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Study on the Stability of Open Pit Slopes Based on Geotechnical and Safety Aspects at the PT. Integra Mining Nusantara Indonesia Nikcle Mine in Pagimana District, Banggai Regency, Central Sulawesi

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Abstract
Slope stability studies in mining areas need to be carried out by applying good mining rules, where in applying these rules it is necessary to study geotechnical aspects and work safety aspects according to Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018. Research objectives This is to determine the characteristics of nickel deposits, carry out slope stability analysis in the pit B mining area, remodel the slope geometry and carry out evaluations related to work safety aspects in the pit B mining area. The stability analysis methodology for this research uses the limit equilibrium method with the probabilistic Monte Carlo method. The analysis process is carried out with the help of 2D Slide Software. The results of this research show that the serpentinite unit was found to be quite extensive in the investigation area so that the laterization process was not very developed. The laterization process was only formed in the peridotite unit or around 27% of the area of the investigation location. Analysis of the stability of the existing slopes showed that the slopes were unsafe in static and dynamic analysis. The safety factor value was <1.3 and the probability of a landslide reached 29.4%. So the slope geometry was redesigned by changing the overall slope angle to 31o, the bench height to 4 and 6 m and the bench width to 5 m. The results of the redesign analysis show that the slope is safe in static and dynamic analysis, characterized by a safety factor value of >1.3 and the highest probability of failure is only 10%. The analysis of safety aspects on the slopes of the Pit B excavation area was carried out by looking at the safety factor (SF) of the slopes, as well as the percentage of possible landslides.

Keywords: *Safety Factors, Probability of Landslides, PT. Integra Mining Nusantara Indonesia, Boundary Equilibrium, Monte Carlo.*

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I. INTRODUCTION

Slope stability is a very important study in implementing safe, productive and environmentally friendly mining. Slope stability is closely related to human safety, equipment safety, and the smooth production of a mining activity [8]. PT. Integra Mining Nusantara Indonesia is a Mining Business Permit (IUP) holder for nickel commodities located in Siuna Village, Pagimana District, Banggai Regency, Central Sulawesi Province. Mining activities that are being carried out apply an open pit mining system using the open pit method at the Pit B mining location. Mining operations are carried out by peeling layers of soil and rock until nickel content is found for further production.

Slope stability study at PT. Integra Mining Nusantara Indonesia needs to be carried out by applying good mining principles (*Good Mining Practice*), namely mining activities that comply with the rules, are well planned, apply appropriate technology based on effectiveness and efficiency, and guarantee mining safety. In order to implement good mining principles, it is necessary to carry out geotechnical studies to support the planning and implementation of mining activities that will be carried out.

Slope stability study at PT. Integra Mining Nusantara Indonesia needs to be carried out by applying good mining principles (*Good Mining Practice)*, namely mining activities that comply with the rules, are well planned, apply appropriate technology based on effectiveness and efficiency, and guarantee mining safety. In order to implement good mining principles, it is necessary to carry out geotechnical studies to support the planning and implementation of mining activities that will be carried out. This value will later be compared with standard values for safety factors and landslide probability to assess geotechnical aspects and use landslide severity criteria (*consequences of failure*) to assess work safety aspects according to Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/ 2018. Based on the importance of this, this research will be carried out with the title "Study of the Stability of Open Mine Excavation Slopes Based on Geotechnical and Work Safety Aspects at the PT Integra Mining Nusantara Indonesia Nickel Mine in Pagimana District, Banggai Regency, Central Sulawesi"

1.1 Regional Geology

Based on the Geological map of Luwuk Sheet, Sulawesi by T. O Simandjuntak, E. Rusmana, and A. Koswara in 1993 (2215 - 2315) scale 1,250,000, Geological Research and Development Center, PT Integra Mining Nusantara IUP location is composed of Mafik Complex rocks (95%). The Mafic complex consists of gabbro, basalt, serpentinite and a little schist and phyllite with a cretaceous age range (geological time scale). The main structures operating in the IUP area are horizontal faults trending East-West and secondary faults trending Northeast and Southeast. The PT. Integra Mining Nusantara Indonesia IUP area generally has a sloping wavy hill morphology [12].

From the slope analysis, it is shown that a good area for the formation of the nickel laterization process is on the east side with an average slope of around 5 ^{o} –15 ^{o} . In theory, nickel laterite is formed on a slope of 5 ^{o} – 15 ^{o} , so it can be interpreted that the IUP area of PT Integra Mining Nusantara Indonesia has the potential for the formation of nickel laterite with supporting data from morphological interpretation. The Central Sulawesi area, especially around Banggai Regency, regional research according to the division of physiographic zones is grouped into the northern part included in the Scale Zone and the southern part included in the Mountain Zone [13].

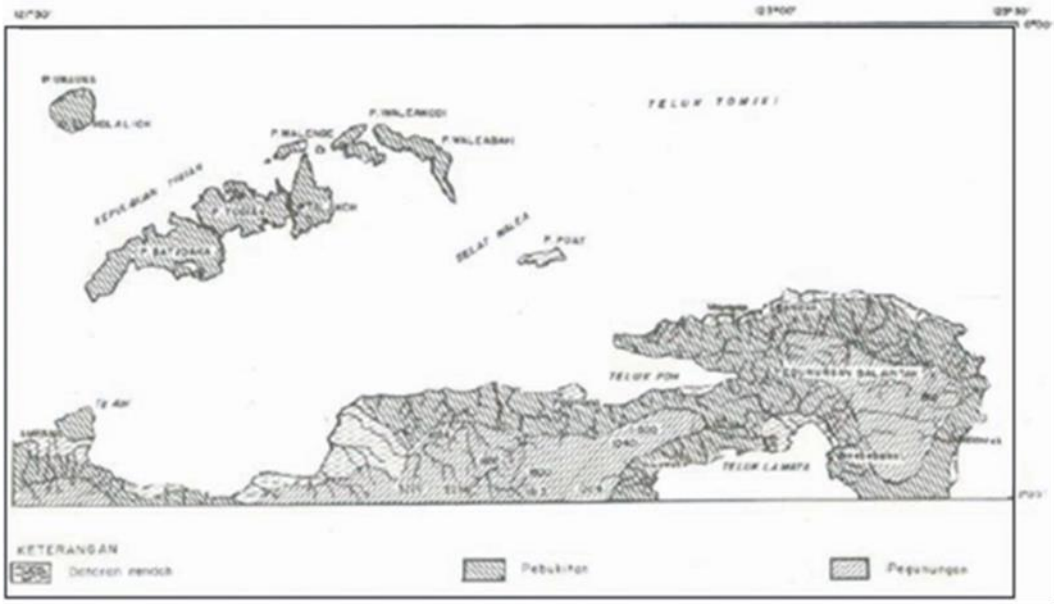

Figure 1. Luwuk Area Morphology [3]

1.2 Nickel Mining Activities

The process of forming nickel laterite begins with intensive weathering of the peridotite rock/parent rock. The parent rock will change to serpentinite due to the presence of hydrothermal solution during magma freezing/serpentinization process. Then weathering occurs (chemical and physical) causing decomposition of the parent rock. Meanwhile, according to Golightly (1981), some of the elements Ca, Mg and Si will experience decomposition and some will be supergene enriched (Ni, Mn, Co, Zn). Or relatively enriched (Fe, Cr, Al, Ti, S, and Cu) [4].

Surface mining is a mining method that is carried out on or close to the earth's surface and the work site is in direct contact with the outside air. Underground mining is a mining method where all activities are carried out below the earth's surface and the work place is not directly connected to the air. Underwater mining is a mining method where excavation activities are carried out below the water table or mineral deposits [6].

Open pit mining is usually carried out for ore or mineral deposits found in flat areas or valley areas. The soil will be dug to the bottom so that it will form a depression or pit. Mining the nickel mineral commodity using an open mining system causes a change in the hue or shape of the topography of an area to become a mining front consisting of several levels (benches) and mining roads [3].

1.3 Slope Stability Analysis Limit Equilibrium Method (LEM)

Limit equilibrium is a method that calculates the resisting force and load by dividing the landslide plane into several discrete pieces, so that horizontal, vertical forces and moments acting on each piece can be calculated [2]. Limit equilibrium analysis is a method of analyzing the balance of potentially moving masses by comparing the driving force and restraining force along the slide plane of the landslide.

1.4 Concept Factor of Safety (FS)

In a place where there are two ground surfaces of different heights, there will be forces that work to push so that the ground that is higher in position tends to move downwards. Apart from the forces that push downwards, there are also forces in the soil that work to resist/resist so that the position of the soil remains stable. If the driving forces are greater than the resisting forces, the soil will start to collapse and eventually the soil will collapse along the continuous plane and the mass of soil above this continuous plane will slide. This event is called slope failure and this continuous area is called the slip plane [9].

Theoretically, the safety factor is used to define slope stability. The value of the safety factor can be defined as a comparison between the shear strength of the soil (shear strength) and the shear stress (shear stress) acting on the soil or landslide area [7].

$$FS = \frac{shear\ strenght\ available}{shear\ strenght\ required\ for\ stability}$$

1.5 Probability of Failure

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

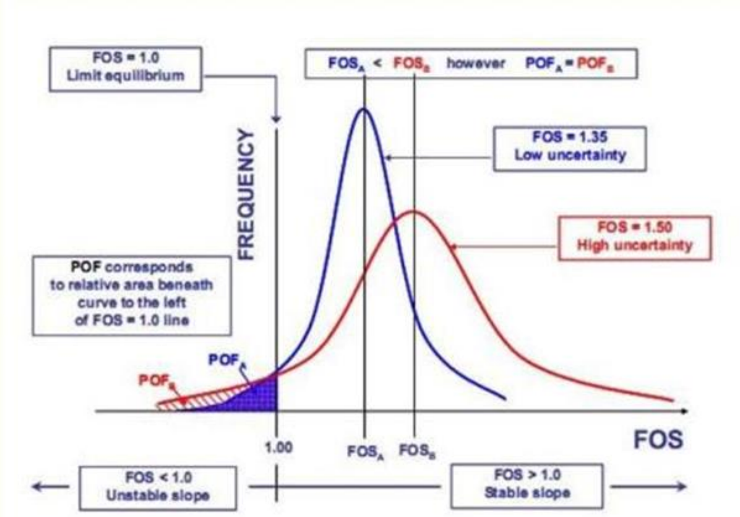

Figure 2. Concept Probability of Failure and Uncertainty Magnitude [1].

Monte Carlo method is a simple probabilistic analysis method, more flexible in combining a fairly large variety of probability distributions without much interpretation, and the ability to model correlation between variables easily [5].

The government through Minister of Energy and Mineral Resources Decree number 1827 K/30/MEM/2018 has determined the safety factor values and probability of mine slope landslides, as can be seen in the following table.

Table 1. Safety Factor Values and Probability of Mine Slope Landslides

Slope Types	***Consequences of Failure/CoF***	**(Acceptance Criteria)** Factor of Safety (FS) Static (Min)	Factor of Safety (FS) Dinamic (Min)	***Probability of Failure*** **(Max) PoF (FK ≤1)**
Single Slope	Low to 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%

1.6 Seismic Load

Seismic loads on slope stability act in two directions, horizontal and vertical. However, in the vertical direction the contribution to slope stability is very small, so only loads in the horizontal direction will be used [11]. Determining the magnitude of the seismic force can be done by knowing the peak ground acceleration obtained from the 2021 Indonesian Spectra Design Application, by entering the coordinates of the location of PT. Integra Mining Nusantara Indonesia. The result obtained from the application of the spectral design is the peak ground acceleration.

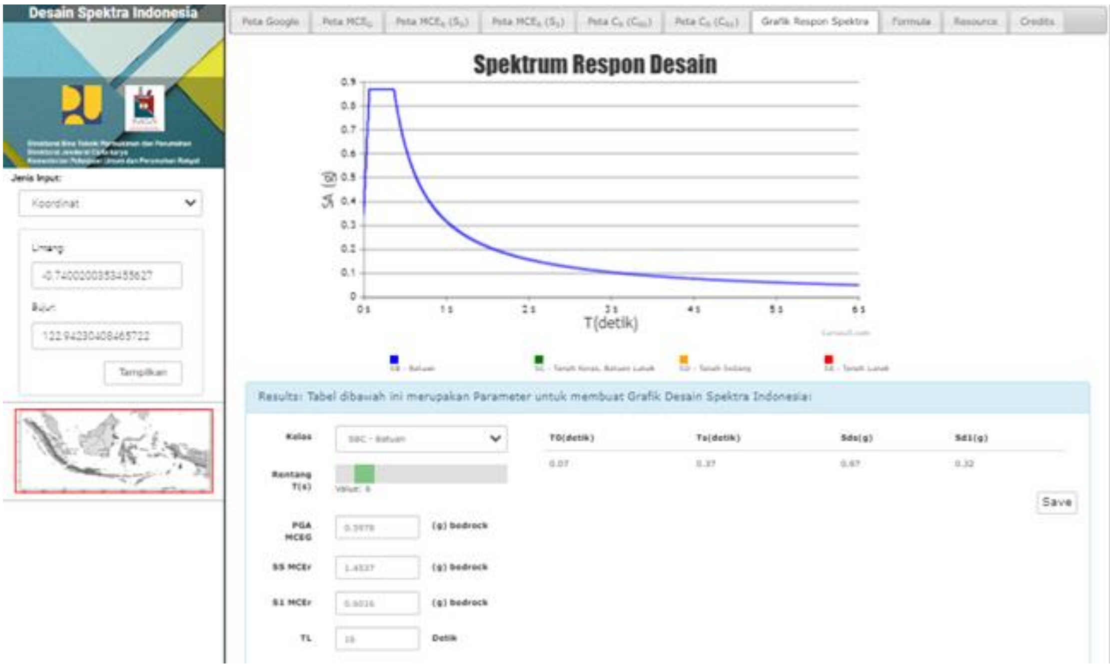

Figure 3. Design Response Spectrum on the Research Area

Calculations regarding peak ground acceleration values based on 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 site class, PGA is the mapped peak ground acceleration while FPGA is the coefficient based on Table 2.

Table 2. Site F $_{PGA}$ coefficients

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 figures using the slice method, it is in the following equation with the analysis variables being the cohesion value (c), length of the pias failure line (Ln), weight of the pias (Wn), angle of inclination of the pias to the center of the circle (an), earthquake coefficient (Kh), and the radius of the circle (R):

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

The Kh value in the formula above is obtained by the equation 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. METHODOLOGY

This research uses a case study methodology combining quantitative and qualitative method approaches. Starting from collecting research data including primary data in the form of slope geometry data on the PT mining business permit. integra Mining Nusantara Indonesia in Pit B and secondary data in the form of topographic maps of the research area as well as data from drilling results and laboratory tests. Some of this data was obtained in the Feasibility Study Document of PT. Integra Mining Nusantara Indonesia in 2022. The research slope incision locations and drill points can be seen in Figure 4 below.

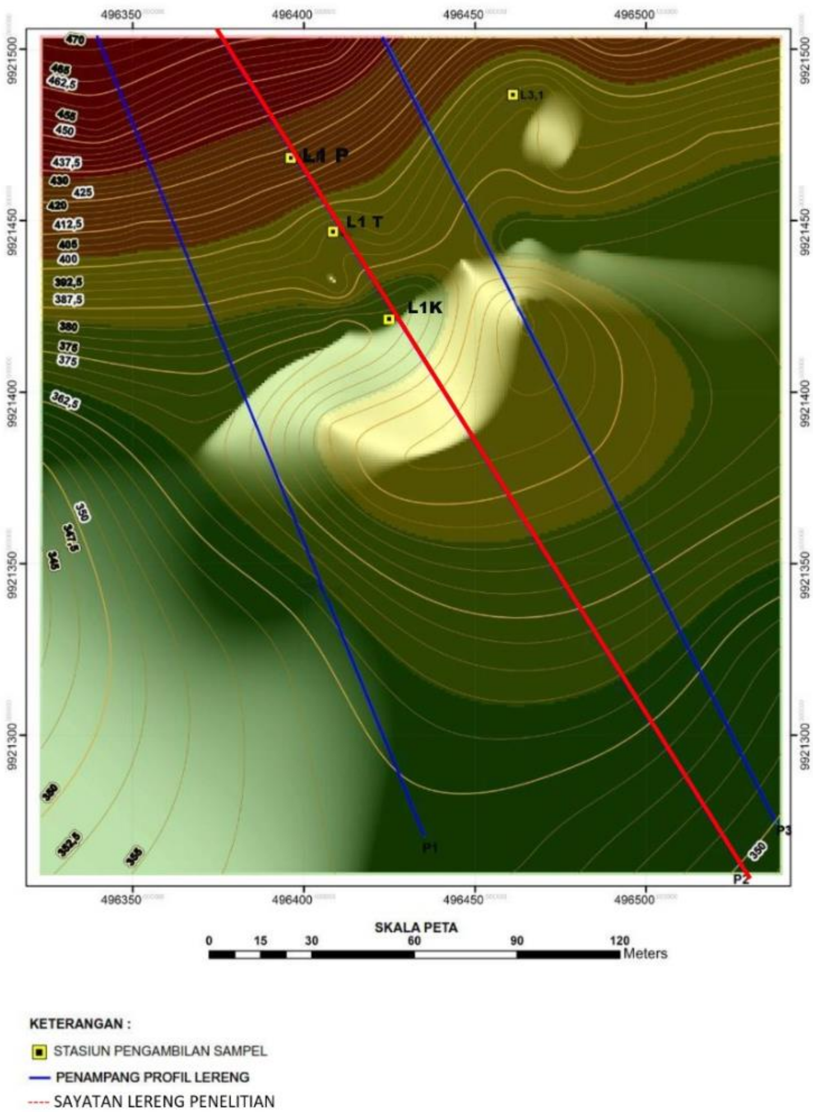

Figure 4. Map of Slope Section

Processing research data begins by making a cross-section of the slope obtained from the slope geometry and topographic map of the research area. The cross-section of the slope is then combined with the thickness of each type of material according to the characteristics of nickel deposits (overburden, limonite, saprolite, and bedrock) in meters based on the results. geotechnical drilling and exploration drilling at several different locations. The slope cross-section that will be used in the simulation is in accordance with the existing slope cross-section at the research location.

The cross-section of the slope with several types of material is combined with the groundwater level, then the cross-sectional data is input into the Slide 2D computer program and input the required soil properties so that it can be simulated in the software to obtain a safe figure for the slope cross-section. This output value will later be analyzed by comparing it with the standards of the Minister of Energy and Mineral Resources Decree 1827 of 2018.

III. RESULTS AND DISCUSSION

3.1 Nickel Characteristics

Based on field observations, the form and distribution of deposits at the research location were obtained in the form of Serpentinite Units; The characteristic of this rock is that it is white and gray in fresh condition and brownish in weathered condition. Medium-fine grained, the mineral composition consists of serpentine, talc, clay, muscovite, olivine, and pyroxine. Next, field samples were taken from the research location from three types of samples taken randomly, namely Limonite, Saprolite and Boulder, and the following results were obtained:

Limonite: 0.71% Ni, 31.6% - 41.68% Fe, 9.6% - 15.56% SiO2, and 0.78% - 0.95% MgO.
Saprolite: 0.85% – 2.367% Ni, 14.41% - 21.12% Fe, 37.86% - 47.9% SiO2, and 8.81% - 22.95% MgO.
Boulder:1.4% - 3.22% Ni, 7.44% - 9.6% Fe, 37.6% - 41.14% SiO2, and 24.26% 29.59% MgO.
The SM ratio for LIMONIT material: 12.2-16.3, SAPROLIT: 1.6 - 5.2, and Boulder: 1.3-1.6.

3.2 Slope Stability Analysis

Slope stability analysis uses the limit balance method with the help of Slide2D software and probability analysis uses the *Monte Carlo method*. Analyzed based on data from soil laboratory tests. Descriptive statistical analysis was carried out on the parameters of bulk density, cohesion and angle of friction in the soil. Descriptive statistical analysis is aimed at determining the size of data concentration (central tendency), the size of data spread (dispersion), and data distribution.

Descriptive statistical analysis of material properties includes bulk weight, cohesion (c), and internal friction angle (Φ). Material property variables are assumed to have a normal distribution that is truncated or limited by certain relative minimum and relative maximum values [10].

Table 5. Descriptive Statistics of Material Property Data

***Descriptive Statistics* Typical L1P**						
Parameter	Unit	N	*Minimum*	*Maximum*	*Mean*	Std. Deviation
Cohesion	kN/m^2	2	23.40	30.30	26.85	4,879
Phi	°	2	23.30	37.32	30,31	9,941
Unit Weight	kN/m^3	2	10.59	12.75	11.67	1,527
***Descriptive Statistics* Typical L1K**						
Parameter	Unit	N	*Minimum*	*Maximum*	*Mean*	Std. Deviation
Cohesion	kN/m^2	2	47.20	56.90	52.05	6,859
Phi	°	2	32.15	38.14	35.15	4,236
Unit Weight	kN/m^3	2	9.03	10.89	9.96	1,315
***Descriptive Statistics* Typical L1T**						
Parameter	Unit	N	*Minimum*	*Maximum*	*Mean*	Std. Deviation
Cohesion	kN/m^2	3	27,20	35.80	33.40	5,415
Phi	°	3	40.74	42.36	41.69	0.846
Unit Weight	kN/m^3	3	11.77	13.05	12.56	0.689

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

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

$$PGA_M = 0{,}5978g \times 0{,}9$$

$$PGA_M = 0{,}538g$$

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

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

$$K_h = 0{,}5\left(\frac{0{,}538}{9{,}81}\right)$$

$$K_h = 0{,}5(0{,}055)$$

$$K_h = 0{,}027$$

The value 0.027 is the value of the horizontal seismic coefficient, Kh which is the result of seismic forces at the research location. So this Kh value is used in slope analysis. The horizontal seismic load is assumed to have a PDF truncated exponential form with a mean value of 2Kh 0.054g, a minimum of 0.027g and a maximum of 3Kh, namely 0.081g. The form and parameter input for the Horizontal Seismic Load PDF can be seen in Figure 5 below.

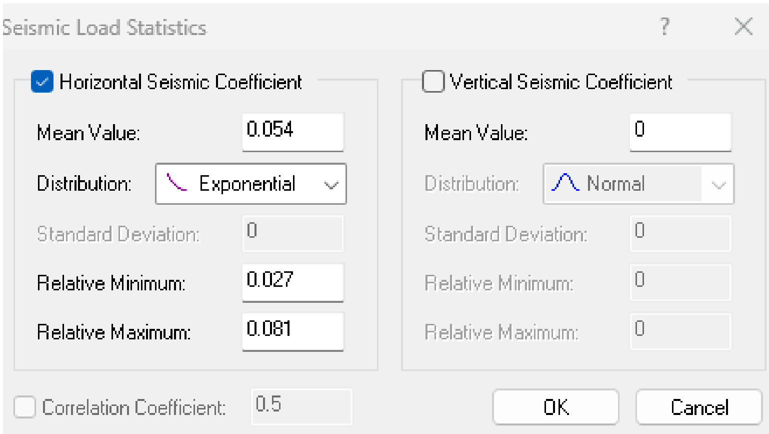

Figure 5. Input PDF Parameters for Horizontal Seismic Load

The method used in the analysis is the Limit Equlibrium Method with Bishop Simplified Methods. The analysis will be carried out under two conditions, namely static and dynamic, the results of the analysis for each simulation can be seen as follows:

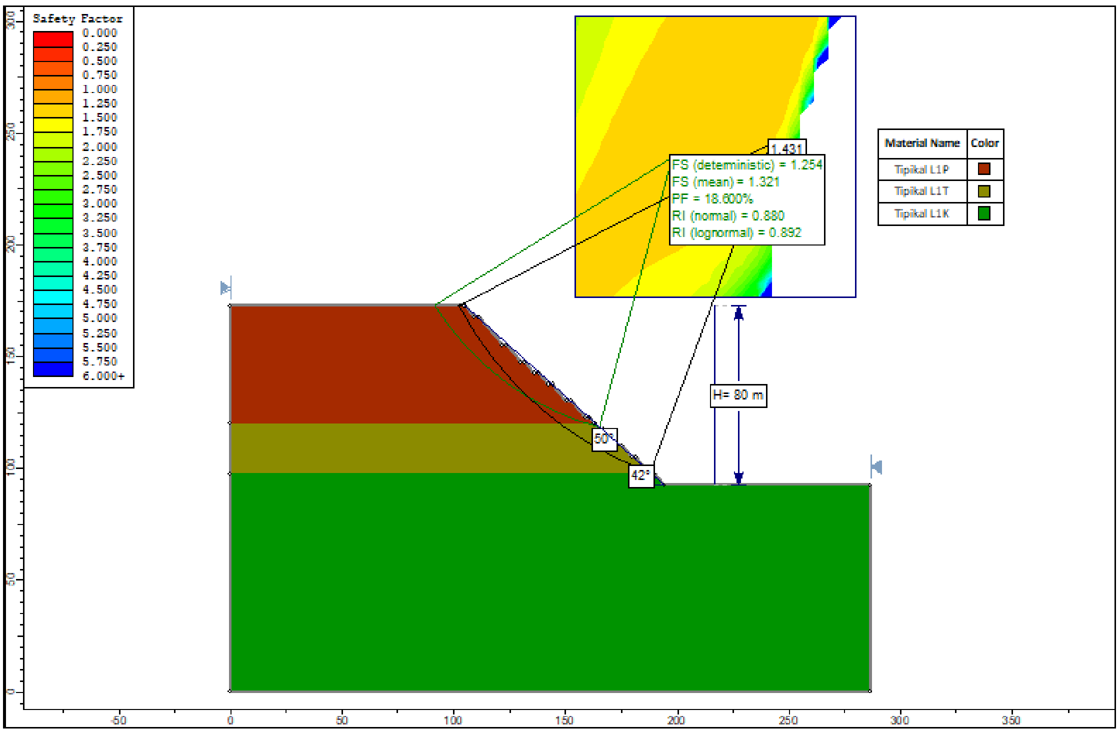

Figure 6. Analysis Probability of Failure on Existing Overall Slope Static

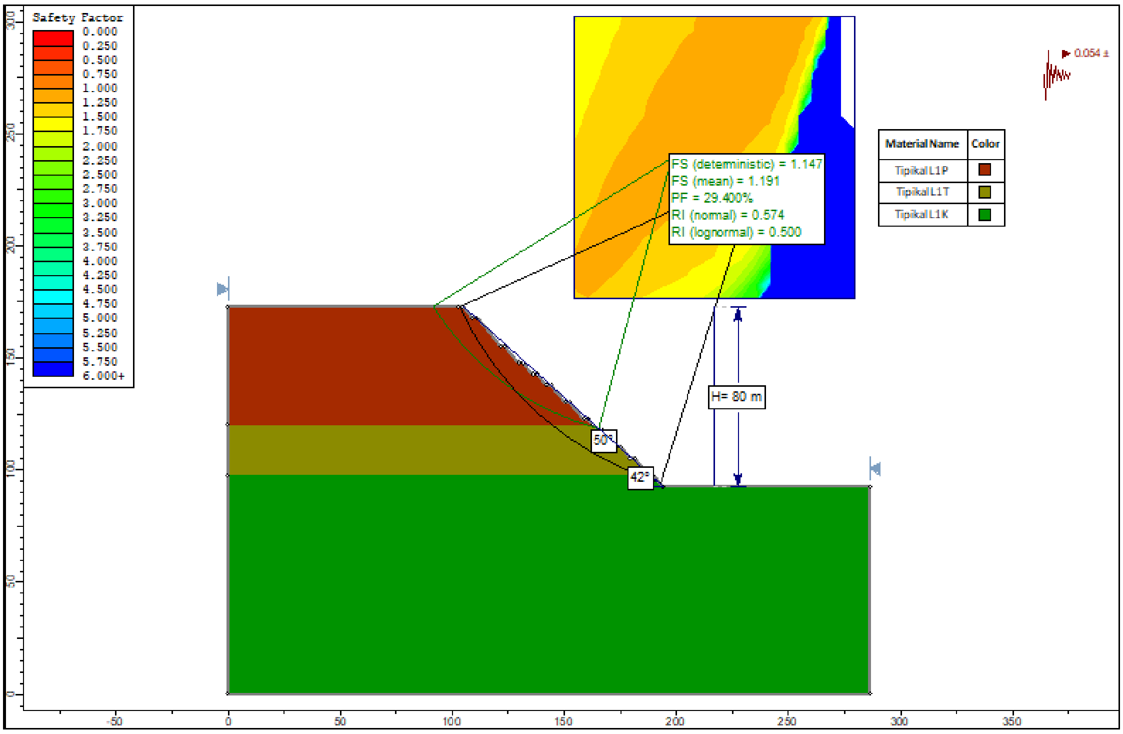

Figure 7. Analysis Probability of Failure on Existing Overall Slope Dynamic

Based on the results of the landslide probability analysis of the entire cross-section using the PK Landslide Probability criteria according to Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM 2018. For medium landslide severity levels, the slope is found to be in an "Unsafe" condition with a deterministic FK value of 1.254 and a landslide probability of 18.6%, where this value exceeds the maximum limit, namely a static min FK of 1.3 and a landslide probability. the maximum is only 10%, which means it has a large landslide risk. Meanwhile, the results of earthquake analysis show a decrease in slope stability, this is indicated by a decrease in the slope safety factor.

From the results of the overall slope analysis seen in Figure 5 and Figure 6, the slip area shown is the most critical slip area, so for this reason the researchers carried out another analysis on each single slope. The results of the single slope analysis are tabled as follows.

Table 6. Existing Single Slope Analysis Results

Condition	*Single Slope*	*Bench High* (m)	*Single Slope Angle* (°)	FS_{det}	PF (%)	Ministerial Decree Requirements		Description
						FK min	Max PK (%)	
	1	5.0	50	3,737	0.00			Safe
	2	12.5	50	2,039	0.30			Safe
	3	7.5	50	2,816	0.00			Safe
	4	5.0	50	3,733	0.00			Safe
	5	5.0	50	3,733	0.00			Safe
Static	6	7.5	50	2,816	0.00	1.1	25-50	Safe
	7	7.5	50	2,816	0.00			Safe
	8	5.0	50	4,615	0.00			Safe
	9	7.5	50	3,582	0.00			Safe
	10	5.0	50	4,690	0.00			Safe
	11	7.5	50	3,582	0.00			Safe
	12	5.0	50	7,346	0.00			Safe
	1	5.0	50	3,472	0.00			Safe
	2	12.5	50	1,902	0.70			Safe
	3	7.5	50	2,613	0.00			Safe
	4	5.0	50	3,467	0.00			Safe
	5	5.0	50	3,467	0.00			Safe
Dynamic	6	7.5	50	2,613	0.00	None	25-50	Safe
	7	7.5	50	2,613	0.00			Safe
	8	5.0	50	4,278	0.00			Safe
	9	7.5	50	3,341	0.00			Safe
	10	5.0	50	4,346	0.00			Safe
	11	7.5	50	3,341	0.00			Safe

12	5.0	50	6,851	0.00		Safe

The results of the analysis on single slopes show that the slopes are in a safe condition for each single slope. However, based on the results of the overall slope analysis, it was found that the slope was in an unsafe condition characterized by a fairly high level of failure probability of up to 29.40% and did not meet the maximum requirement of 10%. So, in this research the researchers remodeled the slope geometry.\

3.3 Slope Geometry Recommendations

Based on the results of the overall existing slope analysis, for laboratory test data analyzed both overall slope and single slope, unsafe slope conditions were obtained. So, based on the results of this analysis, improvements need to be made by remodeling the slope geometry.

The results of *trial and error analysis* obtained an optimum slope design with the *multibench overall slope type* with a design overall slope angle of 31 ^{o} , overall slope height of 80 m, slope angle for each *single slope* remaining 50 ^{o} , bench height of 4 m on single slopes 1 and 2 but at single slopes 3 to 14, the height of the bench is 6 m, and the width of the bench for each single slope is 5 m.

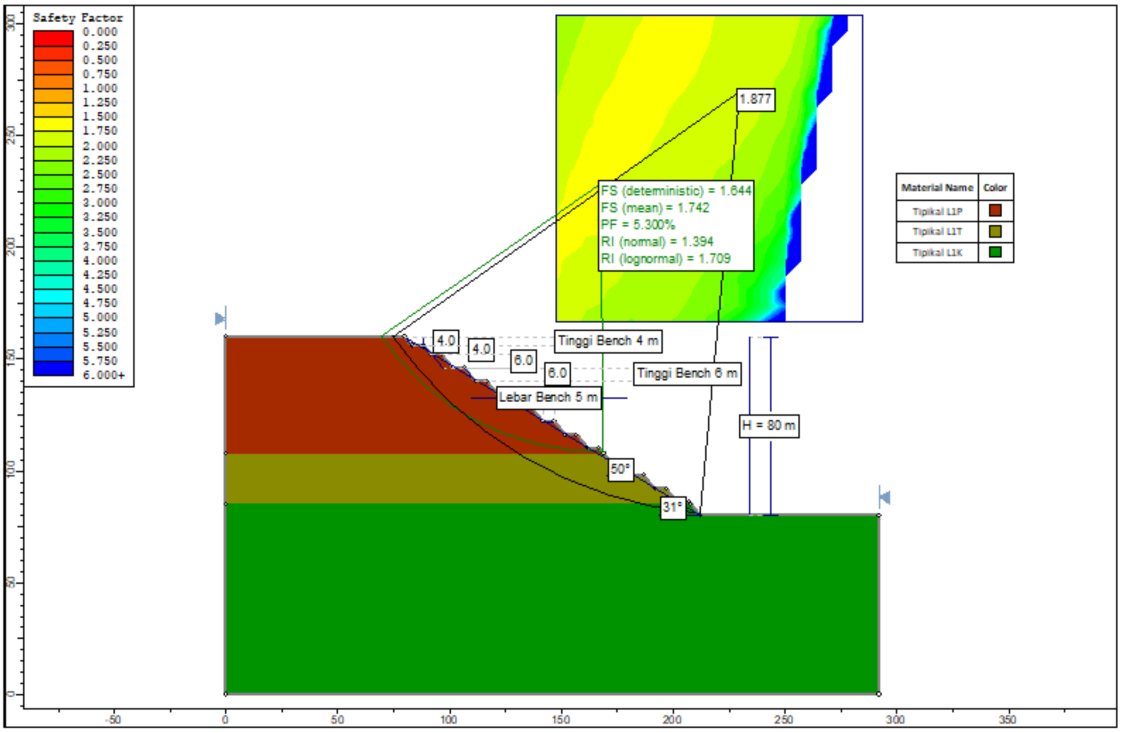

Figure 8. Analysis Probability of Failure on Redesign Overall Slope Static

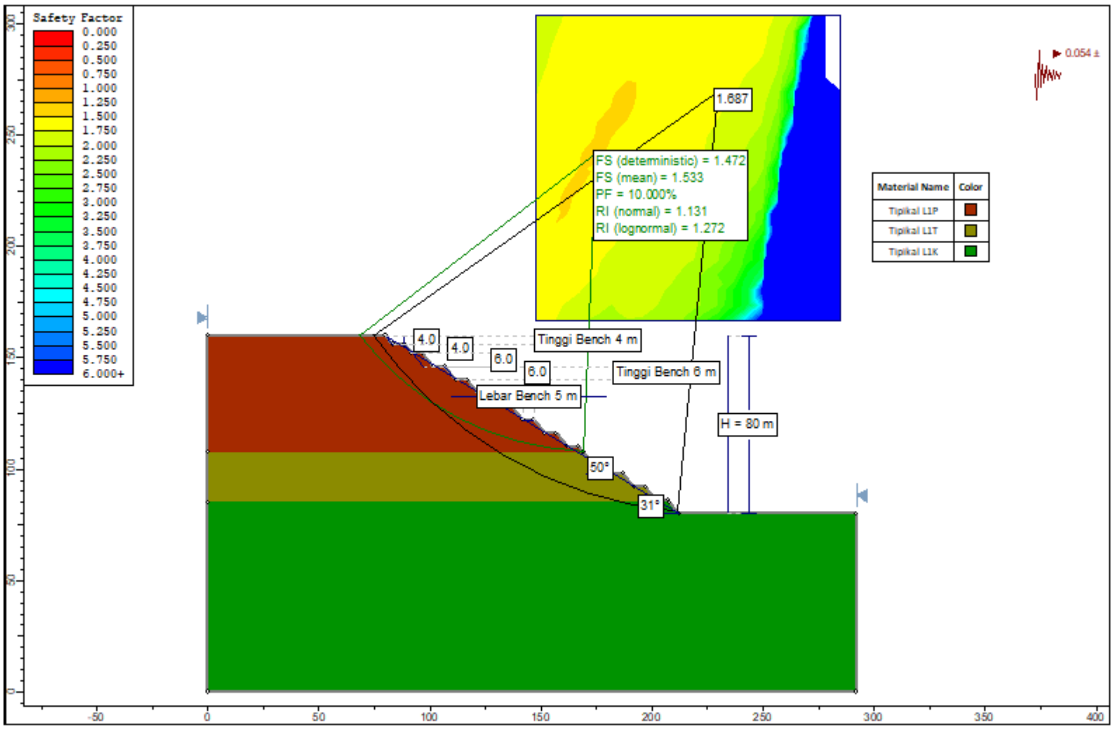

Figure 9. Analysis Probability of Failure on Redesign Overall Slope Dynamic

Based on the analysis results, it was found that the slope condition was stable with a safety factor value for the overall slope of 1.644 while the probability of a landslide was 5.3%. Referring to Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM of 2018 with a medium landslide severity category for the entire slope with a minimum FK requirement of 1.3 and a maximum PK of 10%, it can be concluded that the redesign is in a safe condition. And the results of dynamic slope analysis also show that the slope conditions are safe. The safety factor value obtained is 1.472 and the probability of a landslide is 10%. This value meets the requirements, namely for a minimum dynamic FK of 1.05 and a maximum landslide probability of 10%. The results of the single slope analysis are tabled as follows.

Table 7. Results of Single Slope Redesign Analysis

Condition	*Single Slope*	*Bench High* (m)	*Single Slope Angle* (°)	FS $_{det}$	PF (%)	Ministerial Decree Requirements		Description
						FS min	Max PF (%)	
Static	1	4.0	50	4,407	0.00	1.1	25-50	Safe
	2	4.0	50	4,377	0.00			Safe
	3	6.0	50	3,283	0.00			Safe
	4	6.0	50	3,283	0.00			Safe
	5	6.0	50	3,283	0.00			Safe
	6	6.0	50	3,283	0.00			Safe
	7	6.0	50	3,283	0.00			Safe
	8	6.0	50	3,283	0.00			Safe
	9	6.0	50	3,283	0.00			Safe
	10	6.0	50	4,122	0.00			Safe
	11	6.0	50	4,140	0.00			Safe
	12	6.0	50	4,140	0.00			Safe
	13	6.0	50	4,140	0.00			Safe
	14	6.0	50	5,906	0.00			Safe
Dynamic	1	4.0	50	4,102	0.00	There isn't any	25-50	Safe
	2	4.0	50	4,082	0.00			Safe
	3	6.0	50	3,044	0.00			Safe
	4	6.0	50	3,044	0.00			Safe
	5	6.0	50	3,044	0.00			Safe
	6	6.0	50	3,044	0.00			Safe
	7	6.0	50	3,044	0.00			Safe
	8	6.0	50	3,044	0.00			Safe
	9	6.0	50	3,044	0.00			Safe
	10	6.0	50	3,822	0.00			Safe
	11	6.0	50	3,845	0.00			Safe

12	6.0	50	3,845	0.00	Safe
13	6.0	50	3,845	0.00	Safe
14	6.0	50	5,478	0.00	Safe

IV. CONCLUSION

It was found that the serpentinite unit was quite extensive in the investigation area so that the laterization process was not very developed at the investigation location. The laterization process was only formed in the peridotite unit or around 27% of the area of the investigation location. The results of the analysis on the existing conditions showed that the slopes were unsafe in the overall slope and single slope analysis in both static and dynamic conditions. The safety factor value was <1.3 and the probability of landslides reached 29.4%. So the slope geometry was redesigned. The redesign was designed by changing the overall slope angle to 31 ^{o} , the single slope angle remained 50 ^{o} , but the bench width from 2 m to 6 m. The results of the redesign analysis show that the slope is safe in the overall slope and single slope analysis in both static and dynamic conditions, characterized by a safety factor value of >1.3 and the highest probability of failure is only 10%.

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