SLOPE STABILITY ANALYSIS OF DISPOSAL AREA WITH GROUNDWATER TABLE AND MATERIAL DENSITY VARIATIONS USING THE BISHOP METHOD

Deea Rizki Oziana[1]*, Farhan Ramadhandi[1], Zati Hulwani[1], Hendra harisman[1], Pocut Nurul Alam[1]
[1]Department of Mining Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
*Email: deearizki.oziana@usk.ac.id

ABSTRACT

Slope stability is crucial in mining activities, particularly in disposal areas composed of loose materials with varying geotechnical conditions. Groundwater level and material density are significant factors that influence slope stability. This study aims to analyze the effects of groundwater level variations and material density on the safety factor of disposal slopes using the Bishop method within the GeoStudio SLOPE/W software framework. The research was conducted in a coal mine disposal area, divided into three cross-sections: A–A’, B–B’, and C–C’. Simulations were performed under three conditions: unsaturated (normal), saturated (due to intense rainfall), and threshold (the maximum critical condition still considered stable). The results show that rising groundwater levels significantly reduce the slope’s safety factor (SF). Under saturated conditions, the SF for all three cross-sections dropped below 1.0, indicating unstable slopes. Specifically, the SF declined from 1.15 to 0.72 for section A–A’, from 1.16 to 0.55 for B–B’, and from 1.18 to 0.81 for C–C’. In contrast, an increase in wet material density led to only moderate reductions in SF, with values remaining above 1.0. The combination of high groundwater levels and increased material density poses a critical risk factor for potential slope failure. Continuous hydrogeological monitoring is therefore essential to ensure the long-term stability of mine disposal areas.

Keywords: slope stability, groundwater table, material density

1. INTRODUCTION

1.1 Background

Slope stability in mining is influenced by many factors, including moisture content and density. Increased water content, especially groundwater, reduces slope stability by raising pore water pressure and reducing effective stress (Pan et al., 2020), ultimately decreasing shear strength. Behera et al. (2016) and Hoy et al. (2024) stated that increased pore pressure due to rainfall infiltration is a common trigger of slope failure in disposal areas. High material density can improve cohesion but may also raise driving forces.

Groundwater has a major impact on slope stability (Dwinagara et al., 2020; Brakorenko et al., 2019). Shear strength parameters depend on moisture content due to increased pore pressure and decreased effective stress (Nuraidah et al., 2024). Water also acts as an uplifting force opposing gravity, reducing friction along discontinuities (Brakorenko et al., 2019). Brakorenko et al. (2024) showed regular decreases in cohesion and internal friction angle with increasing water content. Dwinagara et al. (2020) stated that groundwater level influences slope stability by more than 75%; the more saturated, the lower the safety factor.

Material density influences slope stability. According to Nuraidah et al. (2024), saturated density affects soil strength and compressibility. While increased density may improve strength, there is an optimal compaction point beyond which shear strength may decrease. Water saturation reduces shear strength more than density increases it. As saturation exceeds 40%, the increased water film between particles reduces effective stress and cohesion. As dry density increases, particle spacing decreases and cohesion improves due to stronger adsorptive forces.

This research analyzes slope stability under groundwater table variations (saturated and unsaturated) and material density changes. It also assesses the combined impact of both factors—an area less studied in new disposal sites. Limited geotechnical data during early disposal stages hampers risk mitigation. This study addresses that gap using Bishop's method to evaluate slope stability in a new disposal area at PT Indonesia Pacific Energy.

2. RESEARCH METHODS

Research methodology

This study uses a descriptive-quantitative approach, applying the Simplified Bishop Method to assess slope stability in a coal mine's disposal area. The Bishop Method is considered appropriate for simulating actual load conditions on soil and rock (Bishop et al., 2000, in Agbelele et al., 2023). The analysis used geotechnical investigation data processed with GeoStudio SLOPE/W software.

2.1 Research Place

The study area is the disposal site of PT Indonesia Pacific Energy's coal mine. The data used includes secondary lab and geotechnical investigation results. Slope material parameters (Table 1) include.

Table 1. Disposal Slope Material Parameters

Parameter	Unit	Soil	Clay stone	Soft Material	Disposal
Unit Weight (γ)	kN/m³	18	22	15	20
Friction Angle (ϕ)	°	20	25	20	25
Cohesion (c)	kPa	25	40	15	25
Wet Unit Weight (γ)	kN/m³	20	24	16	21

2.2 Slope Cross-Sections

The disposal slope is divided into several cross-sections, namely A–A', B–B', and C–C', each with different geometric configurations and groundwater table depths, as follows:

1. Cross-section A–A': Length 320.5 m, height 6.3 m, slope angle 24°, groundwater table depth 2–10 m.
2. Cross-section B–B': Length 279.2 m, height 10 m, slope angle 22°, groundwater table depth 3–19 m.
3. Cross-section C–C': Length 311 m, height 4.8 m, slope angle 12°, groundwater table depth 9 m.

2.3 Assumptions and Modelling Approach

The slip surface was identified using the Grid & Radius Search algorithm with a circular slip surface, by the assumptions employed in the Bishop method. The phreatic line model was used to represent the groundwater table, with variations in the groundwater condition classified into three main scenarios:

1. Unsaturated condition: Represents the actual groundwater table located beneath the slope surface.
2. Saturated condition: A combined scenario where the soil is at its wet density and the groundwater table reaches its maximum level, assumed to occur during extreme rainfall events.
3. Threshold condition: Represents a scenario where the groundwater table is gradually raised to identify the critical condition at which the Safety Factor (SF) approaches 1.0

2.4 Analytical Procedures

The analysis of the Safety Factor (SF) results is based on the standard KEPMEN ESDM No. 1827K/30/MEM/2018, with the following classification:

1. SF ≥ 1.2: Stable
2. 1.0 ≤ SF < 1.2: Critical
3. SF < 1.0: Unstable

3. RESULTS AND DISCUSSION

3.1 Research Results

Rainfall infiltration into the soil is one of the contributing factors to slope instability (Pan Y., et al., 2020). This occurs because the infiltration of rainwater alters the groundwater table depth, potentially saturating the soil and forming slippery layers that increase the likelihood of soil slippage. The influence of the groundwater table on slope stability is such that the more saturated the soil becomes, the lower the Safety Factor (SF) tends to be, and vice versa.

3.1.1. Safety Factor of Cross-Sections A–A', B–B', and C–C' under Unsaturated Conditions

Cross-section A–A' has a slope length of 320.5 meters, a slope height of 6.3 meters, a single slope angle of 24°, and a groundwater table depth of 2–10 meters under unsaturated conditions. Cross-section B–B' has a slope length of 279.2 meters, a slope height of 10 meters, a single slope angle of 22°, and a groundwater table depth of 3–19 meters in the unsaturated state. Cross-section C–C' has a slope length of 311 meters, a slope height of 4.8 meters, a single slope angle of 12°, and the groundwater table is located 9 meters below the ground surface.

The Safety Factor (SF) analysis results for each cross-section under unsaturated conditions are shown in Figures 1, 2, and 3.

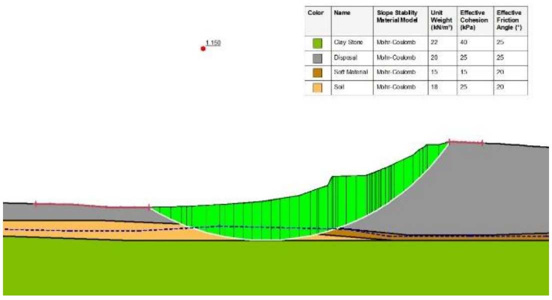

Figure 3.1 Safety Factor (SF) Analysis Result for Cross-Section A–A' under Unsaturated Conditions

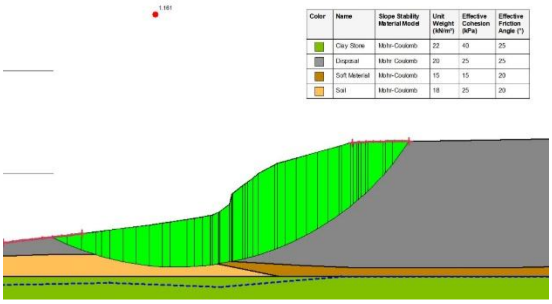

Figure 3.2. Safety Factor (SF) Analysis Result for Cross-Section B–B' under Unsaturated Conditions

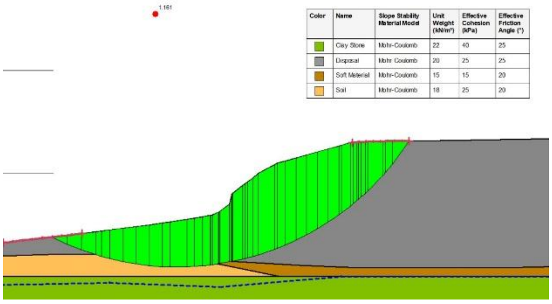

Figure 3.3. Safety Factor (SF) Analysis Result for Cross-Section C–C' under Unsaturated Condition

3.1.2. Safety Factor of Cross-Sections A–A', B–B', and C–C' under Saturated Conditions

Under saturated conditions, it is assumed that the groundwater table rises to the surface along each slope cross-section to represent the worst-case scenario of extreme rainfall. This simulation aims to illustrate the maximum possible saturation level across the disposal slope surface. Cross-sections for saturated conditions are provided below.

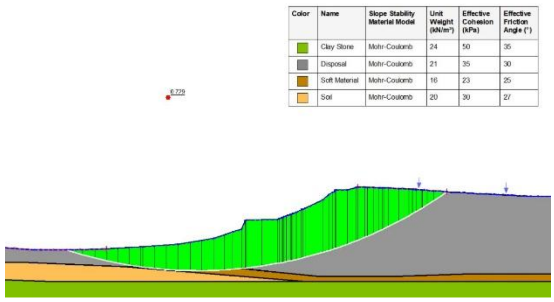

Figure 3.4. Safety Factor (SF) Analysis Result for Cross-Section A–A' under Saturated Conditions

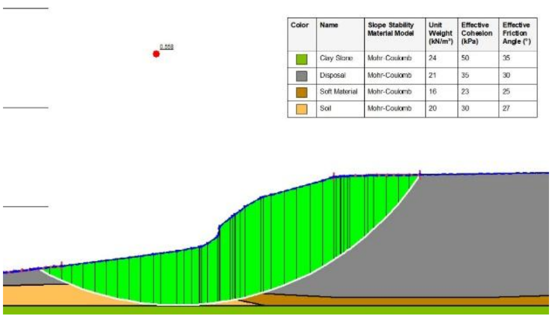

Figure 3.5. Safety Factor (SF) Analysis Result for Cross-Section B–B' under Saturated Conditions

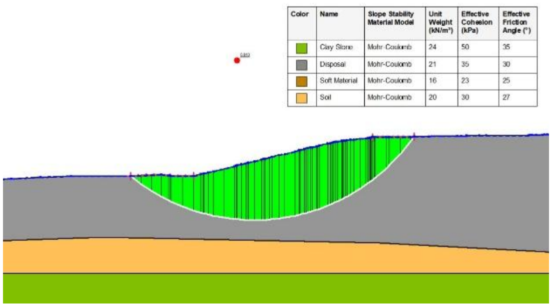

Figure 3.6. Safety Factor (SF) Analysis Result for Cross-Section C–BC' under Saturated Conditions

In cross-section A–A', the groundwater table reaching the highest level leads to a considerable increase in pore water pressure, which in turn reduces the slope's safety factor. The calculated Safety Factor (SF) for this condition is 0.72, indicating an unstable slope according to the KEPMEN ESDM standard. A similar trend is observed in cross-section B–B', where the SF drops to 0.55 under maximum saturation, again classifying the slope as unstable. Likewise, in cross-section C–C', the SF decreases to 0.81 under saturated conditions, which also places the slope in the unstable category.

These results demonstrate that all three slope sections become unstable when subjected to extreme saturation. The sharp decline in SF under these conditions highlights the critical role of pore water pressure in weakening both cohesion and effective shear strength, findings consistent with the theory proposed by Fredlund and Rahardjo (1993) regarding the influence of pore pressure on the stability of unsaturated slopes.

Although the simulation under worst-case scenarios suggests instability, no actual slope failures were observed at the study site. This discrepancy likely results from the fact that real field conditions had not yet reached the extreme parameters modeled in the simulation. Therefore, analyzing the threshold safety factor becomes essential to identify the critical limit before failure occurs.

3.1.3. Safety Factor of Cross-Sections A–A', B–B', and C–C' at Threshold Conditions

The threshold condition is defined as the state in which a slope is considered critical but still remains within a safe limit. This analysis is conducted to determine the maximum allowable groundwater level before the slope reaches an unstable state.

In cross-section A–A', the slope remains stable with a Safety Factor (SF) of 1.01 when the groundwater table is positioned between 0 and 5 meters below the surface. Although this represents a rise from the original 2–10 meter depth range, the slope is still categorized as safe. For cross-section B–B', the groundwater table can rise to a depth of 0–12 meters before the slope reaches a critical state with an SF of exactly 1.00. Similarly, in cross-section C–C', the water table during heavy rainfall may rise from 9 meters to within the 0–5 meter range, with the slope still maintaining a marginally stable condition at an SF of 1.00. These simulations help define the upper limit of groundwater fluctuation that each cross-section can tolerate while remaining stable. The findings are critical for setting warning thresholds and guiding groundwater management to prevent slope failure.

3.2 Discussions

3.2.1 Effect of Groundwater Table Variation on the Safety Factor (SF)

The simulation results for all three cross-sections reveal that increasing the groundwater level under saturated conditions significantly reduces the slope Safety Factor (SF), though the degree of reduction varies between sections. The most substantial decrease occurred in cross-section B–B', where the SF dropped from 1.16 to 0.55 (ΔSF = 0.61). This was followed by section A–A', which saw a decrease from 1.15 to 0.72 (ΔSF = 0.43), and section C–C', which declined from 1.18 to 0.81 (ΔSF = 0.37). These findings are detailed in Table 2, which compares SF values under both unsaturated and saturated conditions.

Table 2. Safety Factor of Slopes under Unsaturated and Saturated Conditions

Cross Sections	Safety Factor		Decrement
	Saturated	*Unsaturated*	
A-A'	0,72	1,15	37,39%
B-B'	0,55	1,16	52,59%
C-C'	0,81	1,18	31,36%

From a technical standpoint, cross-section B–B' experienced the most significant reduction in SF. This is attributed to a combination of geotechnical and morphological factors, particularly related to the type and thickness of the disposal material and the slope geometry. Among the three sections, B–B' has the thickest layer of disposal material, which consists of unconsolidated and heterogeneous overburden waste. This type of material typically has lower cohesion and internal friction angle, making it more susceptible to shear strength reduction when saturated.

Visual interpretation of the slope model also indicates that the surface of section B–B' is irregular, characterized by undulating layers caused by suboptimal compaction during disposal activities. These uneven surfaces create micro-depressions that trap water, accelerating infiltration into the slope body. As rainwater infiltrates and fills the soil pores, pore water pressure rises, leading to a decrease in effective stress (σ') along the potential slip surface, thereby weakening the soil's shear strength.

Fredlund and Rahardjo (1993) emphasize that slope stability is heavily influenced by changes in hydrogeological conditions, especially in unsaturated soils. When infiltration raises the groundwater table, the resulting increase in pore water pressure reduces effective stress, directly impairing shear strength, particularly in loosely packed soils with low strength parameters. Given the high volume and thickness of disposal material in section B–B', along with an unconstrained toe, this section is particularly vulnerable to SF reduction under saturated conditions.

In summary, the drastic drop in SF in cross-section B–B' stems from the interplay of several factors: the physical properties of the disposal material, a taller slope profile, irregular dumping surfaces, and a sharp rise in pore pressure during saturation

3.2.2 Safety Factor Based on Material Density

Changes in the Safety Factor (SF) due to increased wet soil density are influenced by geotechnical conditions, pore water pressure, and the mechanical characteristics of the slope-forming materials. This study compares soil density under saturated and unsaturated conditions, assuming the groundwater level remains in a normal (unsaturated) state.

As shown in Table 3, increasing material density from unsaturated to saturated conditions led to a decrease in SF across all slope cross-sections, although the reductions were relatively minor.

Table 3. Slope Safety Factor in Response to Density Variation

Cross Sections	SF (*Saturated*)	SF (*Unsaturated*)	*Decrement*
A-A’	1,02	1,15	11,47%
B-B’	1,14	1,16	2,15%
C-C’	1,17	1,18	1,76%

In this analysis, shear strength parameters—namely cohesion and internal friction angle—are assumed constant. With this assumption, the observed SF decrease is primarily attributed to the increase in unit weight, which raises the driving force on the slope without a corresponding increase in resisting force. This indicates that while increased density under saturated conditions does affect slope stability, its impact is considerably less pronounced compared to the influence of elevated groundwater levels and accumulated pore pressure.

Therefore, even though the influence of density variation is relatively modest, it remains an important consideration in the design of disposal slopes and should not be overlooked during stability assessments.

4. CONCLUSION

4.1 Conclusion

Based on the results of the research that has been carried out, the following conclusions can be drawn:

1. Variations in the groundwater table have a significant impact on the stability of disposal slopes, primarily through substantial reductions in the Safety Factor (SF). In contrast, changes in material density exhibit only a relatively minor effect on slope stability. Under saturated groundwater conditions, the SF dropped considerably—by 37.39% in cross-section A–A’, 52.59% in B–B’, and 31.36% in C–C’—placing the slopes in a critical state with a heightened risk of failure.
2. Tincrease in wet material density led to only slight reductions in SF: 11.47% for A–A’, 2.15% for B–B’, and 1.76% for C–C’. In these cases, the slopes remained classified as stable.
3. These results emphasize that the combination of a saturated groundwater table and increased material density can significantly compromise slope stability. However, a rise in density alone—without a corresponding increase in groundwater level—does not significantly alter the Safety Factor. This underscores the importance of monitoring groundwater conditions as a primary factor in ensuring slope safety in mine disposal areas.

4.2 Suggestions

Based on the conclusions drawn, the following suggestions are given:

1. Future studies should consider additional geotechnical parameters such as: permeability and hydraulic conductivity, soil suction in unsaturated zones, time-dependent rainfall infiltration, seepage forces, and water retention curves. Because this would improve the realism of slope behavior modeling, especially in dynamic weather conditions.
2. Future research could analyze more diverse slope geometries or expand to other disposal or pit slopes to generalize the findings across different mining conditions.

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