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Analysis of the Effect of Rainwater Infiltration on Slope Stability Using the Limit Equilibrium Method at the Outpit Disposal, Serongga Site, PT Baramega Citra Mulia Persada

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Abstract

Slope stability in mining areas is a critical aspect that must be carefully considered, particularly in regions with high rainfall intensity. Heavy rainfall can increase the risk of slope failure, disrupt mining operations, and reduce planned production targets. This study investigates the effect of rainfall infiltration on slope stability at PT Baramega Citra Mulia Persada, Kotabaru, South Kalimantan, Indonesia. The Limit Equilibrium Method (LEM) using the Janbu method was applied to evaluate the Factor of Safety (FoS) under different moisture conditions and to assess the influence of rainfall infiltration on slope performance in the outpit disposal area. FoS calculations were conducted on four slope cross-sections, namely AA', BB', CC', and DD', based on geotechnical and rainfall data. The results indicate that each slope exhibits variations in FoS under different moisture conditions. Slope AA' shows FoS values of 1.48 (saturated), 1.976 (partially saturated), and 2.007 (dry). Slope BB' has FoS values of 1.311, 1.650, and 1.711, while slope CC' exhibits FoS values of 1.516, 2.187, and 2.279. Slope DD' represents the most critical condition, with the lowest FoS values of 1.106 (saturated), 1.374 (partially saturated), and 1.470 (dry). To improve stability, a geometric modification was applied to slope DD' by adding an additional bench with a height of 4.3 m, which increased the FoS to 1.514 and satisfied the mine slope stability criteria.

Keywords: *rainfall infiltration, slope stability, janbu method, limit equilibrium method*

Abstrak

Kestabilan lereng pada area penambangan merupakan aspek penting yang harus diperhatikan, terutama pada daerah dengan intensitas curah hujan yang tinggi. Curah hujan tinggi dapat meningkatkan risiko longsoran, mengganggu operasional, dan menurunkan target produksi perusahaan. Penelitian ini mengkaji pengaruh infiltrasi air hujan terhadap kestabilan lereng di PT Baramega Citra Mulia Persada, Kotabaru, Kalimantan Selatan. *Limit Equilibrium Method* (LEM) dengan metode Janbu digunakan untuk mengevaluasi faktor keamanan (*Factor of Safety*/FoS) pada berbagai kondisi kadar air serta menilai pengaruh infiltrasi air hujan terhadap kinerja lereng di area outpit disposal. Perhitungan FoS dilakukan pada empat penampang lereng, yaitu AA', BB', CC', dan DD', berdasarkan data geoteknik dan curah hujan. Hasil analisis menunjukkan setiap lereng mengalami variasi nilai FK pada kondisi yang berbeda. Lereng AA' memiliki nilai FK sebesar 1,48 (jenuh), 1,976 (setengah jenuh), dan 2,007 (kering). Lereng BB' menunjukkan nilai FK sebesar 1,311; 1,650; dan 1,711, sedangkan lereng CC' memiliki nilai FK sebesar 1,516; 2,187; dan 2,279. Lereng DD' merupakan kondisi paling kritis dengan nilai FK terendah, yaitu 1,106 (jenuh), 1,374 (setengah jenuh), dan 1,470 (kering). Untuk meningkatkan kestabilan, dilakukan perbaikan geometri lereng DD' dengan penambahan satu jenjang setinggi 4,3 meter sehingga nilai FK meningkat menjadi 1,514 dan memenuhi kriteria kestabilan tambang.

Kata Kunci: *infiltrasi air hujan, kestabilan lereng, metode janbu, metode kesetimbangan batas*

1. Introduction

Indonesia is a tropical country characterized by high annual rainfall, elevated humidity, intense solar radiation, and relatively high temperatures throughout the year [1]. Among these climatic parameters, rainfall is one of the most influential factors affecting mining operations. High rainfall intensity can disrupt mining activities, reduce production targets, and increase operational risks, particularly in open-pit mines where exposed slopes are highly sensitive to hydrological changes. According to [2] extreme rainfall events may trigger landslides, flash floods, inundation, fallen trees, and slippery haul roads, all of which intensify geotechnical hazards in mining areas. In open-pit environments, slope failure remains a primary hazard because rainfall infiltration increases pore-water pressure, reduces effective stress, and subsequently decreases shear strength, resulting in lower slope stability [3] and [4].

Rainfall is one of the most influential climatic factors affecting the mining industry [5]. In mining operations, high rainfall intensity can hinder production activities and reduce planned production targets [5]. Water is a primary trigger of slope instability, as rainfall infiltration increases pore water pressure within soil masses, leading to a reduction in shear strength. In addition, the presence of springs or subsurface water flow can accelerate material softening and further compromise slope stability [6]. Slope failures are also frequently associated with improper slope cutting without adequate reinforcement, as well as additional structural loads placed at the slope crest [7].

Dynamic loads, which are temporary and variable in nature, such as vibrations induced by earthquakes, blasting activities, and heavy equipment operation, can further influence slope stability [8]. The movement of water within soil pores is governed by capillary and gravitational forces. Capillary forces allow water to move in multiple directions, driving flow from wetter zones toward drier soil, whereas gravitational forces direct water downward [9]. As soil moisture increases, capillary forces diminish, particularly in coarse-grained soils, while remaining more effective in fine-grained soils such as clay. Consequently, infiltration rates decrease as soil pores become progressively saturated until the infiltration rate equals the percolation rate [9].

The rate of infiltration is influenced by several factors, including surface water depth, thickness of the saturated layer, initial soil moisture, soil compaction due to rainfall, surface interception, vegetation cover, soil conditions, and rainfall intensity [9] and [10] analyzed slope stability in the Gunungpati area using Rocscience Slide and the Fellenius method, obtaining a Factor of Safety (FoS) of 1.043, indicating a critical and unstable slope condition. Similarly, [11] investigated slope stability at the Pango Bridge along the Medan–Banda Aceh roadway using the Bishop Simplified method and reported an initial FoS of less than 1.25, indicating instability; the application of soil nailing subsequently increased the FoS to 1.926, demonstrating the effectiveness of stabilization measures.

PT Baramega Citra Mulia Persada operates under an open-pit mining system, where the sustainability of production activities greatly depends on maintaining slope stability [12]. Slope stability is typically assessed through the FoS, which represents the ratio between the forces resisting movement and the forces driving potential failure along a slip surface [13]. Monitoring and analyzing FoS under different hydrological conditions is therefore critical to prevent slope failures, especially during the rainy season when infiltration and groundwater rise may significantly weaken slope material.

Previous studies highlight various environmental, geological, and hydrological influences on slope stability. [14] examined the impact of groundwater levels using GeoSlope/W 7.12 and showed significant differences in FoS between stable, critical, and unstable slope regions. However, their study was limited to the Morgenstern–Price method and did not specifically focus on direct rainfall infiltration using the Janbu method. More recent research by [15] employed the Janbu Limit Equilibrium Method in Slide to analyze slope stability under fluctuating groundwater levels in a nickel mine, concluding that increased pore-water pressure drastically reduces FoS under saturated conditions. Similarly, [16] integrated blasting vibration monitoring, groundwater observation, and numerical modeling at PT Bukit Asam, demonstrating that saturated conditions significantly reduce FoS, especially when dynamic loading is considered. These studies underscore the importance of drainage, dewatering, and hydrogeological control in open-pit mines.

Although extensive research has been conducted on rainfall-induced slope instability, limited studies have specifically evaluated the combined effects of tropical rainfall, infiltration, and groundwater rise on slope stability in mineral mining operations using the Janbu method. The Janbu Limit Equilibrium Method, widely used for analyzing noncircular slip surfaces in heterogeneous geological formations, is particularly suitable for Indonesian mining environments characterized by complex lithology [17]. Furthermore, several works highlight the importance of understanding soil parameters, groundwater behavior, and material properties in slope design [18].

Based on these considerations, slope stability analysis is essential to minimize safety risks, prevent landslides, and ensure production continuity in mining operations. The research examines the influence of rainfall infiltration on slope stability at PT Baramega Citra Mulia Persada through the application of the Janbu Limit Equilibrium Method. The analysis evaluates the Factor of Safety (FoS) under saturated, semi-saturated, and dry conditions, providing a comprehensive understanding of slope behavior under varying hydrological conditions. The findings are expected to assist the company in designing effective slope stability management strategies, particularly during periods of high rainfall.

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2. Material and Methods

Research Location

This research was conducted at the Outpit Disposal Area – Serongga Site, operated by PT Baramega Citra Mulia Persada (BCMP). Geographically, the study area is located at coordinates 3°24’31’’ S and 116°00’12’’ E. This disposal area serves as the dumping site for overburden material from mining operations, where slope instability may occur due to rainwater infiltration.

The detailed location description is as follows:

1. Access to the Company Office. The distance from Syamsuddin Noor International Airport, Banjarmasin, to the BCMP office is approximately 271 km, with a travel time of around 5 hours by car.
2. Access to the Serongga Pit Area. The travel time from the BCMP office to the Serongga Pit is approximately 1 hour by car through mine haul roads.

The Serongga Site is characterized by low hilly terrain with varying elevations. High-intensity rainfall commonly occurs in this region, which increases soil saturation and enhances the potential for infiltration, ultimately affecting slope stability within the disposal area.

Research Data

This study utilizes secondary data obtained from the company and supporting documents. The required data include:

1. Slope geometry data, including slope height, slope angle, bench width, and overall disposal geometry.
2. Rainfall data for the year 2023, used to evaluate infiltration effects on slope conditions.
3. Topographic and geological maps, to understand regional morphology and material characteristics.
4. Haul truck pressure data, representing surcharge load on the slope surface.
5. Geotechnical parameters, involving parameters like cohesion (c), internal friction angle (φ), and unit weight (γ).
6. Seismic load data, representing horizontal acceleration due to earthquakes.

The geotechnical properties employed in the analysis are summarized in **Table 1**.

Table 1. Data Material Properties

No.	Depth (m)	Dominant Lithology	Unit Weight (kN/m³)	Cohesion Peak (kPa)	Cohesion Residual (kPa)	Friction Angle Peak (°)	Friction Angle Residual (°)
1	82 – 82.55	Sandstone	22.56	–	–	–	–
2	109 – 109.8	Sandstone	22.56	137	87	30.47	18.72
3	5.76 – 6.67	Claystone	19.61	110	65	24.80	16.21
4	15.6 – 16.3	Siltstone	21.48	131	69	27.80	17.48
5	46 – 83	Coal	13.93	150	102	37.37	25.33
6	56.1 – 56.9	Siltstone	21.18	–	–	–	–
7	100 – 100.7	Siltstone	20.01	121	82	29.37	19.51
8	27.4 – 27.92	Siltstone	21.18	135	79	30.68	18.61
9	41.44 – 42.4	Claystone	20.99	131	73	25.30	16.34
10	1 – 1.5	Waste Material	21.38	105	65	28.27	17.88
11	27.87 – 28.68	Claystone	20.20	126	69	27.64	15.46
12	38.5 – 39.27	Coal	13.83	155	107	40.50	24.80
13	42.4 – 43.05	Sandy Claystone	22.56	123	73	30.79	19.42
14	103.4 – 103.9	Claystone	21.48	106	66	25.50	16.70
15	14.45 – 15.40	Claystone	19.81	148	83	2.73	1.54
16	19.9 – 20.88	Coal	12.06	145	95	38.76	23.74
17	8 – 9	Claystone	19.91	107	66	23.11	14.71

Sumber: PT Baramega Citra Mulia Persada (2023)

Slope Cross-Section Data

Slope cross-section data were obtained from the End of Mine (EOM) model of January 2023, provided by the company. The processing stages are as follows:

1. Importing the EOM model into Geovia Surpac 6.6.2.

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2. Creating section lines at the locations recommended by the geotechnical team.
3. Generating cross-sections in Surpac.
4. Exporting the cross-sections to AutoCAD 2007 for smoothing and visualization improvements.

The resulting slope cross-sections include four profiles: AA’, BB’, CC’, and DD’ as shown below.

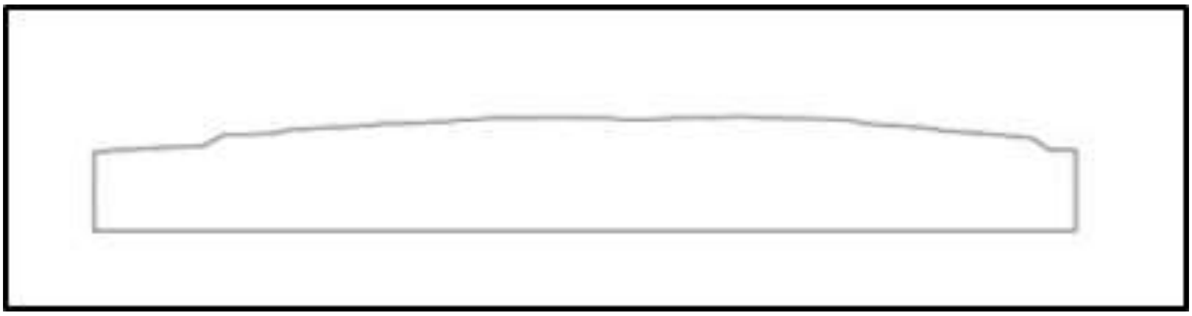


Fig. 1: Cross-Section AA'

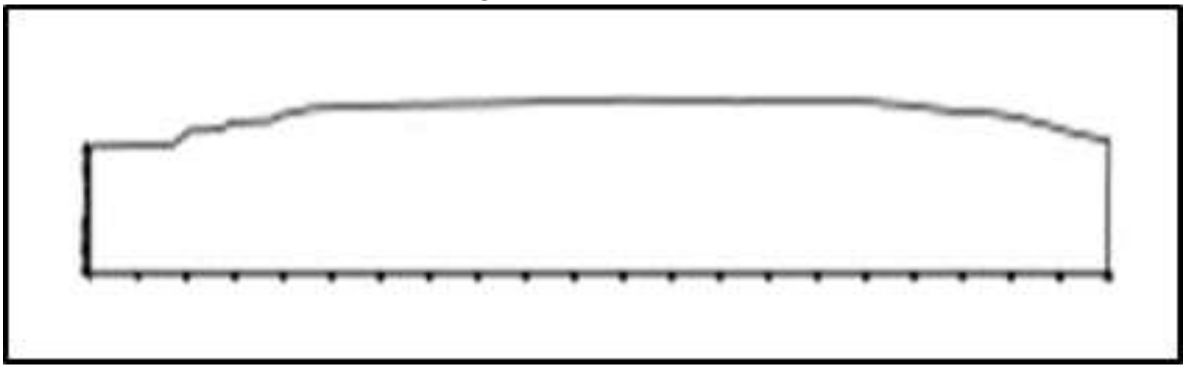


Fig. 2: Cross-Section BB'

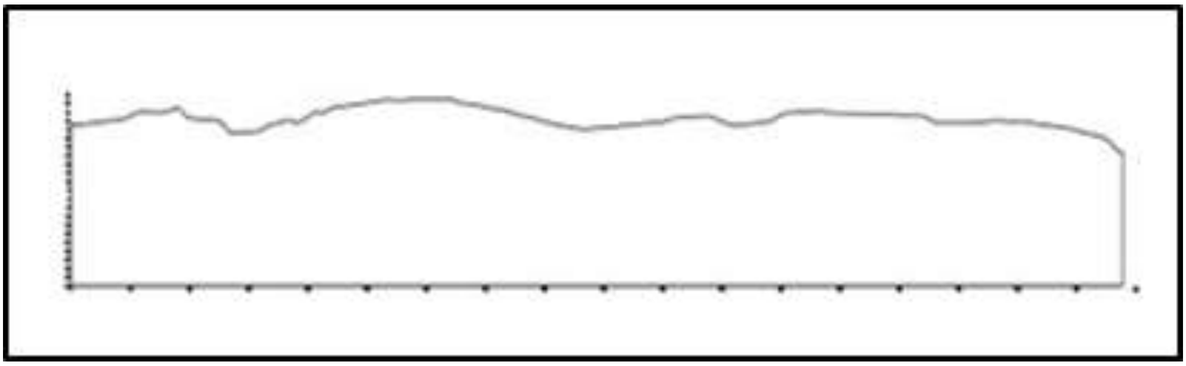


Fig. 3: Cross-Section CC'

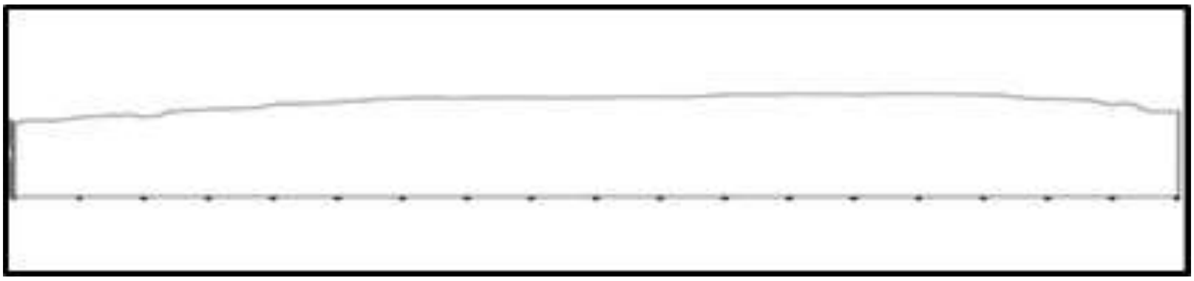


Fig. 4: Cross-Section DD'

Cross-Section Locations

The four cross-sections were selected based on areas with the highest potential for slope instability, as recommended by the mine geotechnical department. The locations of these sections are presented as follows.

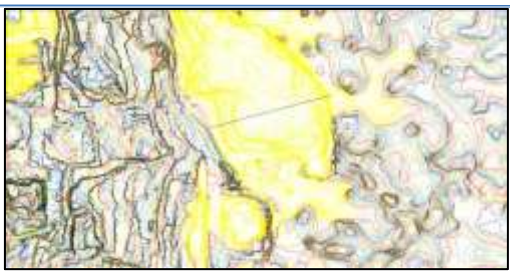


Fig. 5: Location of AA' Section

Fig. 6: Location of BB' Section

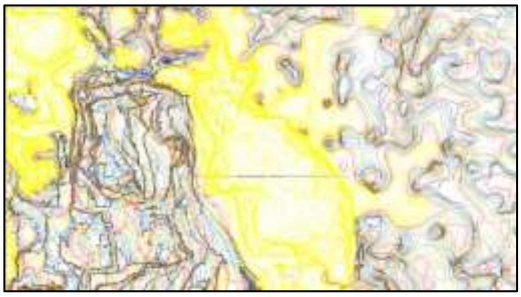


Fig. 7: Location of CC' Section

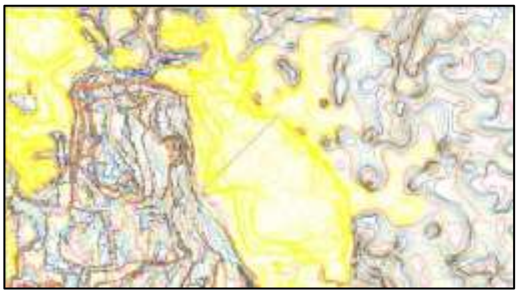


Fig. 8: Location of DD' Section

Groundwater Level Conditions

The groundwater level plays a crucial role in slope stability as increased saturation reduces shear strength parameters. Based on the Geotechnical Study Document of PT BCMP (2022), groundwater assumptions in this study are defined as:

1. Dry Condition. The groundwater table lies near the bottom of the slope, with minimal pore water pressure.
2. Partially Saturated Condition. The groundwater level is assumed to be located at the central height of the slope.
3. Fully Saturated Condition. The groundwater table is considered to follow the slope’s geometry, saturating the entire slope mass.

These three scenarios are incorporated into the LEM analysis to assess the effects of rainfall infiltration on slope stability.

Haul Truck Surcharge Pressure

Surcharge load is generated by heavy equipment traffic on the top of the slope. Observations show that the largest haul truck operating in the study area is the Heavy Duty 785-7. The applied surcharge pressure for analysis is 533 kN/m³, derived from truck specifications and load distribution considerations.

Seismic Coefficient

The seismic load used in this research refers to:

1. The Geotechnical Study Document of PT BCMP (2022), and
2. The 2010 Indonesian Seismic Hazard and Source Map, published by the National Center for Earthquake Studies (PUSGEN).

Based on these references, the seismic coefficient applied in the stability analysis is 0.05 g.

3. Results and Discussion

Factor of Safety for Slope Section AA'

Based on the input of material properties from Table 1, hauling equipment load, and seismic load, the slope stability analysis for cross-section AA' produced the results shown in Figure 9. The saturated condition yields a factor of safety of 1.484, the half-saturated condition results in 1.976 and the dry condition provides the highest stability with a factor of safety of 2.007. These results indicate that the slope remains stable under all three moisture conditions, with the lowest factor of safety occurring during full saturation due to increased pore-water pressure and reduced shear strength.

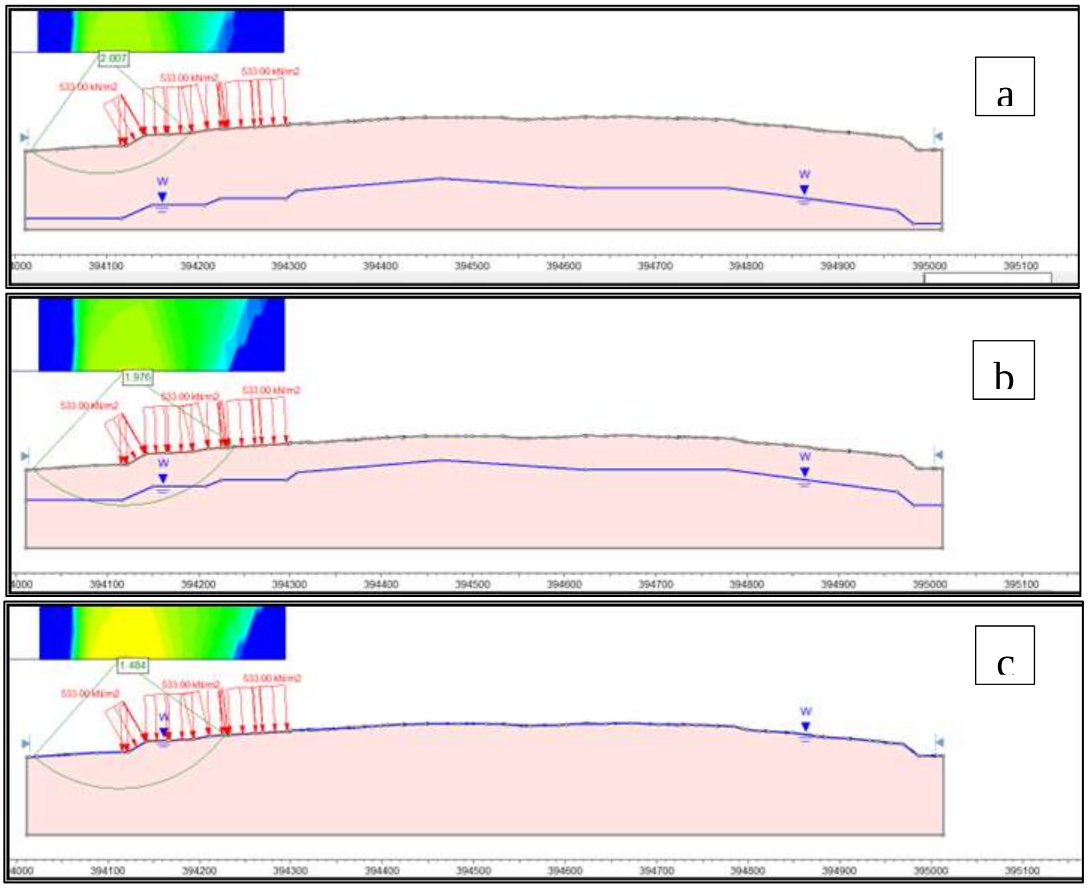


Fig. 9: Cross-section AA': (a) Dry, (b) Half-Saturated, (c) Saturated.

Factor of Safety for Slope Section BB'

For cross-section BB', material properties, equipment loading, and seismic load were analyzed following the same approach. As shown in Figure 10, the saturated condition yields a factor of safety of 1.311, the half-saturated condition increases to 1.650, and The dry condition results in a factor of safety of 1.711. While the slope remains stable under all scenarios, saturation significantly reduces the factor of safety and poses a greater risk of slope deformation compared to the other conditions.

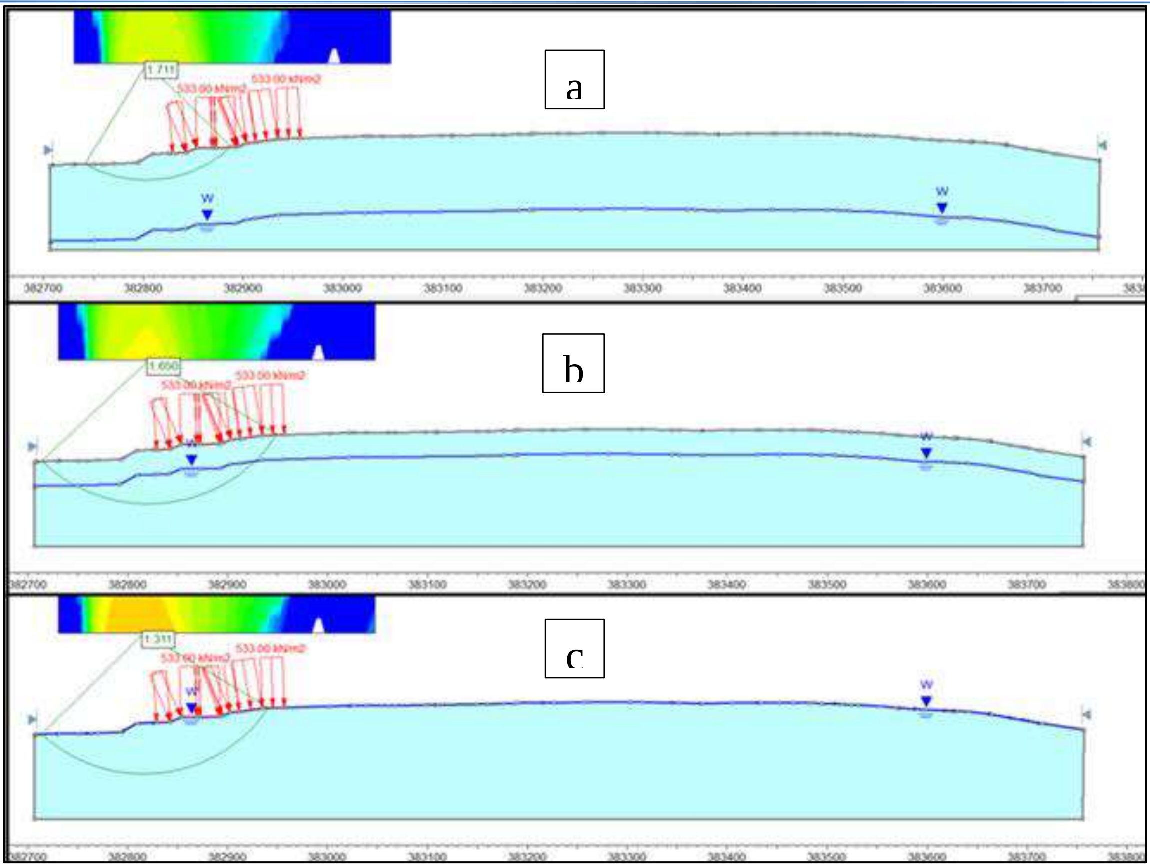


Fig. 10: Cross-section BB’: (a) Dry, (b) Half-Saturated, (c) Saturated

Factor of Safety for Slope Section CC’

The analysis for cross-section CC’ using the parameters in **Table 1**, including hauling load and seismic load, shows that the saturated condition produces a factor of safety of 1.516, the half-saturated condition yields 2.187, and the dry condition yields 2.279 (**Figure 11**). These values demonstrate that section CC’ is stable under all modeled conditions, with minimal reduction in stability during saturation compared to the other slope sections. The difference between the dry and saturated states highlights the sensitivity of the slope to water infiltration.

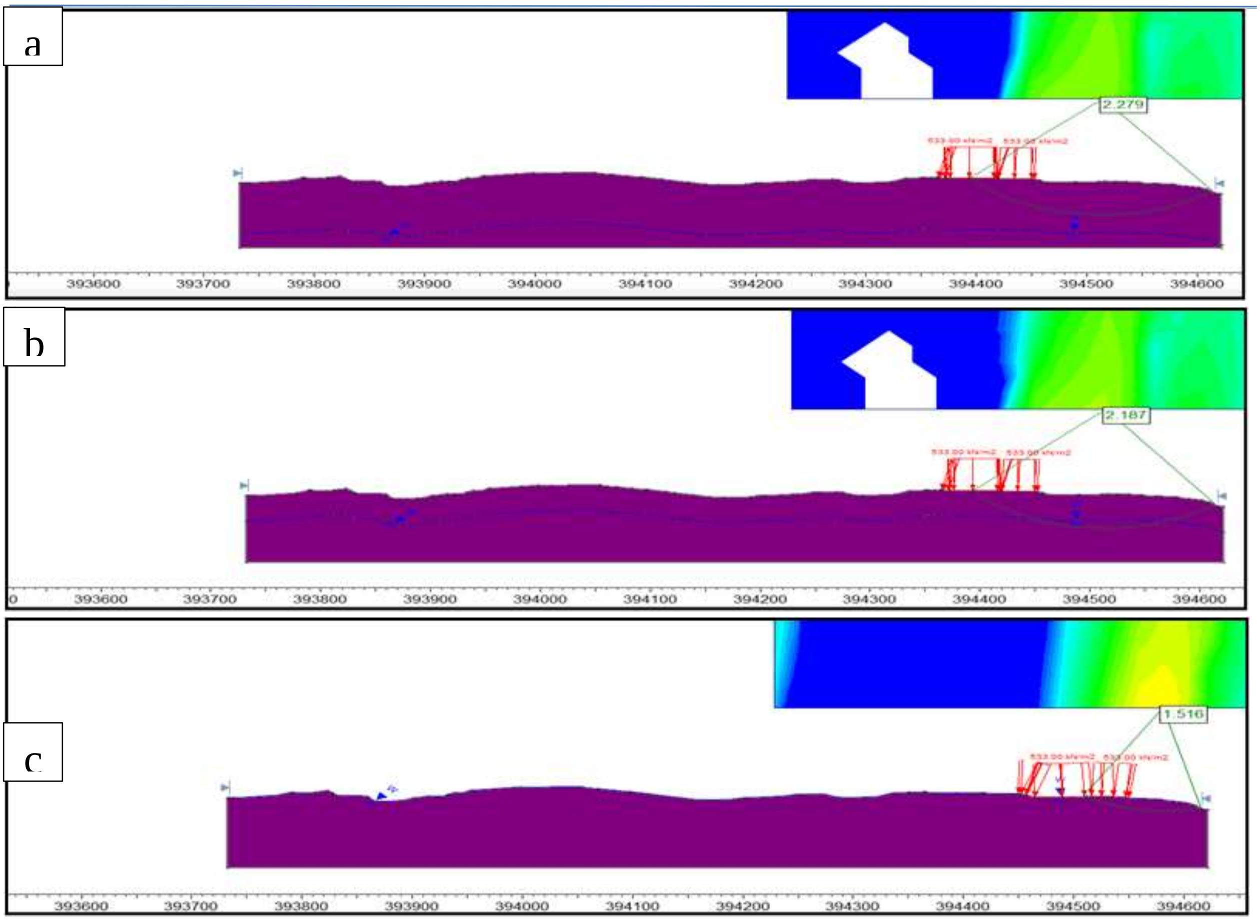
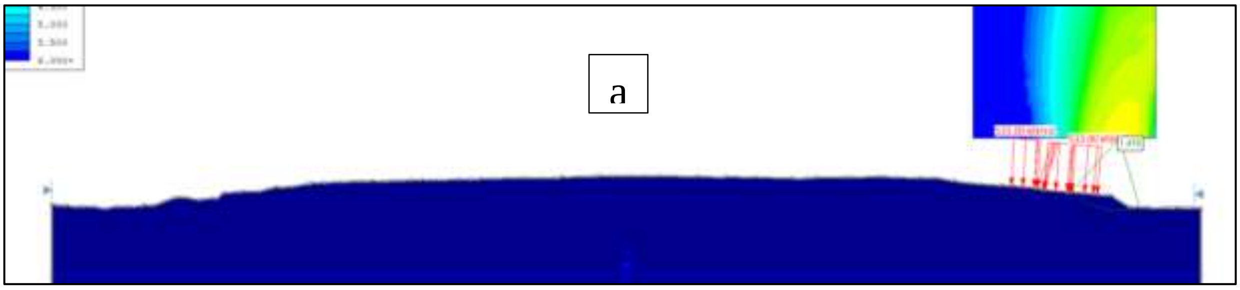


Fig. 11: Cross-section CC': (a) Dry, (b) Half-Saturated, (c) Saturated.

Factor of Safety for Slope Section DD'

Cross-section DD' exhibits the lowest overall stability among the studied sections. As presented in **Figure 12**, the saturated condition yields a factor of safety of only 1.106, which is categorized as unstable according to KEPMEN 1827. Meanwhile, the half-saturated and dry conditions yield factors of safety of 1.374 and 1.470, respectively. The significant reduction under saturated conditions indicates that the slope is highly susceptible to rainfall-induced pore pressure increases and requires corrective measures to ensure long-term stability.



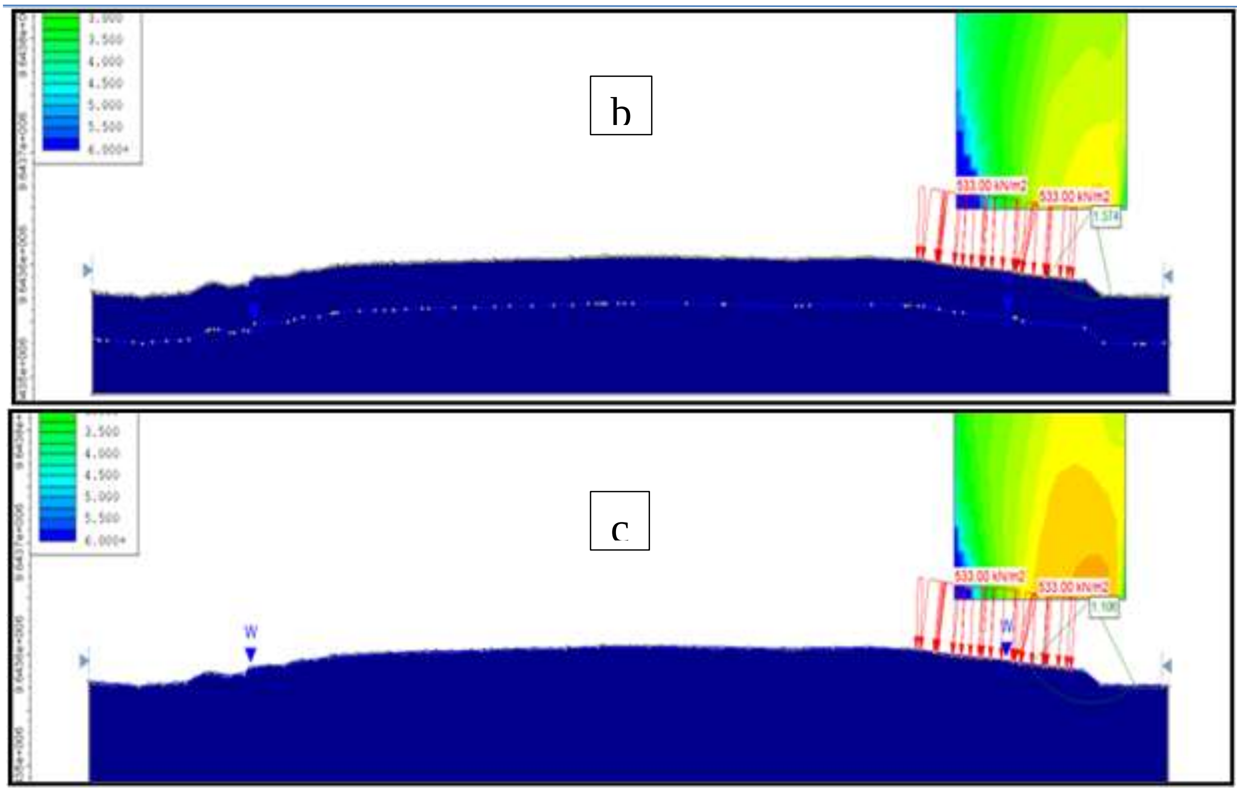


Fig. 12: Cross-section DD’: (a) Dry, (b) Half-Saturated, (c) Saturated.

Slope Improvement

The summary of the factor of safety values for all slope sections is provided in **Table 2**.

Table 2. Overall Factor of Safety Values

No	Condition	AA’	BB’	CC’	DD’
1	Saturated	1.484	1.311	1.516	1.106
2	Half-Saturated	1.976	1.650	2.187	1.374
3	Dry	2.007	1.711	2.279	1.470

Based on Kepmen 1827, slope DD’ under saturated conditions is categorized as unstable because its factor of safety falls below the required minimum threshold (FK < 1.2). Therefore, a geometric improvement was applied to the slope by adding one additional bench with a width of 4.3 meters. The improved configuration is shown in **Figure 13**. Following the geometric modification, the factor of safety rose to 1.514, indicating that the slope regained stability and is better equipped to withstand high rainfall conditions. This improvement is expected to enhance the slope integrity and reduce the likelihood of failure at the outpit disposal area.

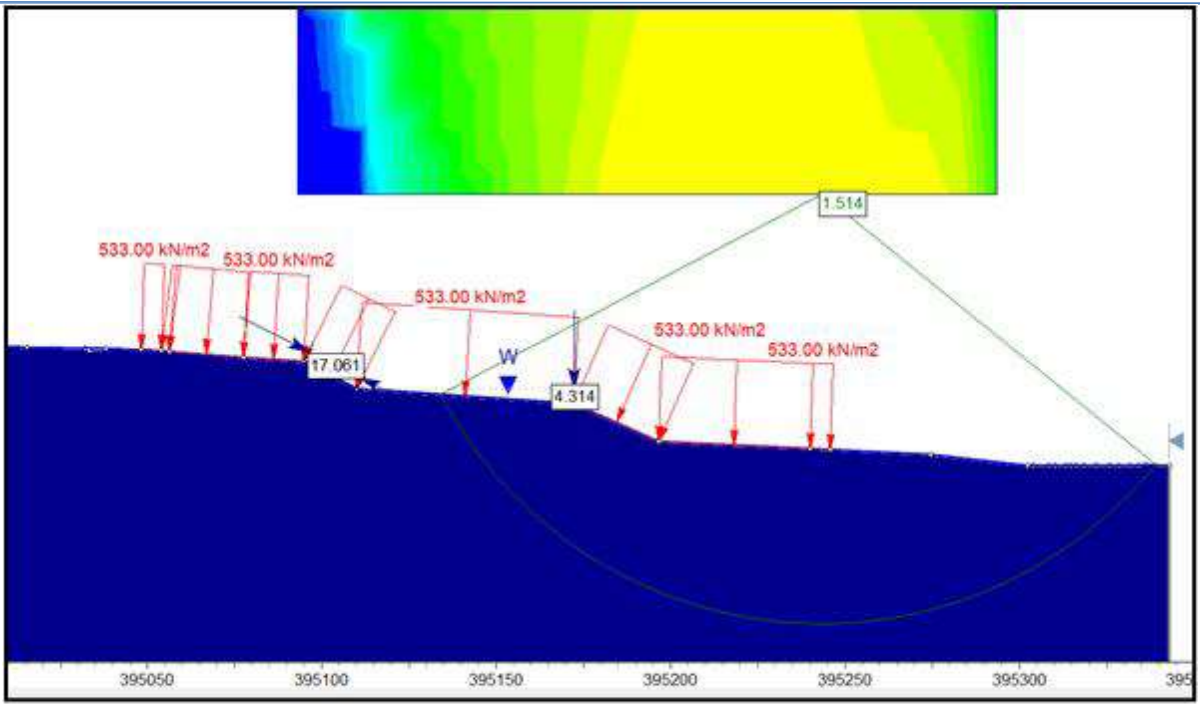


Fig. 13. Improved Slope Geometry for Cross-Section DD'.

4. Conclusion

Overall, the slope stability analysis of the outpit disposal area indicates that the majority of slopes maintain stable safety factors and are expected to reliably support mining activities at PT Baramega Citra Mulia Persada. Since the disposal material consists primarily of residual waste material, high-intensity rainfall has the potential to reduce slope stability. This effect is particularly evident on slope section DD', where maximum rainfall conditions result in an unstable safety factor (FK < 1.2), indicating the need for geometric improvements on this slope. Despite the mine being located in a region with high rainfall intensity, the average safety factor across the Serongga outpit disposal slopes remains above 2 under normal conditions, which is classified as stable. Even under maximum rainfall, the decrease in safety factor approximately 0.5 still places most slopes in a safe condition, given that their dry-condition safety factors exceed 2.

Overall, the stability of the analyzed sections is strongly influenced by groundwater conditions. Lower safety factors consistently occur under saturated conditions, indicating a higher susceptibility to instability when water content increases, while drier conditions provide more favorable stability. This trend highlights the critical role of effective water management and drainage in maintaining slope stability and ensuring safe geotechnical performance across the study area. These results demonstrate that rainfall infiltration significantly influences slope stability, and proper slope design and water management are essential to maintaining safe mining operations.

Based on the results of this study, it is recommended that future research incorporate more detailed rainfall data—particularly duration and intensity—along with the use of geotechnical software capable of real-time infiltration analysis to obtain results that more closely represent field conditions. For the company, improving the consolidation of waste materials is essential to enhance compaction and shear strength, thereby increasing the stability of the outpit disposal slopes. In addition, the application of appropriate vegetation on slope surfaces is advised, as erosion-resistant plants can help bind the soil, reduce erosion, and minimize the potential for slope failure, especially during periods of high rainfall.

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