeast. The midland morphology occupies the area around Tokalimbu and Tosea villages on the eastern shore of Lake Towuti, and the area between Lake Mahalona and Bulu Biniu. Lowland morphology generally has an altitude between 0-50 m above sea level. Undulating hilly morphology, with elevations between 100 and 400 m above sea level. Karst morphology, has an altitude between 400 and 800 m above sea level, characterized by the presence of rough hills, and underground rivers.

Rock units in the Bungku sheet can be grouped and placed in two mandalas, namely the Banggai Sula Mendala and the East Sulawesi Mendala. The East Sulawesi mandala includes the ultramafic complex (Ku) which is still considered the oldest in age. The rocks consist of harzburgite, lherzolite, wehrlit, websterlit, serpentinite, dunite and gabbro [6].

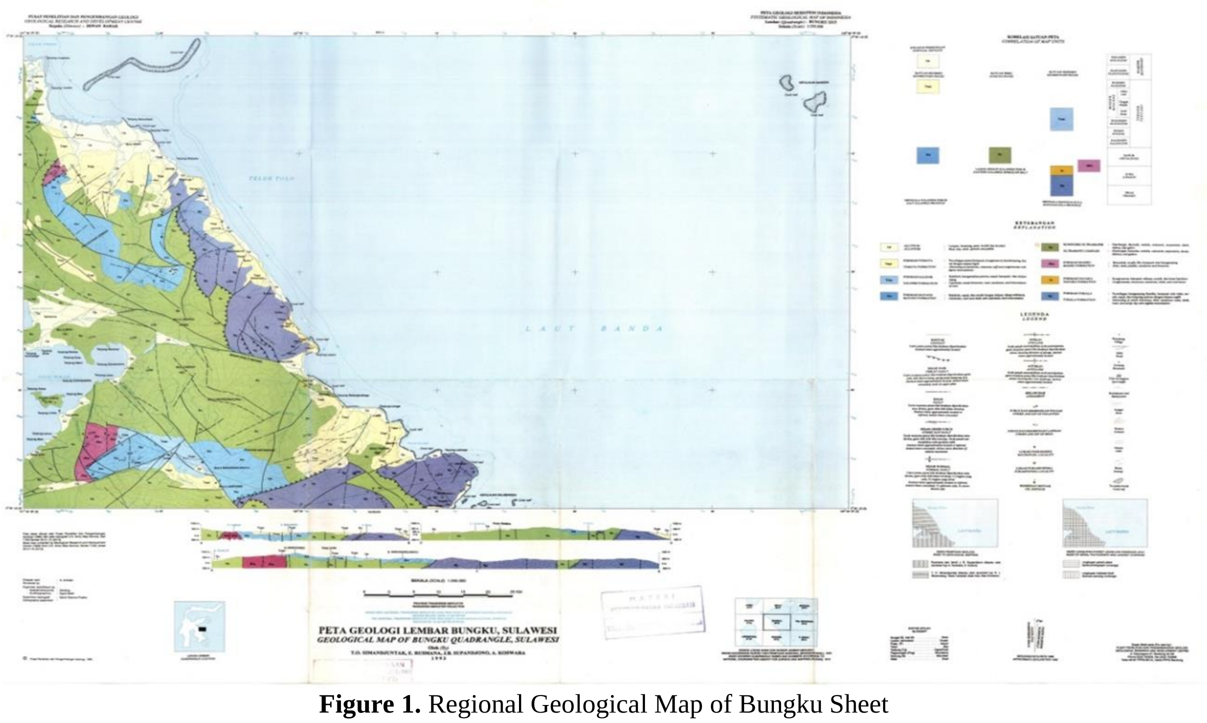

Figure 1. Regional Geological Map of Bungku Sheet

1.2 Analysis of Slope Stability with Limit Equilibrium Method

Limit equilibrium is a method that calculates the restraining forces and loads by dividing the avalanche plane into several discrete pieces, so that the horizontal, vertical, and moment forces acting on each piece can be calculated [2]. Limit equilibrium analysis is a method of analyzing the balance of a potentially moving mass by comparing the driving force and the restraining force along the landslide plane. The comparison of the two forces will produce a safe factor (FS) value of the slope, with the equilibrium limit condition will be achieved when the FS value = 1 [3].

$$Fs = \frac{retaining\ force}{driving\ force} = \frac{R_c + R_\phi}{S} = \frac{c_A + W\cos\psi\, P\tan\phi}{W\sin\psi p}$$

1.3 Probability of Failure

Probabilistic analysis is an alternative that strengthens the FS value with the indicator of the probability of failure (PoF) value. In probabilistic analysis, the input values are random variables, therefore the safety factor value as the ratio between the restraining force and the driving force is also a random variable [1]. The probability of failure (PoF) is calculated as the ratio of the area on the PoF < 1 distribution divided by the total area on the probability distribution curve [1].

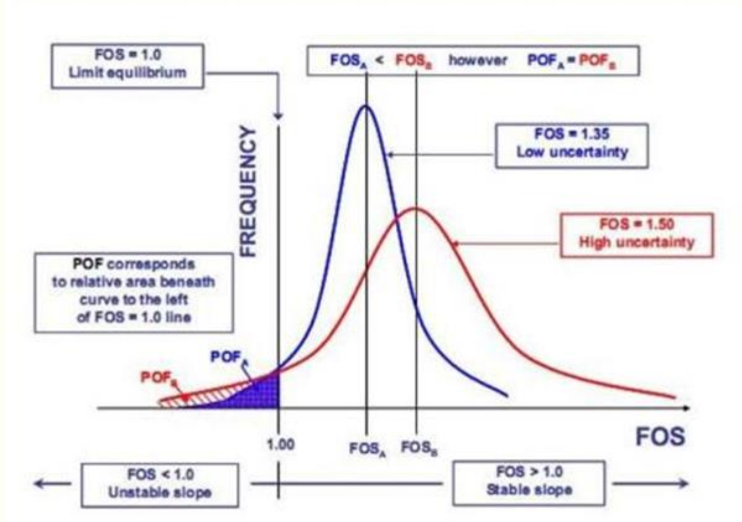

Figure 2. Concept Probability of Failure [1].

The Monte Carlo method is a simple probabilistic analysis method, more flexible in combining a large variety of probability distributions without much interpretation, and the ability to easily model correlations between variables [4].

The government through the Decree of the Minister of Energy and Mineral Resources number 1827 K/30/MEM/2018 has determined the factor of safety (FS) value and probability of failure (PF) on mine slopes [5], as can be seen in the following table.

Table 1. Factor of Safety Value and Probability of Failure on Mine Slope

Slope Types	Consequences of Failure/ CoF	Acceptance Criteria		
		Factor of Safety (FS) Static (Min)	**Factor of Safety (FS) Dynamic (Min)**	**Probability of Failure) (Maks) PoF (FK≤1)**
Single Slope	Low – High	1,1	None	25-50%
Inter-ramp	Low	1,15 – 1,2	1,0	25%
	Medium	1,2 – 1,3	1,0	20%
	High	1,2 – 1,3	1,1	10%
Overall Slope	Low	1,2 – 1,3	1,0	15-20%
	Medium	1,3	1,05	10%
	High	1,3 – 1,5	1,1	5%

1.4 Seismic Load

Seismic loads on slope stability act in two directions, horizontal and vertical. However, for the vertical direction, the contribution to slope stability is very small, so only the load in the horizontal direction will be used [7]. Determination of the amount of seismic force can be done by knowing the peak ground acceleration obtained from the Indonesia 2021 Spectra Design Application, by entering the location coordinates of PT Kencana Bumi Mineral. The result obtained from the spectra design application is the peak ground acceleration.

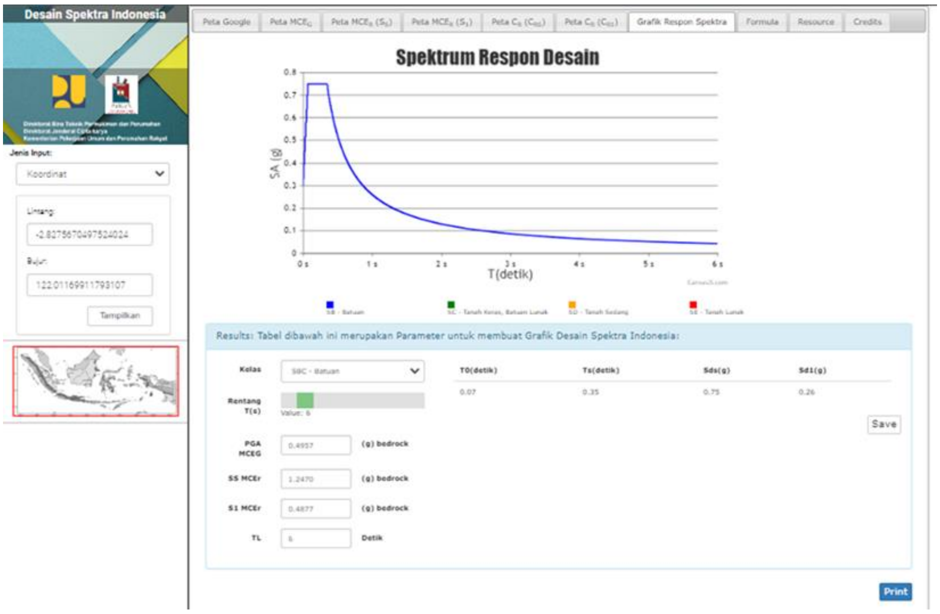

Figure 3. Design Response Spectrum of the Research Area

The calculation of the peak ground acceleration value based on the site class can be done using the following equation.

$$PGA_M = PGA \times F_{PGA}$$

PGA_M is the peak ground acceleration value based on the site class, PGA is the mapped peak ground acceleration while F_{PGA} is the coefficient based on Table 2.

Table 2. Coeficient of Site F_{PGA}

Site Class	PGA ≤ 0,1	PGA = 0,2	PGA = 0,3	PGA = 0,4	PGA = 0,5	PGA ≥ 0,6
SA	0,8	0,8	0,8	0,8	0,8	0,8
SB	0,9	0,9	0,9	0,9	0,9	0,9
SC	1,3	1,2	1,2	1,2	1,2	1,2
SD	1,6	1,4	1,3	1,3	1,1	1,1
SE	2,4	1,9	1,6	1,4	1,2	1,1
SF			SS[a]			

Based on the equation for analyzing the safety number in the wedge method with analysis variables are the cohesion value (c), the length of the collapse line of the wedge (Ln), the weight of the wedge (Wn), the angle of inclination of the wedge to the center of the circle (an), the earthquake coefficient (Kh), and the radius of the circle (R) shown in the following equation:

$$FK = \frac{\sum_{n=1}^{P}(c.L_n.seca_n + W_n cosa_n tan\varphi)}{\sum_{n=1}^{P}\left(W_n sina_n + K_h\left(\frac{L_n}{R}\right)\right)}$$

The Kh value in the above formula is obtained where Kh is the horizontal seismic coefficient, ad is the seismic acceleration and g is the gravitational acceleration.

$$K_h = 0{,}5\left(\frac{a_d}{g}\right)$$

II. THE SIMULATION

This research uses a combined case study methodology approach of quantitative and qualitative methods. Starting from the collection of research data including geological data, geotechnical drilling data, drill log data, geological maps, topographic maps, slope aspect of nickel laterite deposit location slope and rock discontinuity to classify the rock mass to be carried out. The data for this research in the form of geotechnical investigation results were obtained from PT Kencana Bumi Mineral in the PT Kencana Bumi Mineral Nickel Laterite Mining Proposal Study Document. The slope section location of research area can be seen in Figure 4 below.

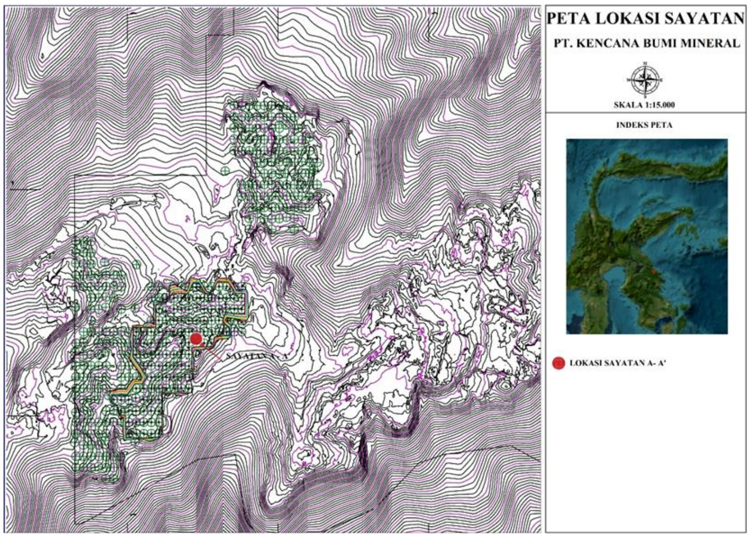

Figure 4. Map of Slope Section Location

After obtaining data on the properties of slope materials, geotechnical investigation data and slope aspect data, then processing and analyzing the data is carried out. The data analysis is carried out by analyzing the classification of rock mass with the aim of knowing the classification of slope building materials based on geotechnical drilling results. Analysis of slope stability and probability of failure is carried out by inputting soil property data and numerical simulation analysis of slope stability. The slope cross section was obtained from the slope geometry and topographic map of the study area to illustrate the dimensions of the mine slope. The slope cross section is then combined with the thickness of each material type (overburden, limonite, saprolite, and bedrock) in meters based on the results of geotechnical drilling and exploration drilling at several different locations. The slope stability analysis stage will be supported by Slide6.0 software and for the analysis of the probability of failure will use the Monte Carlo method. In addition, an optimum slope geometry analysis will be conducted to obtain a slope geometry that can be implemented to the minimum standards of the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018.

III. RESULT AND DISCUSSION

3.1 Nickel Characteristics

Based on field observations, the mapping results of blocks A, B, C, D and E of PT Kencana Bumi Mineral found that the laterite nickel distribution pattern is the result of weathering of Ultramafic (Laterite) rocks. The mapping results in block F found that the distribution pattern of nickel laterite is mostly a product of weathering of Conglomerate (Unlaterite) rocks and the rest is the result of weathering of Ultramafic (Laterite) rocks. The quality of nickel laterite at PT Kencana Bumi Mineral is obtained the nickel ore content in the lab test results greatly varies from 0.67 - 1.27% in limonite or with an average of 0.89% while in saprolite 1.07 - 2.37%. The results of the classification of rock mass rating obtained a total rock score of 52 and 55 described as fair rock class.

Table 3. Total RMR Rating at depths of 1,0-7,5 m

Parameter	Value/Condition	Rating
Strength of Intact Rock Material	48,05 Mpa 41,19 Mpa 31,38 Mpa	4
RQD	50 – 75%	13
Spacing of Discountinuities	0,2 – 0,6 m	10
Condition of Discontinuities	Slighty rough surfaces Gauge < 5mm, Separation 1-5 mm Highly weathered walls	15
Ground Water	Damp	10
Total Rating		**52**

Table 4. Total RMR Rating at depths of 10,0-13,5 m

Parameter	Value/Condition	Rating
Strength of Intact Rock Material	54,92 Mpa	7
RQD	50 – 75%	13
Spacing of Discountinuities	0,2 – 0,6 m	10
Condition of Discontinuities	Slighty rough surfaces Gauge < 5mm, Separation 1-5 mm Highly weathered walls	15
Ground Water	Damp	10
Total Rating		**55**

3.2 Slope Stability Analysis

Slope stability analysis using the limit equilibrium method with using Slide2D software and probability analysis using Monte Carlo method. Analyzed based on soil laboratory test data. Descriptive statistical analysis was conducted on the parameters of unit weight, cohesion and friction angle in the soil. Descriptive statistical analysis is intended to determine the measure of central tendency, the measure of dispersion, and the distribution of data [5].

Descriptive statistical analysis of material properties includes unit weight, cohesion (c), and friction angle (Φ). The material properties variables are assumed to be normally distributed and truncated or bounded by certain relative minimum and relative maximum values [5].

Table 5. Descriptive Statistics of Material Properties

Material Name	*Property*	*Distribution*	*Mean*	*Std. Dev*	*Rel. Min*	*Rel. Max*	*Ket.*
Depth 1-1,5 m	*Cohesion*	Normal	3,74	0,93	2,78	2,78	Ok
Depth 1-1,5 m	*Phi*	Normal	17,53	1,48	4,45	4,45	Ok
Depth 1-1,5 m	*Unit Weight*	Normal	16,72	1,32	3,95	3,95	Ok
Depth 4-4,5 m	*Cohesion*	Normal	5,46	0,87	2,61	2,61	Ok
Depth 4-4,5 m	*Phi*	Normal	11,03	0,52	1,57	1,57	Ok
Depth 4-4,5 m	*Unit Weight*	Normal	16,14	0,13	0,40	0,40	Ok
Depth 7-7,5 m	*Cohesion*	Normal	5,30	0,13	0,40	0,40	Ok
Depth 7-7,5 m	*Phi*	Normal	7,66	2,14	6,43	6,43	Ok
Depth 7-7,5 m	*Unit Weight*	Normal	15,20	0,93	2,78	2,78	Ok
Depth 10-10,5 m	*Cohesion*	Normal	3,27	0,66	1,97	1,97	Ok
Depth 10-10,5 m	*Phi*	Normal	20,95	2,38	7,13	7,13	Ok
Depth 10-10,5 m	*Unit Weight*	Normal	15,56	0,54	1,63	1,63	Ok
Depth 13-13,5 m	*Cohesion*	Normal	4,07	0,47	1,42	1,42	Ok
Depth 13-13,5 m	*Phi*	Normal	20,62	1,91	5,73	5,73	Ok
Depth 13-13,5 m	*Unit Weight*	Normal	15,62	0,63	1,89	1,89	Ok

In this study, the slope design was analyzed by considering the horizontal seismic load coefficient and ignoring the vertical seismic load coefficient due to the earthquake. The horizontal seismic load always leads out of the slope so that it can reduce the stability of the slope. The PGA value in the study area was obtained as 0.496g. The site class is the rock site class (SB). Based on the site class, the FPGA value is 0.9 so that the peak ground acceleration value based on the site class is calculated as follows:

$$PGA_M = PGA \times F_{PGA}$$

$$PGA_M = 0{,}496g \times 0{,}9$$

$$PGA_M = 0{,}4464g$$

After obtaining the peak ground acceleration value, the value is then calculated into Kh, which is the horizontal seismic coefficient as follows:

$$K_h = 0{,}5 \left(\frac{a_d}{g}\right)$$

$$K_h = 0{,}5 \left(\frac{0{,}4464}{9{,}81}\right)$$

$K_h = 0{,}5(0{,}045)$

$K_h = 0{,}023$

The value of 0.023 is the horizontal seismic coefficient, Kh which is the result of seismic forces at the research location. So, this Kh value is used in the slope analysis. The horizontal seismic load is assumed to have an exponential truncated PDF form with a mean value of 0.023g, a minimum of 0.011g and a maximum of 2Kh which is 0.046g.

The method used in the analysis is the limit equilibrium method with Bishop Simplified Methods. The analysis will be carried out with two conditions, which are static and dynamic, the results of the analysis of each simulation can be seen as follows:

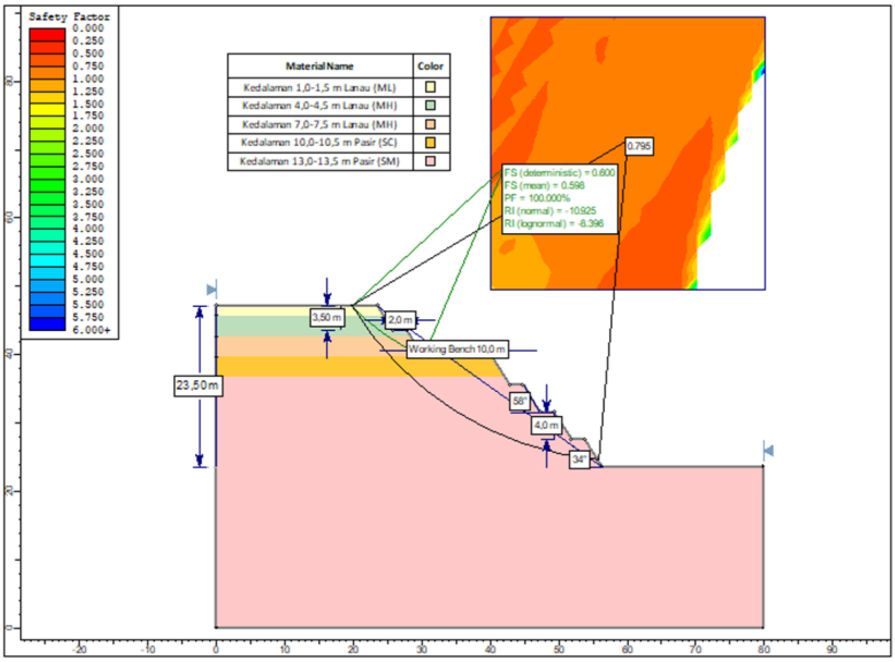

Figure 5. Analysis on Existing Overall Slope without Seismic Load (Static)

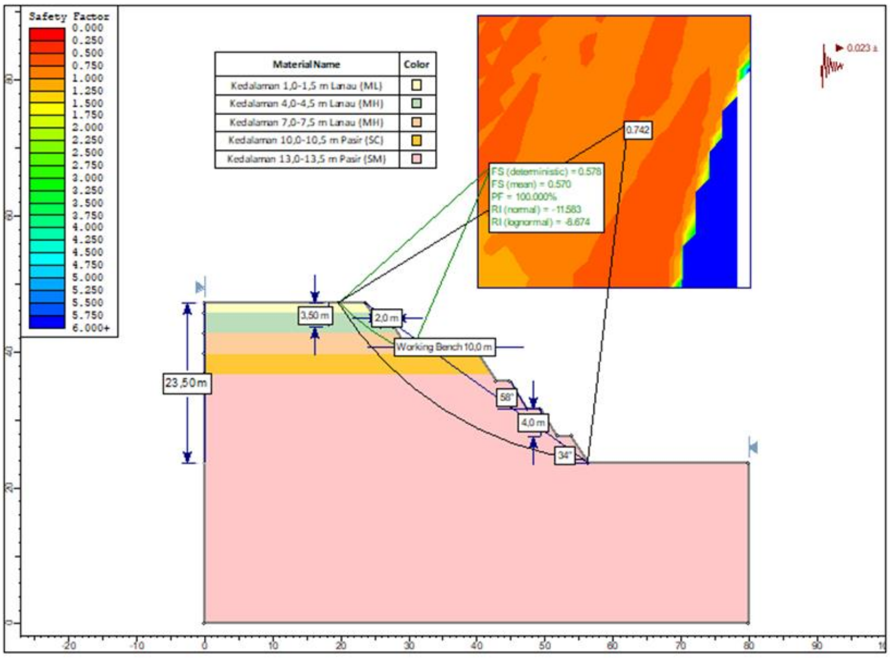

Figure 6. Analysis on Existing Overall Slope with Seismic Load (Dynamic)

Based on the results of the analysis of the entire cross section with the criteria for Probability of Failure (PoF) according to the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM Year 2018. For medium consequences of failure, the slope was found to be in "Unsafe" condition with a FK value of 0.795 and a 100% probability of failure, which means it has a large risk of slope failure. While the results of the analysis with the earthquake showed a decrease in slope stability, this is indicated by a decrease in the number of slope safety factors.

From the results of the overall slope analysis shown in Figure 5 and Figure 6, the slide plane shown is the most critical slide plane, so for this reason the authors re-analyzed each single slope. The results of the single slope analysis are tabulated as follows.

Table 6. Results of Existing Single Slope Analysis

Condition	Single Slope	Bench High (m)	Single Slope Angle (°)	FS	PoF (%)	Terms (According to Kepmen ESDM 1827)		Description
						FS min	PoF max (%)	
Existing Slope								
Static	1	3,50	58	0,751	100,0	1,1	25-50	Unsafe
	2	4,00	58	0,652	100,0			Unsafe
	3	4,00	58	0,803	99,90			Unsafe
	4	4,00	58	0,843	99,20			Unsafe
	5	4,00	58	0,841	98,80			Unsafe
	6	4,00	58	0,841	99,20			Unsafe
Dynamic	1	3,50	58	0,732	100,0	None	25-50	Unsafe
	2	4,00	58	0,636	100,0			Unsafe
	3	4,00	58	0,781	99,90			Unsafe
	4	4,00	58	0,820	99,70			Unsafe
	5	4,00	58	0,819	99,90			Unsafe
	6	4,00	58	0,819	99,70			Unsafe

3.3 Slope Geometry Recommendations

Based on the results of the existing analysis of the overall slope, for laboratory result test data both analyzed in overall slope and single slope, the slope condition is unsafe. So based on the results of this analysis it is necessary to make improvements by remodeling the slope geometry.

The results of trials and error analysis obtained the optimum slope design with overall slope, the slope angle of each single slope is designed from 58° to 30° on single slope 1 and 2, as well as to 40° on single slope 3 to 6, overall slope angle from 34° to 20° and overall slope height of 23.50m. The slope is divided into several single slopes with bench heights of 3.5 m and 4.0 m, bench width of 6 m and accompanied by a 10 m wide working bench.

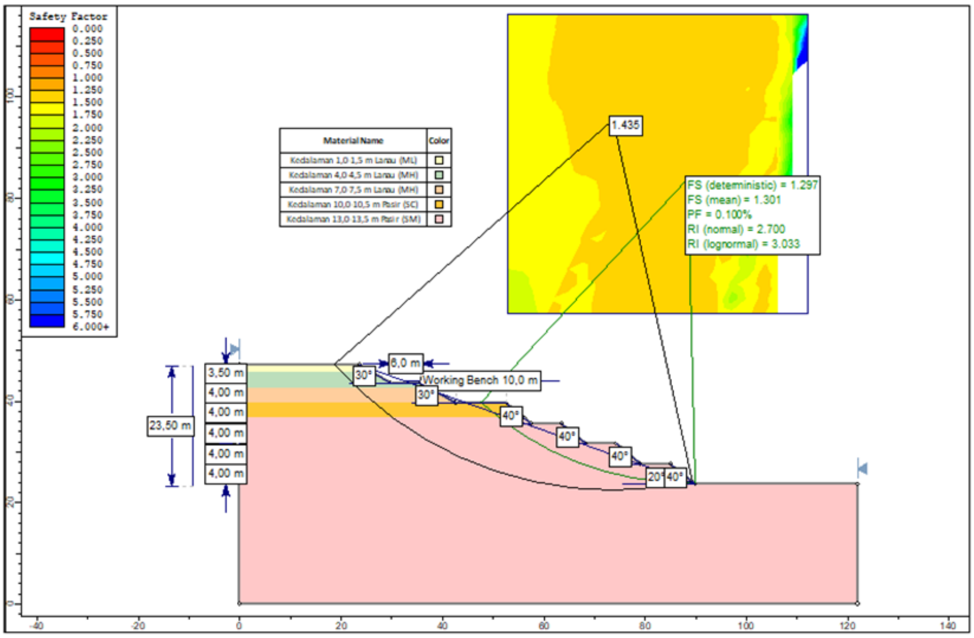

Figure 7. Analysis on Redesign Overall Slope without Seismic Load (Static)

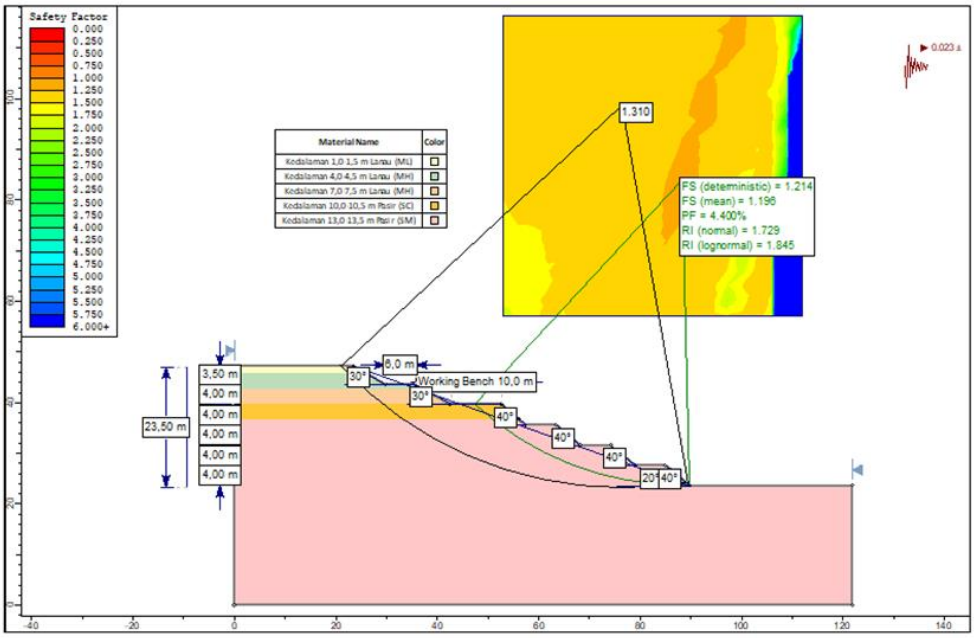

Figure 8. Analysis on Redesign Overall Slope with Seismic Load (Dynamic)

Based on the analysis, it was found that the slope condition is stable with a factor of safety value for the overall slope of 1.435 while the probability of failure is 0%. According to the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM 2018 with the category of medium consequences of failure for the overall slope, the minimum FS requirement is 1.3 and the maximum PF is 10%, so it can be concluded that the redesign is in a safe condition. And the results of dynamic slope analysis also show safe slope conditions. The factor of safety value obtained is 1.489 and the probability of failure is 0%. This value is qualified, which is for a minimum dynamic FS of 1.05 and a maximum probability of failure is 10%. The results of the single slope analysis are table as follows.

Table 7. Results of Redesign Single Slope Analysis

Condition	Single Slope	Bench High (m)	Single Slope Angle (º)	FS	PoF (%)	Terms (According to Kepmen ESDM 1827)		Description
						FS min	PoF max (%)	
Redesign Slope								
Static	1	3,50	30	1,147	4,00	1,1	25-50	Safe
	2	4,00	30	1,143	10,00			Safe
	3	4,00	40	1,104	7,00			Safe
	4	4,00	40	1,159	3,80			Safe
	5	4,00	40	1,144	4,70			Safe
	6	4,00	40	1,145	4,70			Safe
Dynamic	1	3,50	30	1,087	23,50	None	25-50	Safe
	2	4,00	30	1,089	22,10			Safe
	3	4,00	40	1,063	22,30			Safe
	4	4,00	40	1,116	10,70			Safe
	5	4,00	40	1,101	13,40			Safe
	6	4,00	40	1,101	13,40			Safe

IV. CONCLUSION

The characteristics of nickel deposits in the study area are the result of weathering of Ultramafic rocks with nickel ore content varying from 0.67%-1.27% for the limonite zone while in the saprolite zone the nickel ore content varies from 1.07%-2.37%. The results of the analysis in the existing state obtained unsafe slopes in the overall slope and single slope analysis both static and dynamic conditions. The factor of safety (FS) value is obtained <1 and the probability of failure (PoF) reaches 100%. So that the slope geometry redesign is carried out. The redesign was designed by changing the overall slope angle to 20º, the single slope angle to 30º and 40º, and the bench width to 6m. The results of the redesign analysis show that the slope is safe in overall slope and single slope analysis both static and dynamic conditions indicated by a factor of safety (FS) value >1.1 and the largest probability of failure is only 23.50%.

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