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GEOTECHNICAL EVALUATION OF LANDSLIDE THROUGH A BACK ANALYSIS APPROACH ON THE DISPOSAL AREA SLOPE AT PIT 'X', TANJUNG ENIM, SOUTH SUMATRA

EVALUASI GEOTEKNIK KELONGSORAN DENGAN PENDEKATAN ANALISIS BALIK PADA LERENG AREA DISPOSAL PIT 'X', TANJUNG ENIM, SUMATRA SELATAN

GISA N. SUGIAWATI[1*], RADEN I. SOPHIAN[1], MUHAMMAD K. ALFADLI[1], NUR KHOIRULLAH[1], and MEILAN A. PUTRA[2]
[1] Faculty of Geological Engineering, Universitas Padjadjaran
Jalan Raya Bandung-Sumedang KM 21, Jatinangor, Sumedang 45363, Jawa Barat, Indonesia
[2] PT Bukit Asam Tbk
Jalan Parigi No.1, Tanjung Enim, Muara Enim 31716, Sumatera Selatan, Indonesia
*Corresponding author's e-mail: gisanurputri13@gmail.com

ABSTRACT

In open pit mining, the main activities include excavating the material from its original state and transporting it to the disposal area or stockpile, which forms an embankment. Slope stability in the disposal area should be monitored regularly to prevent losses caused by landslides. If a landslide occurs, it is important to identify the cause as a basis for recommending new slope design and implementing appropriate engineering measures to prevent future landslide occurrences. This study was conducted on a slope that had experienced a landslide in the Pit 'X' disposal area, Tanjung Enim, South Sumatra. This study aims to analyze the cause of the landslide by using a back analysis approach. Slope stability analysis was conducted using the Morgenstern-Price boundary equilibrium method, with failure probabilities calculated using Slide 2 software. Input data consisted of cohesion, internal friction angles, and unit weight of slope material. Based on the slope stability analysis, landslides occurred on slopes with a safety factor of 1 and a 40% probability of failure. This was caused by a 67.43% decrease in cohesion caused by the water-saturated condition of the clay material and the influence of the steep slope geometry. The proposed engineering solutions include slope grading, which increases the factor of safety by 30.31%, and the addition of counterweights, which further increases the factor of safety by 32.10%.

Keywords: disposal area, back analysis, slope stability analysis, safety factor, limit equilibrium method.

ABSTRAK

Pada kegiatan penambangan terbuka, aktivitas utama meliputi penggalian material dari kondisi aslinya dan pengangkutannya ke lokasi pembuangan atau penimbunan, yang pada akhirnya membentuk geometri timbunan. Stabilitas lereng pada area disposal perlu dipantau secara berkala untuk mencegah kerugian akibat longsor. Apabila longsor terjadi, identifikasi penyebabnya menjadi penting sebagai dasar untuk merekomendasikan desain lereng baru serta melakukan rekayasa yang tepat guna mencegah longsor di masa mendatang. Penelitian ini dilakukan pada lereng yang telah mengalami longsor di area disposal Pit 'X', Tanjung Enim, Sumatera Selatan, dengan tujuan untuk menganalisis penyebab longsor menggunakan pendekatan analisis balik. Analisis kestabilan lereng dilakukan dengan menggunakan metode kesetimbangan batas Morgenstern-Price, dengan probabilitas kelongsoran yang dihitung menggunakan perangkat lunak Slide 2. Data yang digunakan terdiri dari kohesi, sudut geser dalam, dan unit weight material lereng. Hasil analisis menunjukkan bahwa longsor terjadi pada lereng dengan faktor keamanan (FK) sebesar 1 dan probabilitas kegagalan mencapai 40%, yang disebabkan oleh penurunan kohesi hingga 67,43% akibat jenuhnya material lempung serta pengaruh geometri lereng yang curam.

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Rekayasa yang dapat dilakukan adalah dengan melakukan pelandaian pada lereng yang dapat meningkatkan nilai faktor keamanan sebesar 30,31% dan melakukan penambahan penahan pada kaki lereng yang dapat meningkatkan faktor keamanan sebesar 32,10%.

Kata kunci: area disposal, analisis balik, analisis kestabilan lereng, faktor keamanan, metode kesetimbangan batas.

INTRODUCTION

In coal mining operations, there are two methods used to extract coal reserves: open-pit mining and underground mining. In open-pit mining, the primary activities are removing material from the mining site, including excavating material from its original state and transporting it to disposal sites or stockpiles, forming piles to remove the overburden so deeper layers of coal or ore can be exposed and further mined (Adriansyah *et al.*, 2021). The dimensions of these piles create slope geometries designed to be stable, making slope stability as important aspect that must be regularly monitored and maintained (Imam, Hariyanto and Agung, 2011).

Under undisturbed natural conditions, soil or rock is generally in a stable balance state, maintaining a structural equilibrium influenced by natural factors such as density, slope, and water content. When soil or rock is in its natural configuration, its internal forces can withstand loads without significant deformation, keeping the slope or soil mass stable (Paliwal *et al.*, 2022). This equilibrium is generally influenced by geotechnical forces such as shear stress and normal stress working within mutually supportive limits. However, slope stability is crucial not only in mine excavation areas but also in disposal areas where excavated and mined materials are deposited. Changes in slope stability within disposal area can be caused from several factors, such as the backfilling process, water influence, slope cracks, or other activities around the slope (Cao, Feng and Tao, 2020). To adapt to these changes, the slope will naturally attempt to reach a new stable condition. This process usually involves degradation or load reduction, mainly through landslides or other types of ground movements, until a new equilibrium condition is reached (Arif, 2021).

A landslide occurred at Pit 'X' disposal area, Tanjung Enim, South Sumatra. When a landslide has occurred, it is important to conduct an in-depth analysis of the factors contributed to the event. This process involves performing re-analyzing the landslide through a back analysis to identify the cause based on field data, such as slope geometry, physical and mechanical properties of the materials, and hydrogeological conditions.

Back analysis helps in understanding the behavior of slopes that have already experienced landslides, making it useful for redesigning or engineering the slopes to achieve more stable and safer condition (Ering and Babu, 2016). The material properties obtained from the back analysis are used as input data in the slope stability analysis and failure probability calculation. Probabilistic slope stability analysis calculate the variability and uncertainty associated with geotechnical parameters and can be used to determine slope risk (Sarah *et al.*, 2024). This information serves as a recommendation and provides additional data for designing a new slope based on the back analysis results (Metriani, Anaperta and Saldy, 2019).

METHOD

This research was conducted by analyzing slope stability through several research steps, including data collection, laboratory testing, and slope stability analysis simulation. Data collection involved soil sampling for laboratory analysis, slope cross-section profiling from topographic data, and field studies.

Laboratory tests were conducted to determine the physical and mechanical properties of the materials, particularly those that used in slope stability analysis, including cohesion, internal friction angle, and unit weight. Physical property tests aimed to assess the characteristics and lithology type of the slope material, such as moisture content, plasticity index, grain size, and specific gravity. Meanwhile, laboratory tests to obtain the values of cohesion and internal friction angle were performed using the direct shear test.

Slope stability analysis calculation was performed using the limit equilibrium method, considering all forces working on the sliding surface of the slope. This approach compares the magnitude of resisting forces to driving forces on the slope (Figure 1) (Arif, 2021).

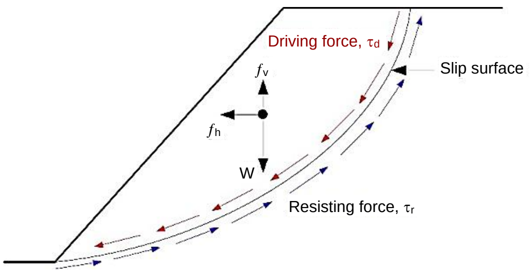

Figure 1. Forces that work on slopes (Zhang, 2015)

$$FoS = \frac{\sum \text{Resisting Forces}}{\sum \text{Driving Forces}} \quad \text{..................................(1)}$$

$$FoS = \frac{\sum (c.\ L \tan\phi + W \cos\alpha)}{\sum (W \sin\alpha)} \quad \text{.................................(2)}$$

Where:
C : Cohesion
ϕ : Internal friction angle
l : Length of slip surface
W : Weight of soil mass

The limit equilibrium method assumes that the shape of the slip surface must be determined and known in advance. To simplify the calculation, the slip surface is usually assumed to be a circular arc, and the slope geometry of the slip surface is divided into a certain number of slices (Arif, 2021).

The study employs the Morgenstern-Price method, which is a slope stability analysis based on the limit equilibrium principles (Takwin, Turangan and Rondonuwu, 2017). This method calculates the equilibrium of forces from each normal force and moment working on slices within the slip surface of the slope and can be applied to all types of landslides, both on slopes with homogeneous or heterogeneous materials (Krahn, 2003). The forces working on each slice of the landslide are as follows.

$$P = \frac{[\,Wn-(X_R - X_L) - \frac{1}{f}\,(c'\left(\sin\alpha - \mu \tan\phi' \sin\alpha\right)]}{\cos\alpha\ (\mu + \tan\alpha\ \frac{\tan\phi'}{E})} \quad \text{................(3)}$$

Where:
P : Normal force
C' : Effective cohesion for drained conditions
Wn : Force due to n-soil load
A : Angle between the midpoint of the slice and the center of the arc of the failure surface
ϕ' : Soil shear angle (use 0 for undrained condition)
μ : Pore water pressure

In conducting the simulation, the study utilized geotechnical software, and a stable slope design refers to the safety factor requirements outlined in the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018 (Table 1).

Table 1. Safety factor and landslide probability in mining areas (Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018)

Slope Type	Landslide Severity	Acceptable criteria		
		Static Safety Factor (FoS) (min)	Dynamic Safety Factor (FoS) (min)	Landslide Probability (max) (FS ≤ 1)
Single Slope	Low - High	1.1	None	25 – 50%
Inter – ramp	Low	1.15 – 1.2	1.0	25%
	Moderate	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%
	Moderate	1.3	1.05	10%
	High	1.3 – 1.5	1.1	5%

RESULT AND DISCUSSION

Lithology of Research Area Conditions

The research area is the disposal area resulting from the excavation of Pit 'X,' forming a slope geometry of the disposal pile. This slope was chosen as the object of study due to its occurrence of landslides, necessitating an investigation into the causes of landslides. Based on the Regional Geological Map of the Lahat sheet (Gafoer, Cobrie and Purnomo, 1986), the disposal area of Pit 'X' is composed of two formations: the Air Benakat Formation (Tma), which consists of alternating layers of claystone and siltstone, and shale that are generally limestone and carbonaceous, as well as the Muara Enim Formation (Tmpm), which consist of claystone, siltstone, tuffaceous sandstone with intercalated coal seams.

Based on the field and laboratory analyses, the lithology of the slope in the research area consists of soil, predominantly clay with a reddish-brown color. The slope material is classified as high-plasticity clay (CH) according to the Unified Soil Classification System (USCS), it is identified based on the grain size of the slope material, which is dominated by clay. The clay in the disposal area is weathered material from the claystone found in Pit 'X', originating from the Muara Enim Formation.

The slope material exhibits high plasticity characteristic. The swelling potential of slope material can be evaluated by measuring the plasticity index, liquid limit and plastic limit values of the soil. These values give an indication of the soil ability to undergo volume expansion when saturated by water. Further assessment is carried out through activity index analysis, which considers the contribution of expanding minerals. This swelling potential is assessed through activity index analysis, the presence of minerals, and swelling potential by comparing two parameters: the plasticity index and the percentage of clay in each sample (Astriani *et al.*, 2022). This comparison provides information about the risk of volume changes that can affect slope stability, especially in water-saturated environments.

Based on its plasticity level, the material constituting the research area exhibits low to normal level of clay mineral activity, primarily consisting of Kaolinite and Illite minerals. Based on calculations using the Seed, Woodward and Lundgren (1963) method, the swelling potential of the slope material is categorized to moderate to high level.

Engineering Geology of Research Area

The research area consists of a waste dump resulting from the stripping of Pit ‘X’, forming a waste dump slope geometry. This slope was chosen as the subject of the study due to its occurrence of landslides, necessitating an investigation into the causes of the landslides. Based on the field and laboratory analyses, the lithology of the slope in the research area is classified as soil with dominant clay particle size. The slope material is categorized as high-plasticity clay (CH) according to the Unified Soil Classification System (USCS).

Laboratory tests were conducted at five sample points within the research area to determine the physical and mechanical characteristics of the slope material. The mechanical properties of the slope material were identified through direct shear laboratory testing, which yielded values of cohesion and internal friction angle. In calculating the safety factor of the disposal area, the cohesion and internal friction angle values used are those obtained under residual conditions, while the unit weight value used corresponds to the saturated condition.

This approach takes into account the reduced shear strength of the material in the residual condition, which represents the strength after significant deformation has occurred. At the same time, the saturated unit weight simulates the potential increase in load due to water infiltration, thus capturing a realistic worst-case scenario for stability analysis. Together, these values provide a conservative estimate of the factor of safety, ensuring that stability considerations address material degradation and increases stress due to saturation (Yang *et al.*, 2024).

This refers to the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018 concerning the Guidelines for the Implementation of Good Mining Engineering Practices regarding the calculation of the safety factor in the disposal area using the internal friction angle and residual cohesion.

Table 2. Material properties

Sample Code	Unit Weight (kN/m^3)		Cohesion (kPa)		Internal Friction Angle (°)	
	Dry	Wet	Peak	Residual	Peak	Residual
DPE – 01	13.88	17.77	42.12	36.9	16.14	12.98
DPE – 02	15.44	18.47	39.76	30.07	18.65	15.41
DPE – 03	15.09	17.88	18.69	14.34	15.41	11.32
DPE – 04	13.54	17.7	20.4	15.48	18.46	12.04
DPE - 05	13.63	17.38	22.93	15.12	14.83	8.96

Initial Conditions of the Research Slope Before Landslide Occurrence

The research slope is focused on section A-A’, which is known to be the area where landslides have occurred (Figure 2). In general, the research slope is part of the disposal area of Pit 'X' (out pit dump), which consists of waste material from Pit 'X'. This disposal area is weak due to the free dumping pattern (uncompacted dumping), and cracks have been observed on the area, which can allow water ingress and trigger landslides (Cao, Feng and Tao, 2020). Infiltrated water can be accumulated within the dumped material, creating conditions that may trigger landslides, particularly during periods of heavy rainfall (Chen *et al.*, 2023). Therefore, careful management of dumping patterns and materials compaction is essential to minimize the risk of water ingress and maintain slope stability.

Figure 2. Research area condition

The slope stability analysis before the landslide event utilized dynamic conditions with a horizontal seismic coefficient of 0.015829, which represents the horizontal seismic coefficient due to vibrations caused by heavy equipment activities in mining area, such as HD Dump Trucks, as it can influence the safety factor by up to 50%. The vertical seismic coefficient can be disregarded, as vertical vibrations do not alter the slope safety factor by more than 10% (Wyllie and Mah, 2004).

The actual groundwater level conditions in the study area were assumed to be saturated due to the lack of hydrogeological data and groundwater management in the disposal area. This saturation is also attributed to the free dumping method used for material placement without compaction, which allows the soil to retain a considerable amount of water. The uncompacted material increases pore spaces, facilitating water retention and leading to higher moisture content throughout the soil mass (Yang *et al.*, 2024). Furthermore, standing water was observed on the surface of the disposal area, along with a sump located at the southern part of the slope, reinforcing the assumption that the groundwater level in the study area is saturated to provide a conservative outcome. The calculation of the safety factor employed the limit equilibrium method proposed by Morgenstern-Price, with the slope limit restricted to the area where the landslide occurred.

In the landslide area, the height of the slope is 4.8 meters with a gradient of 20°. The results of the safety factor simulation yield a deterministic factor of safety (FS) of 2.666, an average FS of 2.699, and a probability of failure (PoF) of 0.1% (Figure 3). The landslide area on cross-section A-A’ is considered stable, referring to the Safety Factor and Landslide Probability and Mineral Resources Decree No. 1827 K/30/MEM/2018 concerning the Guidelines for the Implementation of Good Mining Engineering Practices.

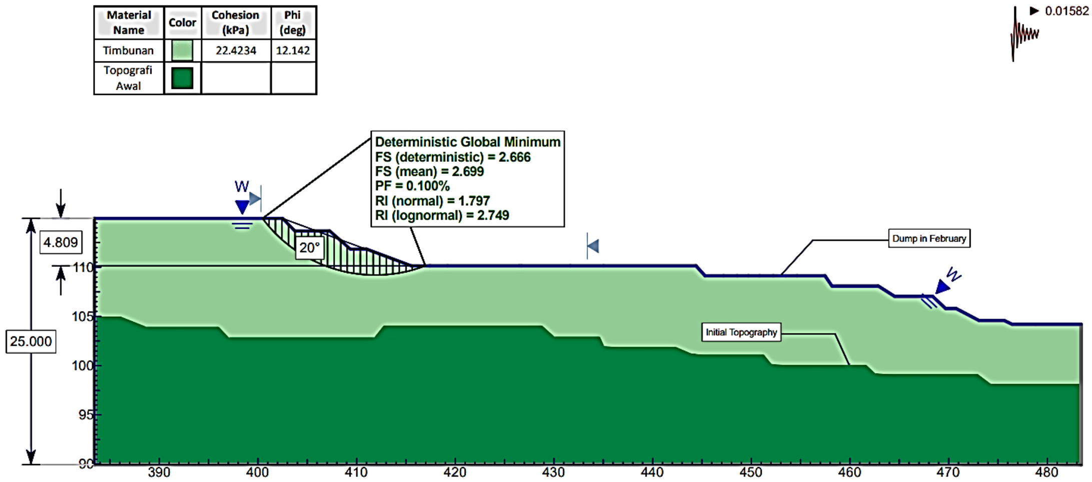

Figure 3. Initial condition of research slope

Although the landslide area on cross-section A-A’ is classified as stable with a PoF 0.1%, a landslide occurred at the beginning of 2024, necessitating a back analysis to determine the causes of the landslide. Through back analysis, changes in material properties in the landslide area just prior to the occurrence of the landslide can be identified.

Back-Analysis of Landslide Events

Material properties are plotted on a sensitivity plot to determine the values of the material properties at the point when the slope has a FS of 1 (Rizaldi and Heriyadi, 2020). The results from the sensitivity plot indicate that the only material property that changes when FS = 1 is the value of cohesion (Figure 4).

The results of the back analysis indicate that the changing material property is cohesion, which has decreased by 67.43% compared to the laboratory test results of the disturbed sample. This change is influenced by the sensitivity of the slope, where cohesion is the material property that most significantly affects the stability of the slope in the research area.

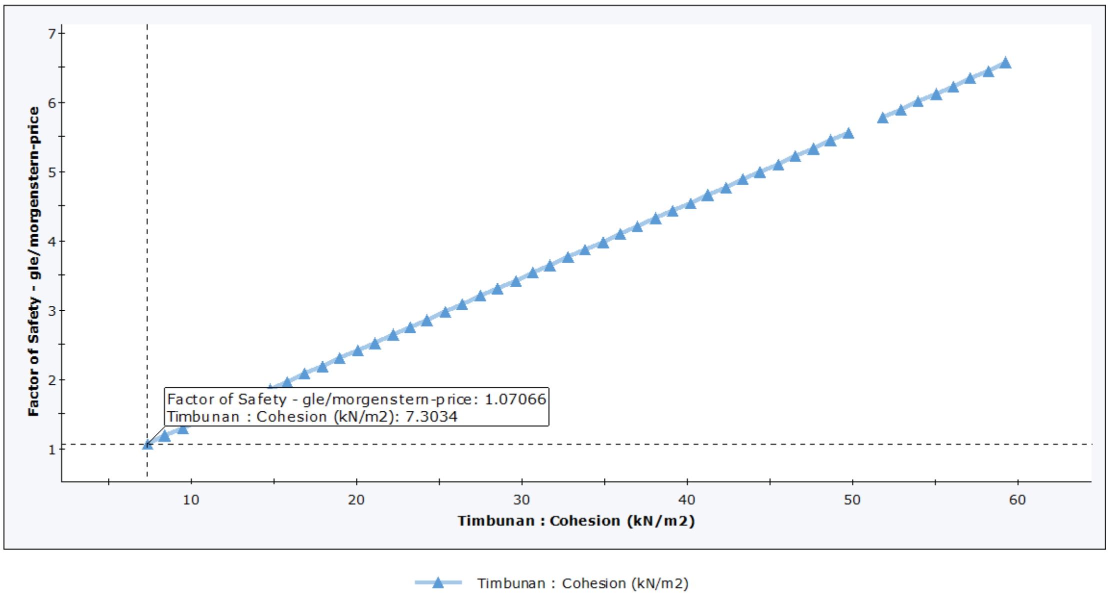

Figure 4. Plot sensivity graph on cohesion

Based on the material properties obtained, a slope stability analysis was conducted again to determine the FS just before the landslide occurred, using the material properties derived from the back analysis as input data. The analysis yielded a deterministic FS value of 1.003, an average FS of 1.003, and a PoF of 46.55% (Figure 5). This condition is classified as an unsafe slope, according to the Classification of Safety Factor Values and Landslide Probability based on the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018.

Factors Affecting Slope Stability
Material Properties

The material properties of the disposal slope constituents are a crucial factor affecting slope stability. To identify the material properties that affect slope stability, a sensitivity analysis was performed using Slide 2 software.

Based on the sensitivity analysis results, it was found that the cohesion value exhibited a steeper slope compared to the internal friction angle (Figure 6). This indicates that cohesion is more sensitive and has a greater impact on the safety factor than the other material properties. Changes in the cohesion value significantly influence the safety factor (Chen *et al.*, 2023). High cohesion values provide enhanced resistance against shear forces, which is essential for maintaining structural integrity in sloped terrains (Widiaswara *et al.*, 2018). In slope stability analysis, variations in cohesion can lead to substantial changes in the factor of safety, underscoring its significance compared to other properties like internal friction angle (Yang *et al.*, 2024). Therefore, understanding and measuring cohesion accurately is vital for predicting slope behavior and designing effective stabilization strategies in geotechnical applications.

The decrease in cohesion values can be affected by the physical properties of the slope material, including particle size, moisture content, and consistency limits making most of the soil problems in engineering are expansive clays which are cohesive soils (Utama, Yuliet and Andriani, 2006). Under moist conditions, clay soil can maintain its strength because cohesion increases due to water filling to the voids between particles. However, when the soil reaches its maximum moisture content where too much water has been added, the soil can become saturated, leading to a decrease in cohesion and resulting in softer, less stable soil. Therefore, the moisture content in clay soil can significantly affect its strength and stability (Tchakalova and Ivanov, 2022). Clay soil also possesses high cohesive properties due to its fine and very small particles that adhere strongly to one another. The cohesion value significantly affects slope stability because cohesion is one of the primary resisting factors in fine-grained soils (Umam, Nugroho and Wibisono, 2017).

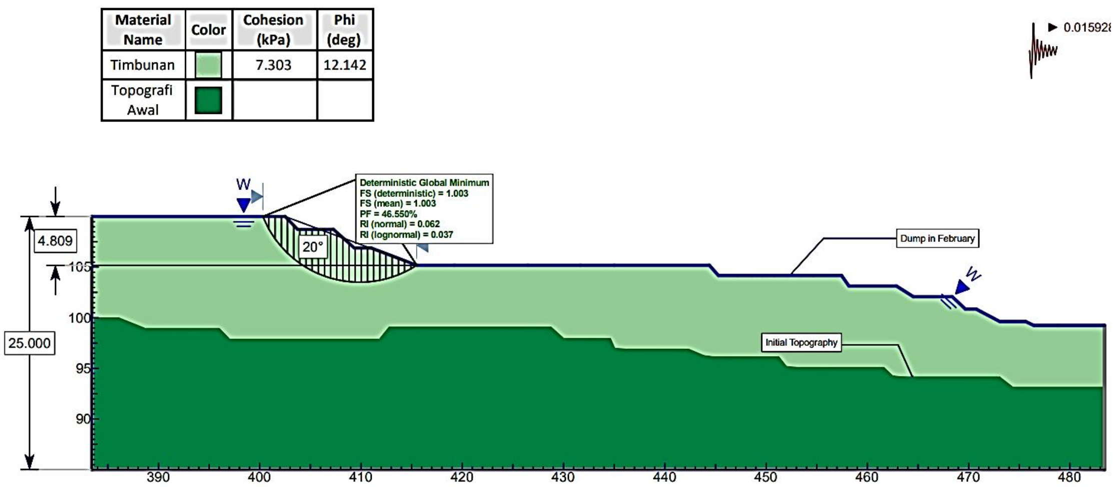

Figure 5. Results of slope stability simulation in section A-A'

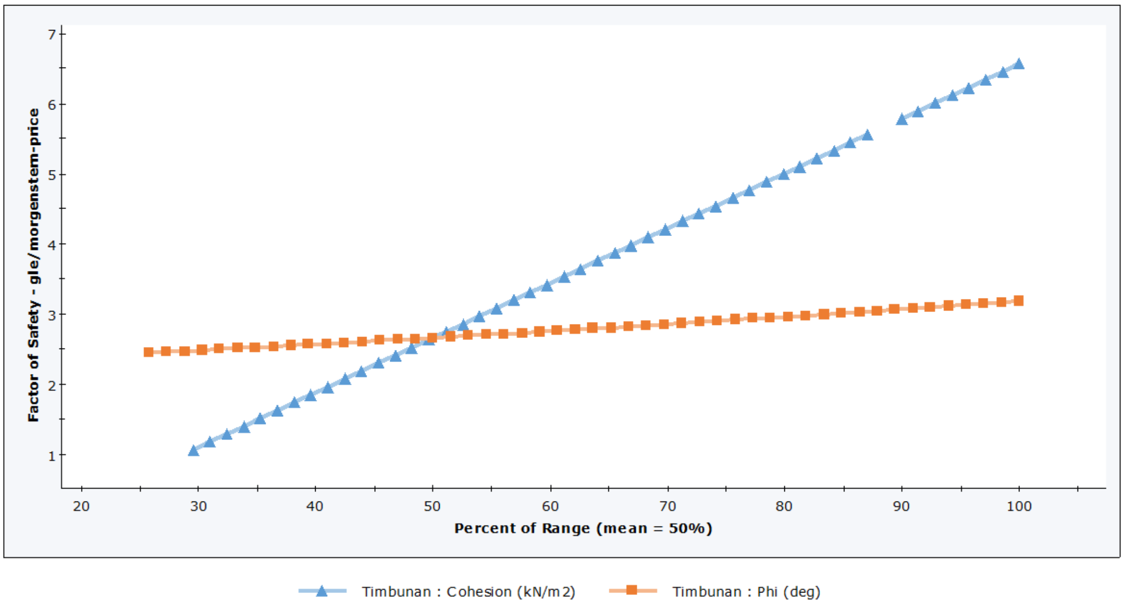

Figure 6. Sensitivity plot graph of material properties

In the graph depicting the relationship between cohesion value and particle size, it is evident that as particle size increases, the resulting cohesion value will decrease (Figure 7). This happens because the surface area of smaller particles is bigger, which means that molecules can interact with each other more easily. This makes the forces that hold particles together stronger (Das and Sobhan, 2014).

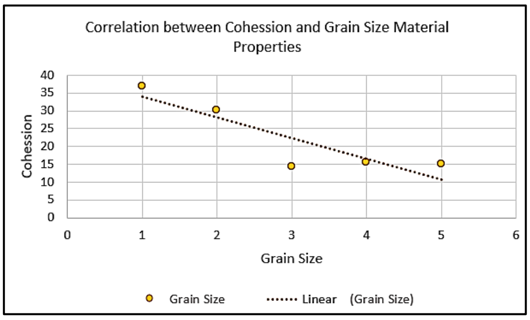

Figure 7. Graph of correlation between cohesion and grain size material properties

In addition, changes in cohesion parameters significantly affect the shear stress characteristics of the soil, as a fundamental aspect in analyzing slope stability. In the context of the Mohr-Coulomb failure criterion, cohesion (c) and internal friction angle (ϕ) play very important but different roles in determining the total shear strength (τ) of the soil (Siswanda and Riswandi, 2024).

While cohesion contributes linearly to the shear strength, providing a constant resistive component independent of the normal stress, the internal friction angle contributes nonlinearly. As the result, any variation in cohesion will have a direct and proportional effect on the shear strength of the soil, thereby changing the slope stability profile. This sensitivity of shear strength to cohesion variations underscores the importance of accurate cohesion measurements, as even small changes can significantly affect the assessment of slope stability and, in turn, the reliability of the overall geotechnical design in slope engineering.

Groundwater Table Condition

The groundwater condition in the disposal area is assumed to be saturated, based on the premise that the clay material, which is the primary component in the research area, can easily retain water, thereby reducing shear strength and affecting the factor of safety. One factor that can lead to the saturation of clay material is high water infiltration caused by rainfall.

Based on the recorded rainfall data, it was found that during the landslide occurrence, specifically in February, the cumulative rainfall reached 428.2 mm, with heavy rainfall lasting for 28 consecutive days. Such prolonged high intensity rainfall can have a major impact on the geotechnical properties of the slope, mainly by increasing the pore water pressure within the soil matrix. The increased pore pressure will disturb the force balance in the soil by reducing the effective stress, which is the main component that binds soil particles together and contributes to soil strength. This expansion weakens the interparticle bond, effectively reducing cohesion and, consequently, reducing the overall shear strength of the soil (Chen *et al.*, 2023). With lower cohesion, the soil becomes increasingly prone to failure due to shear stress, ultimately reducing its capacity to resist the gravitational forces working along the slope and, thus, increasing the risk of landslides. In addition, the groundwater table, which is significantly affected by continuous rainfall, influences the activity and behavior of slope materials.

The materials composing the slope are clays with high plasticity, containing Illite and Kaolinite minerals. Both Illite and Kaolinite exhibit moderate water absorption capabilities, leading to expansiveness when exposed to water, although not much extent as Montmorillonite. Expanding soils tend to become softer, resulting in increasing pore water pressure, consequently reducing the effective strength of the soil. Therefore, the activity of the materials composing the slope, influenced by groundwater conditions, significantly impacts the stability of the slope.

Slope Engineering Recommendations

Slope engineering is conducted to achieve a safe FS as a preventive measure against potential landslides in the future. Based on the slope conditions before the landslide occurrence, it was hypothesized that the slope should not maintain a gradient of 20° under saturated conditions to ensure a safe FS. Therefore, slope engineering simulation is necessary to obtain a safe FS value. Simulation is conducted by calculating the FS based on the material properties obtained from the back analysis, applying the recommended slope engineering conditions under saturated groundwater levels.

One of the engineering interventions that can be implemented is to readjust the slope geometry through re-sloping, which involves flattening the bench angle to create a gentler overall slope. This flattening is carried out on the actual slope using a pushback method, where the crest of the slope is pushed back. The bench face angle on the actual slope ranging from 21° to 45°, is flattened to 20°, resulting in an overall slope angle reduction from 20° to 12°. The simulation results (Figure 8) indicate that this slope flattening increases the FS to 1.307, with a landslide probability of 0.9%, which falls within the safe criteria as stipulated in the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018.

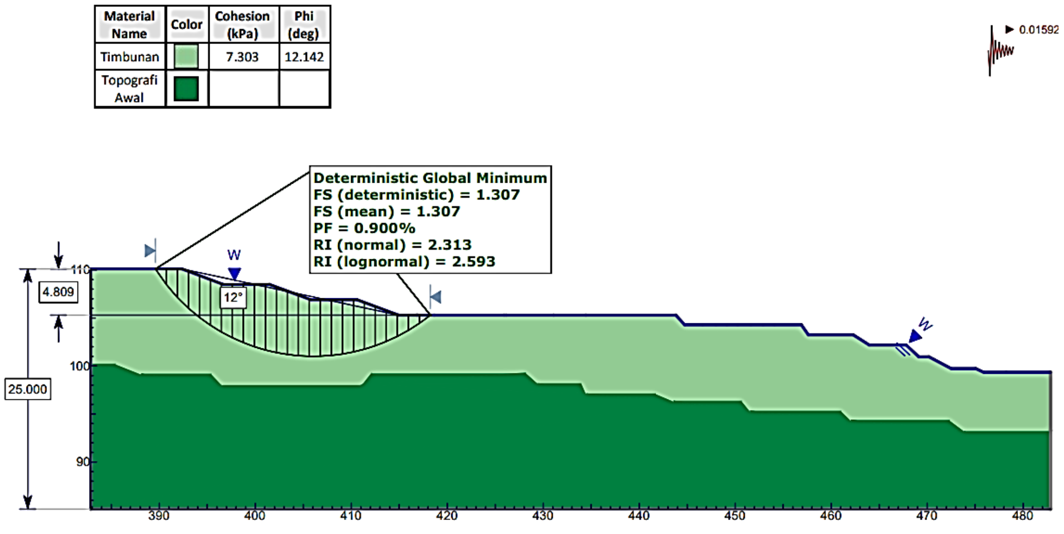

Figure 8. Re-sloping engineering simulation results

In addition to slope flattening, the addition of reinforcement using counterweights can enhance the stability of embankment slopes in disposal areas (Takwin, Turangan and Rondonuwu, 2017). This method serves to augment resisting forces, thereby reducing the risk of landslides, controlling pore pressure, and ensuring even pressure distribution (Nugroho *et al.*, 2022). Counterweights can be applied at the toe of the slope or along the entire bench of the disposal area, taking into account the local conditions, material types, and the design and techniques of the dumping process. The addition of counterweights provides supplementary support that reduces shear forces, thus improving the FS (Haris, Lubis and Winayati, 2018). The additional load increases the normal force perpendicular to the slip surface, resulting in a decrease in shear stress on the slope due to the higher normal force.

The simulation of load addition on the slope as reinforcement was carried out on the entire slope, with adjusted geometric dimensions, specifically an additional fill height of 1.6 meters and a bench angle of 20°. This resulted in a FS of 1.323 (Figure 9), with a PoF 0%, which falls within the safe criteria as stipulated in the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018.

However, if the counterweight is not adequately compacted, the addition of the counterweight can become a new sliding plane due to the increased load on the slope. Therefore, careful consideration must be given to the counterweight addition process, particularly concerning compaction. Compaction can be achieved using heavy machinery, depending on the type of material, the size of the area, and the desired level of compaction. This compaction also helps to reduce the number of pores in the soil, thereby decreasing its water absorption and reducing the potential for swelling. However, soil with high swelling potential can still experience swelling if exposed to large amounts of water over extended periods.

CONCLUSION AND SUGGESTION

Conclusion

Based on the explained research above, the conclusions are as follows:

- In general, the disposal area in the research area consists of reddish-brown clayey soil with a dominant particle size of clay. According to the Unified Soil Classification System (USCS), the soil lithology is classified as CH, inorganic clay of high plasticity. The slope under investigation has an average cohesion value of 22.42 kPa, an internal friction angle of 12.142°, and a unit weight of 17.84 kN/m³.

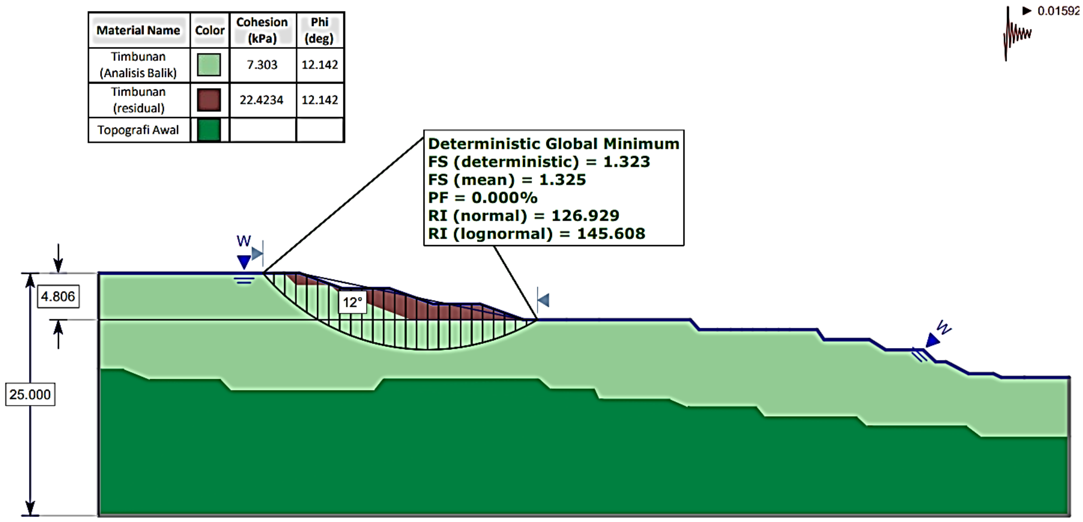

Figure 9. Slope engineering results with counterweight addition

- Modeling the initial slope conditions using the Morgenstern-Price limit equilibrium method revealed that the FS at section A-A' was in a stable condition, specifically 2.666. When modeling the slope conditions just before the landslide occurred (FS = 1), a safety factor of 1.003 was obtained, indicating a decrease in cohesion value of 67.43% derived from the back analysis results. Therefore, it is essential to identify the causes of the landslide so that engineering solutions can be implemented to achieve a safe safety factor following the Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018.
- The decrease in cohesion value is caused by the saturation of the slope material, consisting of clay. The type of slope material is high-plasticity clay with a significant swelling potential. As the water content reaches its maximum, the soil becomes saturated and has the potential to expand, leading to a reduction in shear strength and, consequently, a decrease in the safety factor.
- The engineering measures that can be implemented include slope flattening, which yields a FS of 1.307 with a landslide probability of 0.9%, and the addition of a counterweight, which results in an FS of 1.323 with a landslide probability of 0%.

Suggestion

Data collection should be done using a drill to produce undisturbed samples and reach the hard layer. In addition, the number of samples should be taken more than 5 points to better represent the condition of the research slope. All parameters related to ground movement from seismic earthquakes are ignored, so this recommendation is given without taking into account any factors affecting ground movement. All ground movement analyses should be recalculated to obtain new slope engineering designs and recommendations considering seismic waves of the earthquake as a long-term slope design consideration.

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