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OPTIMIZATION OF SLOPE GEOMETRY IN THE HIGHWALL SECTION A-A' OF THE MAHAYUNG PIT, MUARA ENIM, SOUTH SUMATRA

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ABSTRACT

Slope stability is one of the most critical factors in open-pit mining operations. Slope stability has a direct impact on operational safety and production continuity. A slope failure in an open-pit mining operation can result in significant losses, both in terms of human life and material assets. Therefore, slope stability analysis is essential in open-pit mines planning. This study aims to evaluate the safety factors at the Mahayung Pit based on current conditions and the 2026 Pit Design, to subsequently perform design optimization for the Highwall Section A-A'. Slope stability was analyzed using the Morgenstern-Price limit equilibrium method with the Mohr-Coulomb failure criteria. The Morgenstern-Price method was selected because its analysis process satisfies the equilibrium of forces and moments, making it suitable for this application. The analysis was also performed using two groundwater level scenarios: actual conditions and saturated conditions, the effects of vibrations were also accounted for in this slope stability analysis. The geotechnical parameters used include cohesion, internal friction angle, and unit weight, which were obtained from company data. The analysis results indicate that the 2026 Pit Design does not yet meet the minimum safety factor threshold required by Ministerial Decree No. 1827 K/30/MEM/2018. Therefore, geometric optimization was performed by modifying the slope geometry configuration. The results of the design optimization can increase the minimum safety factor (SF) to 1.496 under saturated groundwater conditions. This safety factor value meets the required regulatory standards.

Keywords: Mohr-Coulomb, Morgenstern-Price, open-pit mining, safety factors, slope stability

INTRODUCTION

The Mahayung Pit was previously a waste disposal area that is currently being re-excavated to access the underlying coal seam, which is considered economically viable. The thickness of this old dump material is one of the factors affecting slope stability. Therefore, a geometric evaluation is required to ensure slope stability and guarantee operational safety (Amrullah et al., 2019; Pebrianto et al., 2024). Slope geometry is a critical aspect of open-pit mining because it can directly affect the continuity and smooth operation of mining activities. Ongoing mining operations can cause changes to the shape of slopes in the mining area. These changes affect slope geometry, including height, width, angle, and the condition of the exposed rock (Brady & Brown, 2004).

Slope geometry in the planning phase is generally designed based on initial geotechnical assumptions. However, actual field conditions often yield different data due to variations in rock types, hydrological influences, and heavy equipment operations, making periodic evaluations essential (Hustrulid et al., 2013). The most recent study conducted in the vicinity of this research site, located in Lahat, South Sumatra, demonstrates that slope stability analysis using the Morgenstern-Price limit equilibrium method is effective for determining the optimal slope geometry design (Bagaskoro et al., 2023). The rapid development of Mahayung Pit indicates that the current slope geometry may not be optimal in terms of safety factors. Therefore, slope geometry optimization is necessary to identify the best configuration that maintains safety factors above the required minimum values (Simbolon et al., 2020).

RESEARCH LOCATION

The study was conducted in an open-pit mining area managed by PT. Pamapersada Nusantara is located in Muara Enim Regency, South Sumatra Province (Figure 1).

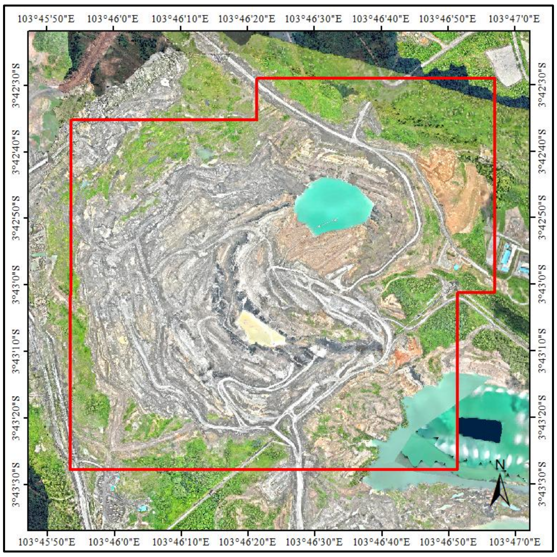

Figure 1. Situation map of the research area (Scale 1 : 12.500)

The study was conducted at the Mahayung Pit, which is part of the Air Laya Mine (TAL) and has a Mining Business License covering an area of 7,582 hectares.

Regional Stratigraphy

In general, the study area is located within the South Sumatra Basin, which consists of the following strata in order from oldest to youngest: Basement, Lahat Formation, Talang Akar Formation, Baturaja Formation, Gumai Formation, Air Benakat Formation, Muara Enim Formation, and Kasai Formation (Barber et al., 2005) (Figure 2).

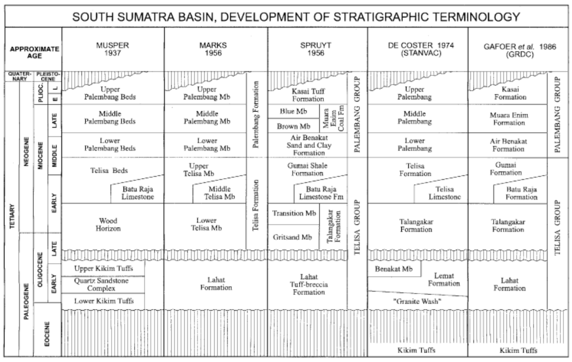

Figure 2. Regional stratigraphic column of the South Sumatra Basin (Barber, et al., 2005)

The specific study area is located within the Muara Enim and Kasai formations which are included in the Lahat Geological Map Sheet (Gafoer et al., 2007), which are listed from youngest to oldest as follows:

1) The Muara Enim Formation (Tmpm)
   This Formation dates from the Late Miocene to Early Pliocene and has a thickness of 450–1,200 m. This formation consists of lithologies including claystone, mudstone, and tuffaceous sandstone with coal interbeds.
2) The Kasai Formation (Qtk)
   This Formation dates from the Early Pliocene to Early Pleistocene with a thickness of 850–1,200 m. It consists of tuff, sandy tuff, and tuffaceous sandstone containing pumice.

The Mahayung Pit study area is characterized by alternating sequences of claystone, siltstone, tuffaceous sandstone, and coal seam intercalations. The stratified structure of these lithologies plays a significant role in analyzing slope stability. This is because layers of claystone and mudstone tend to have low shear strength, making these materials more susceptible to failure. When these inherently vulnerable materials are subjected to high pore water pressure due to groundwater infiltration, the potential for failure increases significantly.

Regional Structure

The Mahayung Pit is located within an anticline fold structure with a northwest-southeast-trending axis, which is part of the Muara Enim Formation (Tmpm) in the Lahat Geological Map Sheet (Gafoer et al., 2007).The pit located on this anticline has an impact that can affect slope stability (Figure 3).

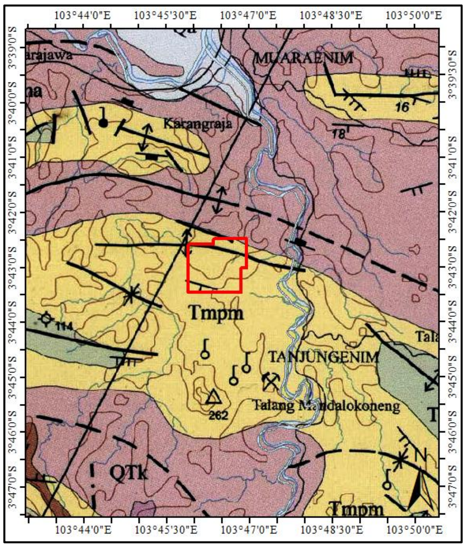

Figure 3. Geological map of the study area (Modified from Gafoer et al., 2007)

The dip of strata parallel to the slope plane can form a slip plane that acts as a trigger for both plane failure and circular failure mechanisms (Arif, 2016). Faults formed due to tensile stress in the anticline zone act as pathways for groundwater infiltration, which can increase pore water pressure and reduce the effective shear strength of slope material (Brady & Brown, 2004). The lithological diversity of the Muara Enim Formation can also increase the potential for landslides, the overburden and interburden alternating with coal layers have the potential to form weak layers that control critical landslide planes (Read & Stacey, 2009).

RESEARCH METHOD

Slope geometry optimization was performed using an iterative trial-and-error approach in Slide 6.0 software. The analysis was conducted using the Morgenstern-Price limit equilibrium method and the Mohr-Coulomb failure criteria. The optimization process begins by identifying cross-sections with a safety factor (SF) value below the minimum threshold required by Indonesian mining regulations (KEPMEN 1827 K/30/MEM/2018), which stipulate SF ≥ 1.3. For slopes with values below the established standard, slope geometry optimization was performed by altering the bench width, bench height, and single-slope angle without changing the material properties constituting the slope. Each slope geometry reconfiguration experiment was conducted under actual groundwater level and saturated groundwater level conditions using the applied seismic coefficient. Reconfiguration was performed until the lowest safety factor value was achieved in all scenarios above the established standard.

Slope Safety Factor

Landslides occur as a result of a disturbance in slope stability. This equilibrium is determined by the relationship between the driving force and the resisting force. The driving force is calculated based on unit weight, while the resisting force is calculated from the shear strength of the material, which consists of cohesion (c) and the angle of internal friction (φ). Slope stability, as assessed by its safety factor (SF), is calculated by comparing the resisting force to the driving force (Arif, 2016).

$$\left(\mathrm{SF} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}\right)$$

This study uses the safety factor standards set forth in Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018 on Guidelines for the Implementation of Good Mining Practices (Table 1).

Table 1. Safety factor (SF) values and landslide probability (PoF) for mine slopes (Ministerial Decree No. 1827 K/30/MEM/2018, 2018)

Type of Slope	Consequences of Failure	Acceptance Criteria		
		Static SF (Min)	Dynamic SF (Min)	PoF (Max)
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%

Factors Affecting Slope Stability

Arif (2016) identified factors that can affect slope stability, including:

1) Slope Geometry: Slopes with steeper gradients and greater elevations can generate greater thrust, thereby reducing slope stability.
2) Physical and Mechanical Properties of Materials: Material properties such as high unit weight and low shear strength (low cohesion and low internal friction angle) can affect slope stability and increase the risk of failure.
3) Geological Structure: Discontinuities such as faults, fractures, and rock bedding can act as water pathways that function as weak layers, increasing the risk of slope failure.
4) Weather and Climate: Rainfall can affect slope stability because it increases the moisture content and saturation level of the slope material.
5) Groundwater: Groundwater can affect slope stability because its presence can increase pore water pressure and slope load, causing the shear strength of the material to decrease under saturated conditions.
6) Vibrations: Seismic activity can affect slope stability because it can disrupt the slope's equilibrium due to vibrations caused by earthquakes or mining activities.

This study has limitations regarding groundwater level measurement data due to limited access to monitoring records at the study site. Consequently, the groundwater conditions used in the slope stability analysis were established based on available site information and engineering assumptions.

Two groundwater scenarios were evaluated: (1) the actual groundwater condition, represented by a phreatic surface located approximately 5–7 m below the ground surface, and (2) a fully saturated condition representing a conservative scenario. The actual groundwater level was interpreted from available site observations rather than direct piezometric measurements. Therefore, the groundwater conditions adopted in this study should be considered as assumptions used for analytical purposes.

The effect of vibrations is considered using an earthquake acceleration value of 0,0135 g as the horizontal coefficient, derived from calculations according to Hynes-Griffin & Franklin (1984), which state that the Kh value is equal to 50% of the peak ground acceleration (PGA).

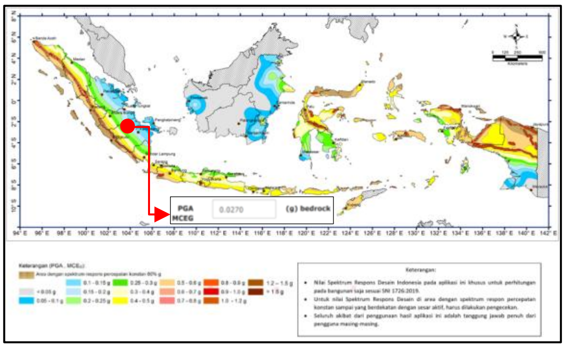

Figure 4. Map of the Maximum Considered Earthquake (MCE) (Desain Spektra Indonesia, 2021)

The PGA value used is 0,027 g based on the Maximum Considered Earthquake (MCE) Map (Figure 4). The effects of heavy equipment activity are also incorporated into the slope stability analysis as a vertical coefficient. In this study, seismic loads use coefficients ranging from 0,013 to 0,03 g (Ningrum et al., 2019). These coefficient values are derived from the heavy equipment activities of the Dump Truck HD and DT units (Table 2).

Table 2. Vibration measurement data obtained using the Blastmate III (Ningrum et al., 2019)

No	Description	Total Load (ton)			PPV(mm/s)			PPA (g)		
		Empty	Content	Total	Trans	Ver	Long	Trans	Vert	Long
1	HD 465	43,1	50	93,1	0,13	0,13	0,13	0,027	0,03	0,013
	HD 785	72	100	172						
2	DT HINO	35	24,02	59,02	0,13	0,13	0,25	0,027	0,03	0,027
	HD 465	43,1	50	93,1						
	HD 785	72	100	172						

Slope Stability Analysis Methods

a. Limit Equilibrium Method

The Limit Equilibrium Method is a commonly used approach for analyzing the stability of slopes under rotational and translational forces. In this method, the safety factor (SF) is calculated based on force equilibrium, moment equilibrium, or a combination of both, depending on the chosen calculation method. The basic principle of this method is to calculate the ratio between the resisting force and the driving force.

b. Morgenstern-Price Method

The Morgenstern-Price method is a slope stability analysis method based on the principle of limit equilibrium, developed by Morgenstern and Price in 1965. This method analyzes the equilibrium of normal forces and moments acting on each slice of the potential landslide plane. The main assumption in this method is that the shear stress gradient between sections is directly proportional to a specific function. The equilibrium conditions that must be satisfied include equilibrium of vertical forces, horizontal forces, and moments (Krahn, 2004).

Geotechnical Parameters

According to data obtained from the company (Table 3), the Highwall Section A-A′ of the Mahayung Pit consists of several materials, each with geotechnical parameters such as unit weight (γ), cohesion (c), and internal friction angle (φ).

Table 3. Material properties for slope stability analysis

Material	Unit Weight (kN/m^3)	Cohesion (Kpa)	Internal Friction Angle (°)
Old Dump	18,63	19,34	11,27
Top Soil	16,98	23,43	11,40
OB A1	20,40	60,30	15,26
Seam A1	12,01	174,21	24,18
IB A1-A2	19,12	97,70	18,99
Seam A2	12,02	223,56	18,73
IB A2-B1	20,15	59,62	15,94
Seam B1	12,16	165,29	28,87
IB B1-B2	20,75	38,82	16,08
Seam B2	11,95	284,67	24,71
IB B2-C	20,51	68,83	15,19
Seam C	11,79	173,61	25,35
UB C	20,73	79,02	16,28

RESULT

Slope Stability Analysis

Slope stability analysis was conducted by considering influencing factors such as the groundwater level and vibrations. The influence of the groundwater level is a critical factor that must be taken into account in optimizing the geometry of open-pit mine slopes (Wijengshe et al., 2024). In general, the actual slope conditions of Highwall Section A-A′ have an overall slope of 8° with an overall slope height of 96 meters. Highwall Section A-A′ is divided into 7 benches based on the actual slope conditions with the following details is on Table 4.

Table 4. Actual geometry of highwall section A-A'

Highwall Section A-A′			
Bench	Slope (°)	Height (m)	Width (m)
1	42	9	132
2	11	2	132
3	45	6	209
4	6	6	112
5	26	9	112
6	19	19	30
7	25	12	33

The results of the slope stability analysis for Highwall Section A-A′ indicate that the safety factor (SF) values, both under actual groundwater level (GWL) conditions and saturated conditions, fall into the unstable category, specifically 1.085 and 0.807 (Figure 5 and Figure 6).

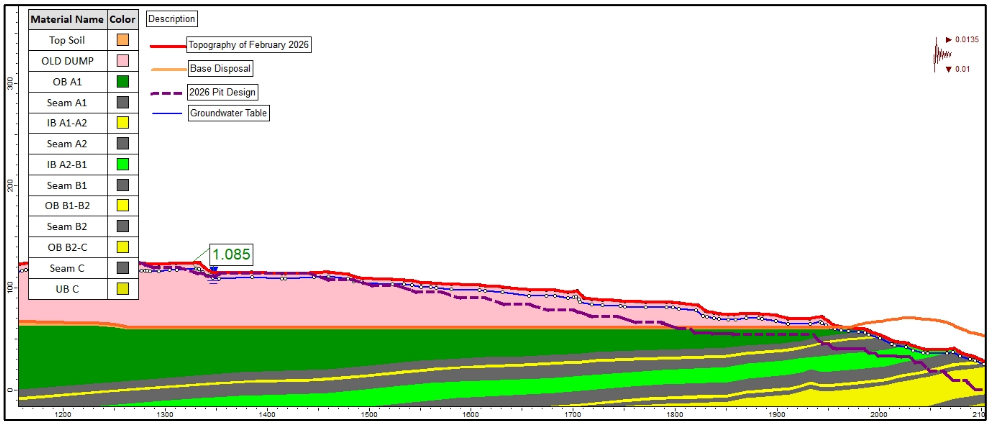

Figure 5. Simulation of slope safety factor values under actual GWL conditions

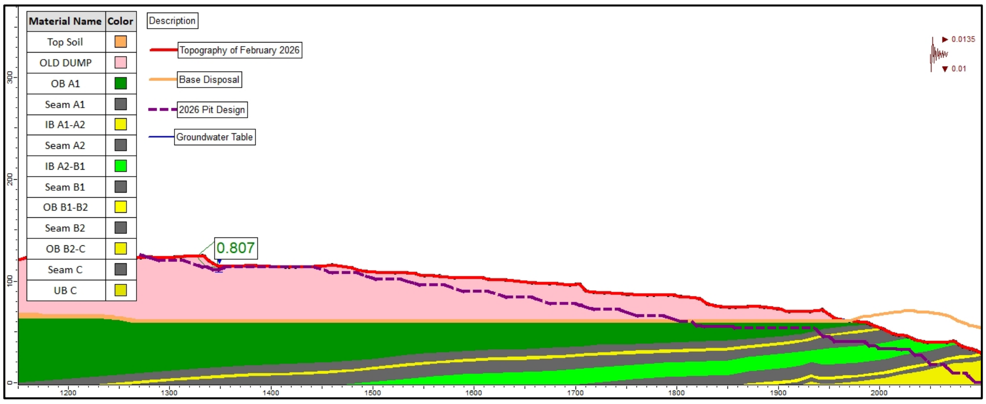

Figure 6. Simulation of actual slope safety factor values for saturated GWL conditions

2026 Pit Design

Based on the 2026 Pit Design, the slope conditions of Highwall Section A-A’ have an overall slope of 10° with an overall slope height of 114 meters. Highwall Section A-A’ is divided into 18 benches with the following details on

Table 5. Geometry of the Highwall 2026 Mahayung Pit Design (Section A-A’)

Highwall Section A-A’			
Bench	Slope (°)	Height (m)	Width (m)
1 - 9	18	6	25
10	45	4	11
11	45	9	115
12	45	4	5
13	45	4	30
14	45	4	5
15	45	5	30
16	45	9	6
17 - 18	45	9	13

The results of the slope stability analysis for the 2026 Pit Design on Highwall Section A-A’ indicate that the safety factor (SF) values—both under actual groundwater level (GWL) conditions and saturated conditions—fall into the unstable category, at 1.098 and 0.950, respectively. This indicates that the 2026 Pit Design cannot yet guarantee slope safety and cannot improve the slope safety factor under actual conditions; therefore, optimization is required to improve the slope safety factor (Figure 7 and Figure 8).

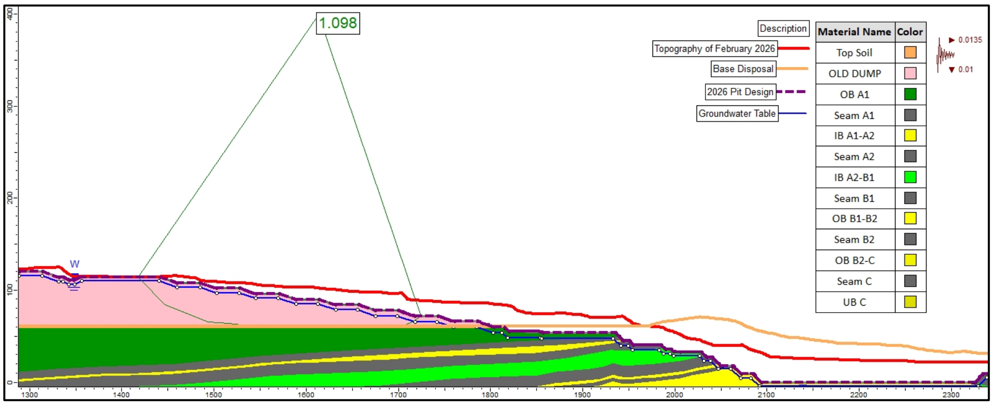

Figure 7. Simulation of the 2026 Pit Design safety factor under actual GWL conditions

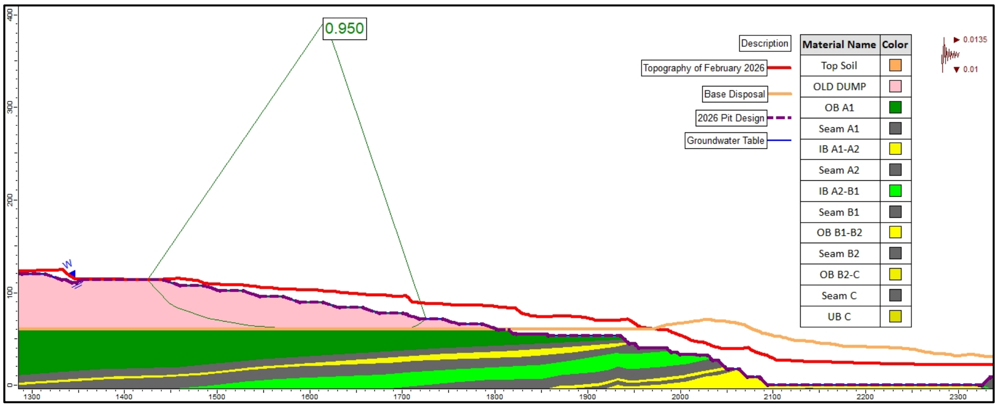

Figure 8. Simulation of the 2026 Pit Design safety factor under saturated GWL conditions

Slope Geometry Optimization

Based on the results of the slope stability analysis for the 2026 Pit Design, it is evident that optimization is possible. This is because the safety factor falls below the standard, indicating that the slope is in an unstable condition. In this design recommendation, an optimized design will be developed for both actual and saturated groundwater conditions.

The simulation results show that to achieve a safety factor that meets the standard, design optimization can be performed on the old dump material slope. The slope on the old dump material is designed with 8 benches, each having an overall slope of 8°. The slope design for the in-situ material follows the 2026 Pit Design. In general, the total slope height is 114 meters with an overall slope of 10°, with the following details is on Table 6. The results of the slope stability analysis for the optimization of Highwall Section A-A′ show that the safety factor (SF) values—both under actual groundwater level (GWL) conditions and saturated conditions—fall within the stable category, at 1.826 and 1.496, respectively (Figure 9 and Figure 10).

Table 6. Geometry of the Highwall Design Optimization (Section A-A′)

Highwall Section A-A′			
Bench	Slope (°)	Height (m)	Width (m)
1 - 4	18	6	25
5	18	6	40
6 - 8	18	6	25
9	40	2	6
10	18	6	25
11	45	4	11
12	45	9	115
13	45	4	5
14	45	4	30
15	40	2	6
16	45	5	30
17	45	9	6
18	45	9	13

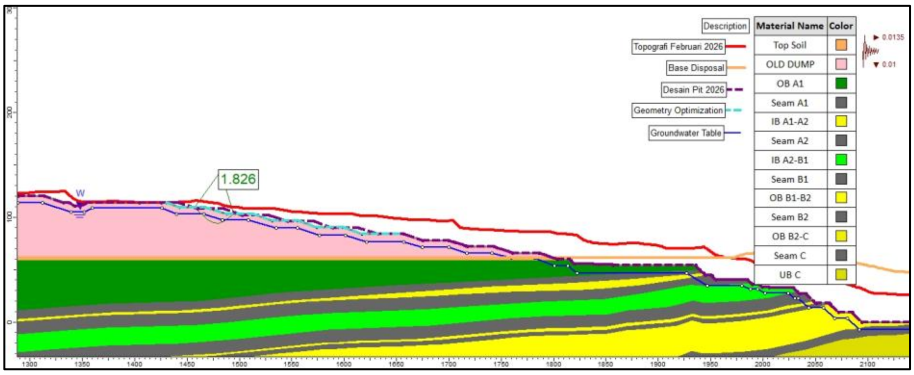

Figure 9. Simulation of safety factor values for slope geometry optimization actual GWL conditions

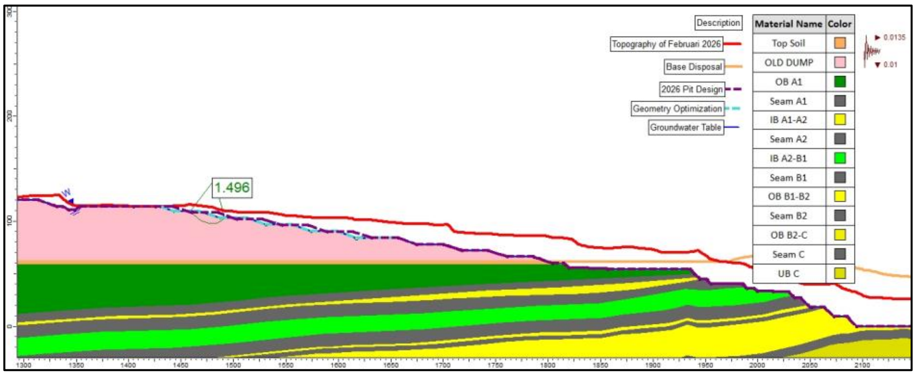

Figure 10. Simulation of safety factor values for slope geometry optimization under saturated GWL conditions

DISCUSSION

The results indicate that the safety factor values under both the actual condition and the 2026 Pit Design are below the minimum standard prescribed by KEPMEN 1827 K/30/MEM/2018, which mandates a static SF ≥ 1.3 for overall slopes under medium to high consequence of failure. The marginal difference between the actual slope (SF = 1.085) and the 2026 Pit Design (SF = 1.098) under actual groundwater conditions suggests that the planned design was developed without adequate consideration of the geomechanical characteristics of the old dump material, making geometry-based intervention necessary.

Slope stability analysis for Highwall Section A–A' uses materials with diverse geotechnical characteristics. This diversity can influence slope behavior. Table 3 presents the proposed material data for several material units, such as the old dump, cover layer, intermediate layer, and bottom layer, obtained from laboratory test results. Overburden and interburden materials have varying shear strength values, while the coal layer, which has relatively higher strength properties, acts as a potential weak plane depending on the orientation of its layer inclination relative to the slope. The old dump material is one of the primary factors controlling slope instability because its shear strength values tend to be lower (c = 19.34 kPa, φ = 11.27°) compared to all other materials. Other materials have a secondary influence because the shear planes identified through Morgenstern-Price analysis consistently pass through the old dump layer.

Old dump material is a mixture of overburden and interburden lithologies, consisting of claystone, siltstone, and sandstone, resulting from previous mining excavation activities. This is consistent with previous research conducted at the Air Laya Mine disposal site, which identified the old dump material as generally loose, dominated by clay-silt grain sizes with low shear strength (Aprilian et al., 2021). The re-compaction process resulting from accumulation during the disposal of excavated material causes a decline in the material’s engineering properties. The properties of old dump material, characterized by low cohesion and low internal friction angle, mean that when this material is in saturated groundwater conditions, it can accelerate the loss of its effective shear strength. This makes old dump material have a significant influence on the overall stability of the highwall section a-a’ slope. The slope also exhibits sensitivity to changes in the groundwater level, as evidenced by a significant decrease in the safety factor from 1.826 to 1.496 between actual and saturated groundwater level conditions in the design optimization results. This decrease is caused by an increase in pore water pressure that reduces the effective normal stress along the potential slip plane (Wijengshe et al., 2024); ignoring the influence of this saturation level in open-pit slope optimization can result in unsafe design outcomes. Therefore, dewatering and surface drainage management measures must be considered as operational complements to the optimized geometry. Changing the slope geometry of the material in the old dump to 8 benches with an angle of 18° was shown to increase the safety factor above the standard used for both groundwater level conditions without altering the physical and mechanical properties of the material. The increased safety factor value following optimization is influenced by changes in slope geometry and the overall slope angle. These changes reduce the thrust forces acting on the slope mass while maintaining the same material strength parameters, thereby achieving a better balance between retaining forces and thrust forces. These results align with the findings of Simbolon et al. (2020) and Amrullah et al. (2019), whose research at the Air Laya Mine confirmed that targeted geometric adjustments in zones of weak material are effective for improving slope stability in the context of coal mining.

CONCLUSION

Slope geometry and the groundwater level are the two most significant factors in determining slope stability in the highwall section A-A'. Slopes with relatively steep gradients generate greater thrust forces, thereby reducing the slope's resistance to failure. When the slope reaches saturated conditions, the risk of failure increases significantly, as evidenced by the decrease in the safety factor from 1.098 under actual groundwater level conditions to 0.950 under saturated conditions in the 2026 design. This decrease causes the safety factor value to fall far below the standard of SF ≥ 1.3 required by Ministerial Decree No. 1827 K/30/MEM/2018. This is caused by water filling the voids between soil particles, thereby increasing pore water pressure and weakening the cohesive forces between materials, which ultimately leads to slippage.

The minimum safety factor for the 2026 Pit Design was determined to be 1.098 under actual groundwater level conditions and 0.950 under saturated conditions, based on the results of the analysis conducted. These values fall below the established safety factor standards. The safety factor values are also below standard under actual slope conditions, namely 1.085 under actual groundwater level conditions and 0.870 under saturated conditions. This indicates that both the 2026 Pit Design and the actual slope conditions do not meet the required standards, necessitating design optimization. After design optimization is performed, the minimum safety factor can increase significantly to 1.826 under actual groundwater level conditions and 1.496 under saturated conditions. This indicates that a slope with better stability can be achieved through geometric adjustments without altering the physical or mechanical characteristics of the constituent materials.

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