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Geotechnical study of mudcell as a management strategy for slurry overburden material at mine sites

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Abstract

The challenge of managing the substantial volume of high-moisture content slurry overburden material at active mine sites is fundamentally a geotechnical problem. Uncontrolled and direct disposal of this material leads to low shear strength and delayed consolidation, significantly compromising the overall stability of the disposal facility and posing substantial geotechnical failure risks. This research proposes the mudcell concept as a structured, engineered solution to mitigate these risks. Specifically, this study aims to geotechnically evaluate the stability of the proposed mudcell geometry by determining its Factor of Safety (FoS). The analysis employs the Limit Equilibrium Method, a standard approach for assessing slope and fill stability, to rigorously calculate the FoS against critical failure modes. The results demonstrate that implementing the mudcell principle provides an effective strategy for enhancing the mechanical properties of the fill. Crucially, the final design achieves a Factor of Safety (FoS) that meets the design criteria Factor of Safety satisfying the minimum requirement, thereby confirming the required long-term stability and feasibility of the mudcell approach for large-scale slurry management.

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Keywords

Geotechnical, Mudcell, Slurry management, Factor of safety, Limit equilibrium method

Introduction

The Overburden disposal utilizes two main methods: placing material in an Out-Pit Dump (OPD), located outside the active mine area, or using In-Pit Dumping (IPD), which involves concurrent backfilling of mined-out pit sections, advancing with the mining sequence [1]. A Mudcell is a structured container or compartment that is specifically designed and constructed to hold or dispose of soft material (mud) [2]. Disposal failures typically result from three factors: diminished material shear strength due to high pore water pressure, non-compliant dump slope geometry, and unsystematic soft material placement [3][4][5][6].

This study aims to geotechnically evaluate the stability of the proposed mudcell geometry by determining its Factor of Safety (FoS). Specifically, limit equilibrium methods will be employed to simulate various loading conditions and subsurface material parameters. This evaluation incorporates comprehensive material mechanics data, such as shear strength of lithological layers to ensure the calculated FoS meets the minimum technical standards for long-term structural integrity. Ultimately, the findings will provide essential insights into risk mitigation and structural optimization for the construction site.

Current literature on waste dump stability has extensively discussed the Factor of Safety (FoS) using various limit equilibrium methods. Most studies, such as those by [7], focus on the mechanical behavior of general overburden materials and the geometrical optimization of disposal benches to prevent slope failure.

However, there is limited research specifically addressing the stability of mud-filled disposal sites, which exhibit significantly different shear strength characteristics compared to rocky overburden. Previous models often overlook the high-moisture content and the rapid pore-water pressure buildup inherent in mud material, leading to oversimplified FoS values that may not reflect actual field risks. The stability of an embankment during lifting operations is highly dependent on the controlled placement of soft materials within the disposal site. If materials like swamp mud are deposited without precision, they may act as a low-strength interface, facilitating a slip surface for the overlying load and potentially leading to catastrophic failure [2].

Research regarding slope stability in mining disposal is well-established; however, most existing studies focus on standard overburden material [7]. This research distinguishes itself by specifically analyzing the safety factor of mud disposal, which presents unique challenges due to its low shear strength and high-water retention. By evaluating the specific interaction between mud layers and containment structures, this work fills the void in practical safety guidelines for non-standard material dumping.

The stability of disposal slopes is traditionally calculated based on granular overburden material [4] [5]. However, the disposal of mud-material introduces a unique challenge due to its low cohesive strength and susceptibility to liquefaction. While previous researchers have established general safety factor standards, they often fail to account for the ‘undrained’ behavior of mud when subjected to rapid dumping sequences or heavy rainfall.

The current state of the art in mudcell design often relies on simplified or homogenous material assumptions, which may not accurately reflect the complex geomechanically behavior of layered disposal systems. This study addresses this limitation by providing a detailed geotechnical evaluation of heterogeneous disposal material layering, specifically focusing on the interaction between contrasting soil properties. While conventional assessments often overlook the critical interface between low-strength and structural fill materials, this research evaluates the stability challenges posed by soft, saturated mud characterized by undrained properties (15 kN/m^3 unit weight, c = 17 kN/m^2, and phi = 0^o). By integrating OB plan as a strategic backfill material leveraging its moderate shear strength (c = 35 kN/m^2 and phi = 18^o) to provide necessary structural support, this study offers a more nuanced understanding of stability limits and Factor of Safety (FoS) determination. Ultimately, this approach fills the existing research gap by establishing a robust framework for optimizing disposal geometry in challenging, high-moisture environments.

Method

This research utilizes the Limit Equilibrium Method (LEM) to determine the slope's Factor of Safety (FoS) based on Equation(1). The calculations were facilitated using the Rocscience Slide 6.0 software, with an acceptable Factor of Safety limit of 1.05 specified for the research location. Minister of Energy and Mineral Resources Decree Number 1827 K/30/MEM/2018 concerns the Guidelines for Implementing Good Mining Engineering Principles (or Good Mining Practice).

$$Factor\ of\ Safety(FoS) = \frac{Strength}{Stress} \quad (1)$$

The Strength constitutes the shear strength parameters of the slope material, comprised of cohesion and the angle of internal friction [4]. Meanwhile, stress refers to the load affecting the slope, further compounded by the factor of water pressure.

Operational procedures and design specifications are shown in Figure 1 and Figure 2, as described below. The condition of each side of the mud cell is shown in Figure 3.

a. Mud Disposal Area: Mud material is designated for disposal within the area highlighted in blue, up to the elevation of RL 53.
b. Overburden Dumping Sequence: Overburden (OB) material dumping is conducted continuously from the east side progressing westward, maintaining a limit of 100 meters perpendicular to RL 50.
c. Fresh OB Dumping Clearance: A minimum distance for fresh OB dumping must be maintained from the outermost crest of the disposal.
d. Support Equipment Requirement: A minimum of one dozer unit is required to support both OB and mud dumping activities, specifically for reshaping the dumped material.
e. Mudcell Drainage: The spillout channel within the Mudcell area must be ensured to function effectively to optimize the dewatering (drainage) process of the mud.

The determination of material types and properties in the *mud cell* area is based on company data, referring to geotechnical laboratory test results (Table 1). These data include parameters such as cohesion (c), internal friction angle (ϕ), and unit weight (γ), which serve as the basis for slope stability analysis using Slide 6.0 software.

Figure 1. Operating procedures of mudcell[10]

Figure 2. Progress of Dumping Overburden in mudcell[11]

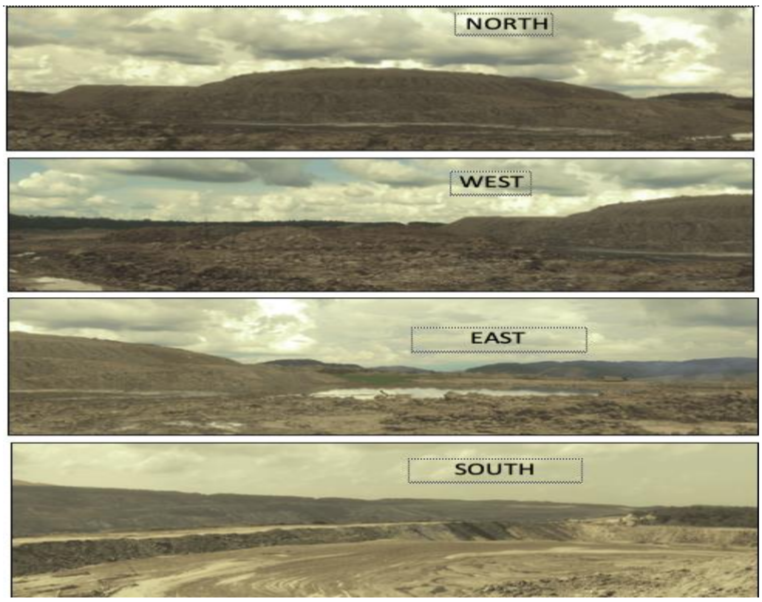

Figure 3. Mud cell photos: north, west, east, and south views [11]

Table. 1 Material Properties [11]

No	Nama Material	Strength Type	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Phi (degrees)
1	Soil	Undrained	18	60	
2	Claystone	Mohr-Coulomb	21.6	308	24.4
3	Coal	Mohr-Coulomb	20	400	28.7
4	Ob Existing	Mohr-Coulomb	16.64	28	14
5	Mud	Undrained	15	17	
6	Ob Layer mud	Mohr-Coulomb	15	15	7
7	Ob Plan	Mohr-Coulomb	16.64	35	18

Prior to analyzing the results, it is necessary to create cross-sections of the mud cell area under investigation. The determination of these cross-sections is based on line sections that have been adjusted to actual field conditions and the primary slope inclination. The selection of these line sections aims to represent the geometric characteristics and material visualization of the studied area (Figure 4; Figure 5; Figure 6).

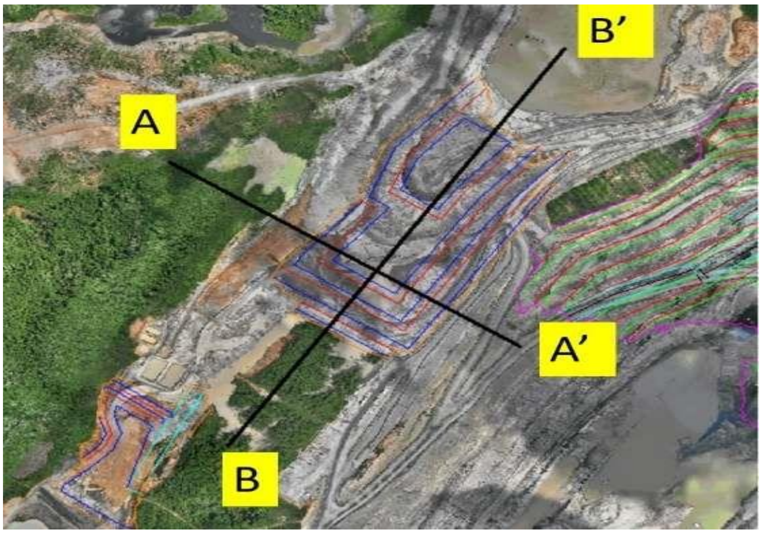

Figure 4. Line Sections of mudcell area on the map [11]

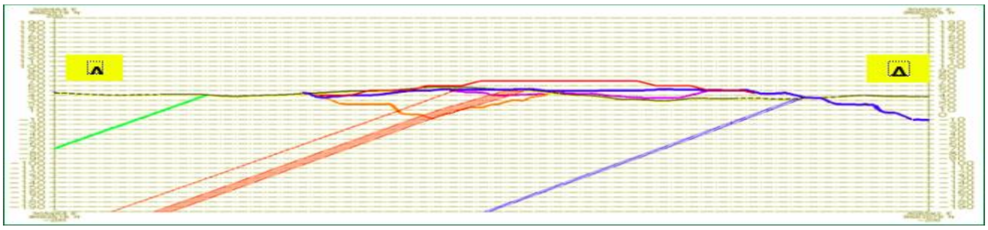

Figure 5. Cross section A-A' of mudcell area

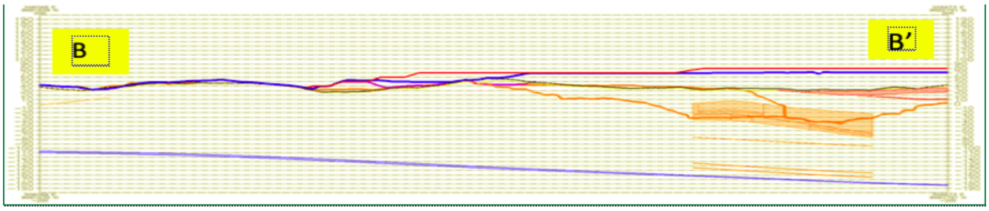

Figure 6. Cross section B-B' of mudcell area

Two sections depicting the mudcell slopes are identified, AA' and BB'. These sections were then analyzed on the west, east, and south sides, both under actual conditions and under the embankment design. The following presents the results of the slope safety factor analysis for the mudcell construction.

The cross-sections are divided into two sections. The first section represents the west and east sides, while the second section represents the south side. Each section is taken perpendicular to the slope design direction and follows the lowest contour lines that are directly connected to the dumping design. As shown in Figures 5 and 6, the blue boundary lines represent the actual conditions, while the red boundary lines represent the planned dumping design.

The determination of the Factor of Safety (FS) for both actual and planned dumping conditions was performed using Slide 6.0 software, employing the General Limit Equilibrium (GLE) method with the Morgenstern-Price approach. This method was selected because it provides accurate analysis results by accounting for both force and moment equilibrium across all potential slip elements. Input data, including material characteristics such as cohesion, internal friction angle, and unit weight, were obtained from laboratory test results and project data provided by the company.

The geotechnical boundary parameters used in this study are as follows:

a. Material boundary models are based on the topography data "241116_SIT_ACT".
b. The method used to determine the slope safety factor is the Limit Equilibrium Method (LEM), specifically the GLE/Morgenstern-Price method, in accordance with the regulations at PT Antang Gunung Meratus, Ida Manggala site.
c. The groundwater level is assumed to be in a saturated condition.
d. The seismic load used for the analysis is 0.03g.
e. Slope stability analysis is performed using Slide 6.0 software.
f. Slope conditions are assumed to be fully saturated.
g. The failure surface method utilized is the Circular Auto Refine Search.
h. The required slope safety factor (FS) is > 1.05, referring to the company's parameters which consider moderate landslide severity under dynamic conditions.

Results and discussion

Determine of safety factor each section for actual conditions and Reconstuction of new design of mudcell for the low safety factor.

Results

This research provides safety factor values for the actual and planned mud cell slope designs. The following section first describes the characteristics of the materials composing the mud cell. The result from the material properties (Table 1) we know that The primary material involved is mud, characterized by its soft and saturated nature with undrained properties (unit weight = 15 kN/m^3, c = 17 kN/m^2, and phi = 0). Due to its high deformability, this material is a critical factor in stability assessments. Furthermore, 'OB Layermud', a mixture of overburden and mud, exhibits low shear strength under saturated conditions, with Mohr-Coulomb parameters of c = 15 kN/m^2 and phi = 7 degrees.

In contrast, 'OB_plan' is designated as the backfill material for the final mud cell design. Given its moderate shear strength (c = 35 kN/m^2, phi = 18 degrees), it provides the necessary stability for the disposal layers. Analyzed under Mohr-Coulomb criteria, this material is assumed to be saturated, with the phreatic surface aligned with the water level. While 'OB_plan' is intended to reinforce slope stability, its mechanical interaction with the underlying soft mud layers requires thorough technical evaluation.

The determination of the Factor of Safety (FS) for the actual mud cell conditions is divided into two sections: Section A and Section B. These sections represent the east, west, and south sides. In Section A–A', the resulting factor of safety values are 1.471 for the west side and 1.448 for the east side. Based on these results, the slopes are classified as stable, as they exceed the minimum safety threshold of FS ≥ 1.05.

In Section B–B', the FS value obtained for the south side is 1.028, indicating that the slope is in a critical or 'alert' condition, requiring mitigation measures to enhance stability. The low safety factor is attributed to the insufficient resisting force at the toe of the southern slope. Consequently, the proposed mitigation strategy to secure the actual condition of the south side involves increasing the resisting force by constructing a counterweight or toe buttress. With the addition of this material at the slope's toe, the FS value for the south side increases to 1.275, which is categorized as stable.

Based on the determination of the Factor of Safety (FS) for the dumping design in Section A and Section B, the resulting FS values are 0.904 for the east direction, 0.944 for the west direction, and 0.934 for the south direction. These results indicate that the slope conditions across all cross-sections are unstable. The decrease in the FS values is attributed to the additional load from the overburden (OB) material placement, combined with the characteristics of the foundation soil, which tends to be soft and saturated. Consequently, improvements or adjustments to the slope geometry design are required to achieve a stable condition.

Based on the slope stability analysis using Slide 6.0 software, the dumping design across the two sections representing the south-east and west directions indicates unstable conditions. The resulting Factor of Safety (FS) values fall below the company's minimum threshold of 1.05. This instability is attributed to the combination of soft and saturated mud characteristics and the placement of overburden (OB) material in the dumping area, which negatively impacts the overall shear strength of the slope.

As a corrective measure, modifications to the slope geometry were recommended to reduce the driving forces. This reduction was achieved by adjusting the slope angles and modifying bench heights to reach a safety factor that meets the required standards. These changes aim to enhance the stability of the dumping design, thereby minimizing the potential for failure and ensuring operational safety for the subsequent stages.

PT Antang Gunung Meratus, Ida Manggala site, maintains specific standards for slope geometry: a maximum single slope angle of 30°, a single bench height of 10 meters, and a maximum overall slope angle of 20°. Following the geometric adjustments to the dumping design, a reassessment of the safety factors was conducted across all sides. After these modifications, the FS values increased to 1.119 for the west side, 1.113 for the east side, and 1.08 for the south side. The FoS of mudcell can be seen at Table 2 for actual mudcell condition and Table 3 for design of mudcell, also Figure 9 until Figure 18 for all section actual, design, and re-design of dumping mudcell area.

Table 2. Factor of Safety (FoS) value for actual condition of mudcell

No.	Condition	Side	FoS	Description
1	Actual	West	1.471	Stable
2	Actual	East	1.448	Stable
3	Actual	South	1.028	Unstable
4	Actual after revised	South	1.275	Stable

Table 3. Factor of Safety (FoS) value for Dumping Design condition of mudcell

No.	Condition	Side	FoS	Description
1	Design of Dumping	West	0.944	Unstable
2	Design of Dumping	East	0.904	Unstable
3	Design of Dumping	South	0.934	Unstable
4	Re-Design of Dumping	West	1.119	Stable
5	Re-Design of Dumping	East	1.113	Stable
6	Re-Design of Dumping	South	1.080	Stable

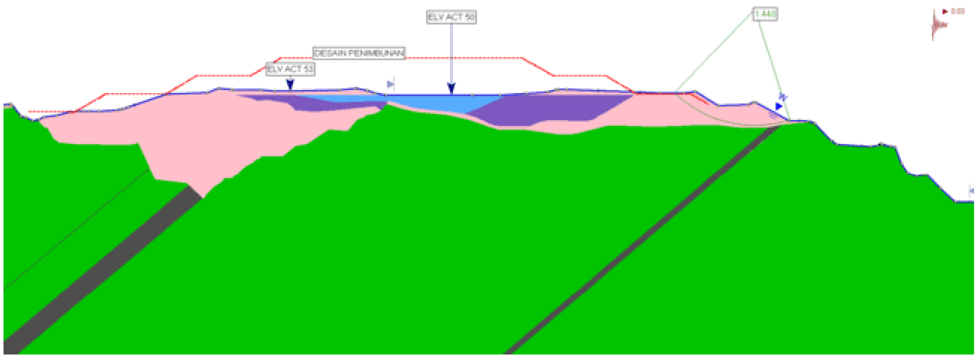

Figure 9. Section A-A'. Actual *mudcell* east FK = 1.448 (stable)

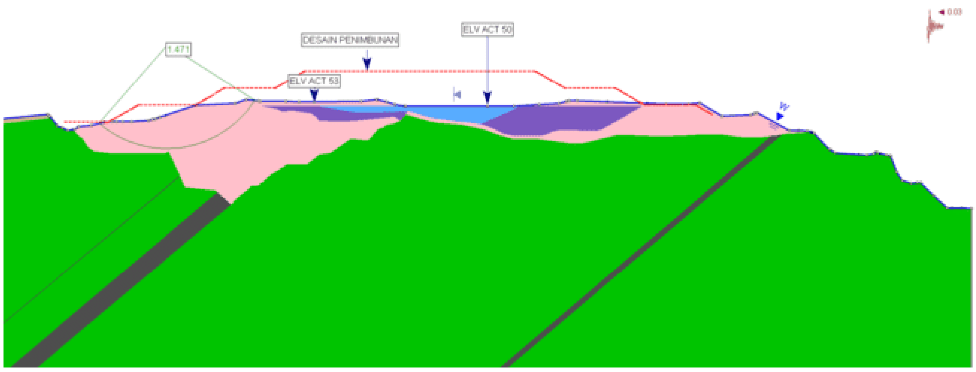

Figure 10. Section A-A'. Actual *mudcell* west FK = 1.471 (stable)

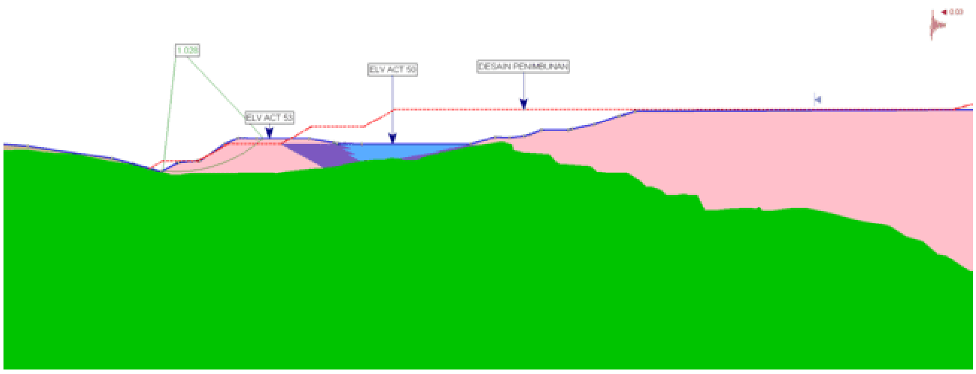

Figure 11. Section B-B'. Actual *mudcell* south FK = 1,028 (unstable)

Table 3 and Figure 13 to 18 illustrates the comparative Factor of Safety (FoS) values across three sectors (West, East, and South) before and after the design modification. The initial designs yielded FoS values below the ESDM regulatory threshold of 1.05, specifically 0.944 (West), 0.904 (East), and 0.934 (South). Following the design optimization, all sectors demonstrated improved stability, exceeding the minimum requirement with values of 1.119, 1.113, and 1.08, respectively. For unstable slope of mudcell can be re designed or simulations for the installation of drain pipes in the mud cells are performed to assess their impact on optimizing water drainage within the mud cell structure [8].

Disposal reconstruction was executed by constructing a counterweight through a 3-meter elevation of the existing reclamation road, relocating the drainage ditch beyond the mudcell boundaries, and optimizing the material dumping sequence during the mudcell closure phase. These measures resulted in the successful closure of the mudcell, enabling its subsequent conversion into an in-pit dump and reclamation area [9], [10].

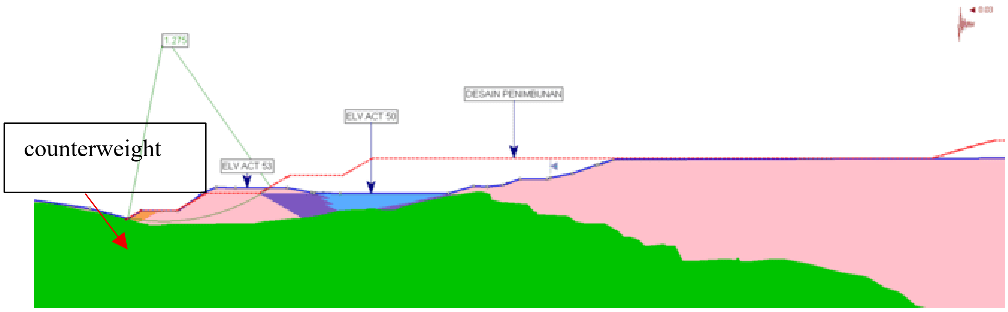

Figure 12. Section B-B'. Actual *mudcell* south after modification FK = 1,275 (stable)

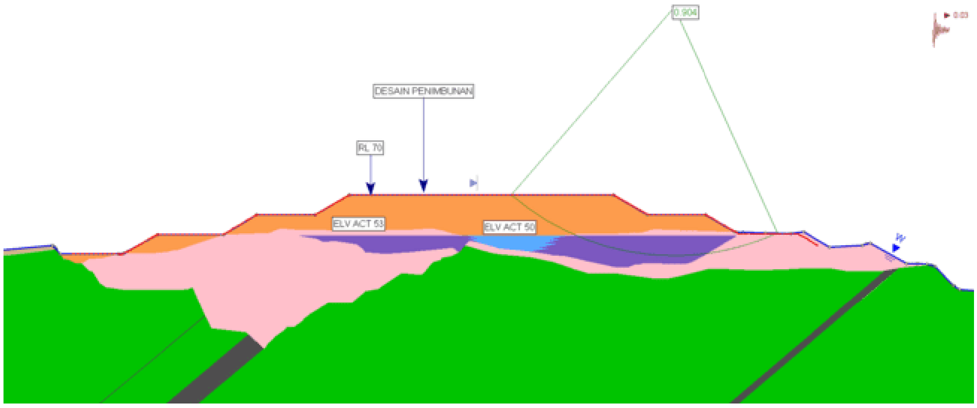

Figure 13. Section A-A'. Dumping design east FK = 0.904 unstable

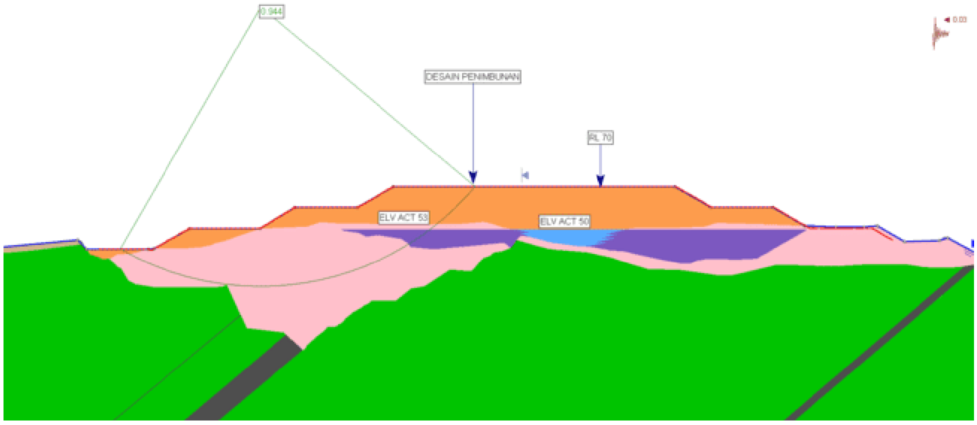

Figure 14. Section A-A'. Dumping design west FK = 0.944 unstable

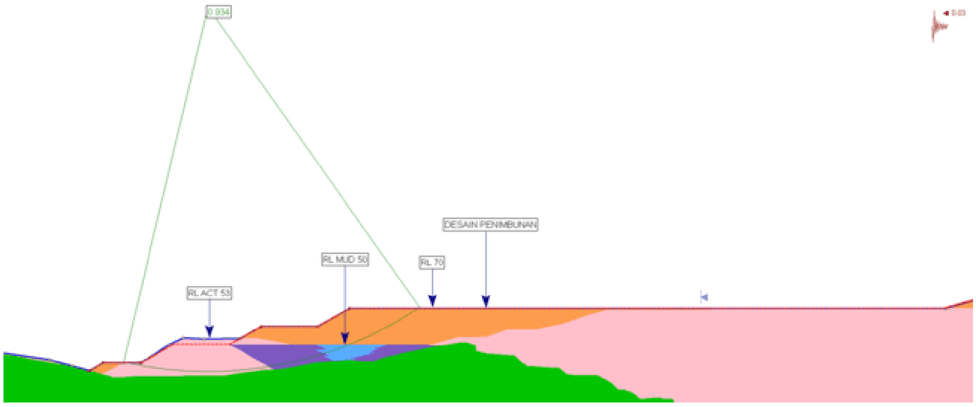

Figure 15. Section B-B'. Dumping design south FK = 0.934 unstable

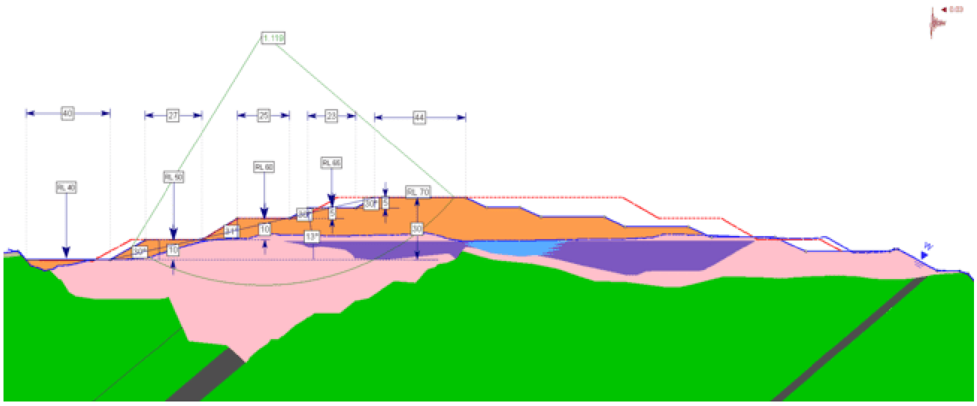

Figure 16. Section A-A'. Recomendation of re-design west FK = 1.119 (stable)

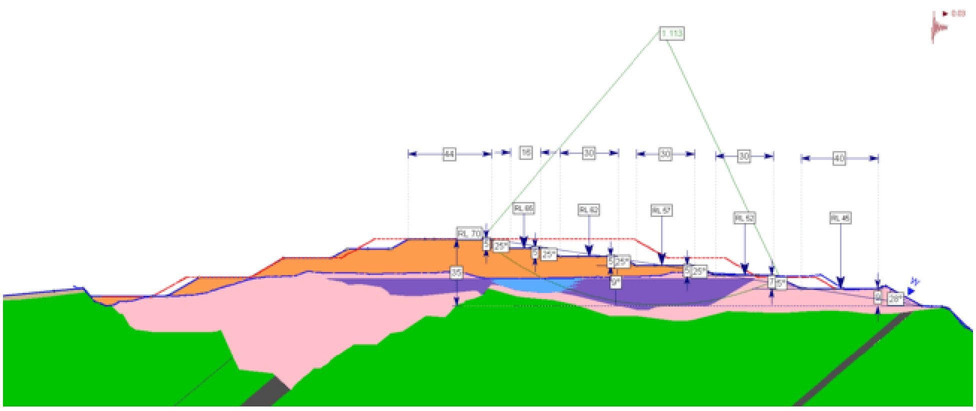

Figure 17. Section A-A'. Recomendation of re-design east FK = 1.113 (stable)

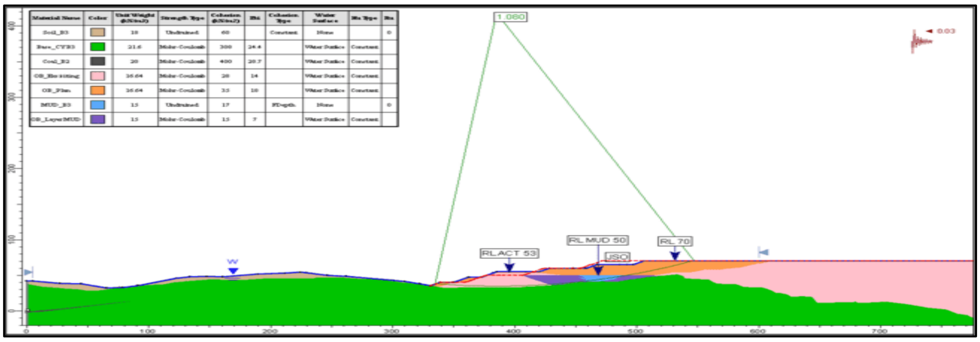

Figure 18. Section B-B'. Recomendation of re-design south fk = 1.080 (stable)

Discussions

The input process, utilizing soil unit weight, cohesion, and angle of internal friction values within the Slide Software employing the Morgenstern-Price method, yielded the following Factor of Safety (FoS) results for the Mudcell slope under existing (actual) dynamic conditions: West side: 1.471; East side: 1.448; and South side: 1.028. This FoS determination was conducted under dynamic conditions, considering a seismic load of 0.03g. Based on Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018, the FoS value for Section A remains in the safe category, as it exceeds the minimum threshold specified by the company (FoS ≥ 1.05). Conversely, the FoS value obtained for Section B was deemed unsafe. Consequently, remedial efforts were undertaken, involving the addition of a buttress fill at the toe of the slope to increase the resisting forces. Following this remediation, the FoS of the south side slope increased significantly to 1.275.

The Factor of Safety (FoS) values for the design of dump structure were determined as 0.944 for the west side, 0.904 for the east side, and 0.934 for the south side. These results indicate that the slope conditions across all sections are currently unstable. This decrease in FoS is attributed to the additional loading from the overburden (OB) placement, coupled with the inherent characteristics of the soft and saturated foundation soil.

Therefore, remediation or adjustment of the slope geometry design is required to achieve stable conditions. As a preventive measure, a modification to the slope geometry was recommended through adjustments to the overall slope angle, bench height, and bench width. Post-modification evaluation results demonstrate an increase in the FoS across all cross-sections. Specifically, the FoS increased to 1.119 on the west side, 1.113 on the east side, and 1.080 on the south side.

Conclusion

Analysis of Section A–A' indicates stable conditions with FS values of 1.471 (West) and 1.448 (East). Conversely, Section B–B' (South) initially showed a critical FS of 1.028. Stability was successfully improved to a stable state (FS 1.275) by constructing a toe buttress to increase resisting forces.

The initial dumping design across all sections was found to be unstable (East: 0.904; West: 0.944; South: 0.934), with FS values falling below the 1.05 threshold. This instability resulted from the additional overburden load placed upon soft and saturated mud foundations. Remedial measures involved modifying the slope geometry in accordance with PT Antang Gunung Meratus standards (10m bench height, 30° single slope angle, and 20° overall slope angle). The geometry modifications significantly enhanced the stability of the dumping design, resulting in improved FS values: West (1.119), East (1.113), and South (1.08). All sections now meet the required operational safety standards.

The method of mud placement in the disposal area (Mudcell) constitutes one measure for managing mud encountered at the mine site. A Mudcell is constructed by building peripheral bund walls using competent overburden material to form its boundaries. Mud material is then deposited in the central section. Subsequently, overburden (non-mud) material is continuously dumped on one side of the Mudcell, extending up to 100 meters. Remediation recommendations to increase the Factor of Safety: The addition of a buttress fill at the toe of the slope to increase the resisting forces.

A modification to the slope geometry was recommended through adjustments to the overall slope angle, bench height, and bench width. Implementation of a good drainage system, periodic slope monitoring, avoidance of overfill or overdump, and vegetation planting.

Acknowledgement

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