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Slope Geometry Design Optimization in the Final Wall Pit Area of Sijebi PT. Solusi Bangun Indonesia Tbk, Narogong Factory, Bogor Regency

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ARTICLE INFORMATION

Journal of Science and Technology – Volume 28 Number 1, May 2024

Page:
19 – 30
Date of issue :
May 31, 2024

DOI:
10.31284/j.iptek.2024.v28i1.5136

ABSTRACT

Slope design is an important component that must be considered in open-pit mining. It affects mine safety as well as the maximization of mining activities. These two things have an inversely proportional relationship and must be optimized with each other. This research aims to provide optimal recommendations related to geometry design that considers the stability of slope mining. The methods utilized in this research are Rock Mass Rating (RMR), Geological Strength Index (GSI), Slope Mass Rating (SMR), kinematics analysis, and limit equilibrium method. Based on the investigation that has been carried out, it is known that the value of the safety factor on the research slope is 4.192 for natural conditions and 3.967 for water-saturated slopes. The slope's safety value factor is known to be a very safe condition. Maximizing the mine design is crucial to achieving optimal extraction of mining materials. The most appropriate slope geometry design for the specified research area requires a single slope angle of 80°, a height of 10 m, and a width of 3 m, resulting in an overall slope of 68°. According to the findings of this recommendation, the safety factor value obtained is 2.076 for natural conditions and 2.050 under water-saturated conditions.

Keywords: *Safety Factor; slope geometry; slope stability; landslide*

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ABSTRACT

Desain lereng merupakan komponen penting yang harus diperhatikan dalam kegiatan penambangan terbuka. Hal inilah yang berpengaruh terhadap keselamatan tambang dan maksimalisasi kegiatan penambangan. Dua hal tersebut memiliki hubungan yang berbanding terbalik, serta harus dioptimalisasi satu sama lain. Penelitian ini bertujuan untuk memberikan rekomendasi yang optimal terkait desain geometri yang memperhatikan kestabilan lereng penambangan pada daerah penelitian. Metode yang dimanfaatkan dalam penelitian ini adalah klasifikasi massa batuan *Rock Mass Rating* (RMR), *Geological Strength Index* (GSI), *dan Slope Mass Rating* (SMR), analisis kinematika, serta metode kesetimbangan batas. Berdasarkan penyelidikan yang telah dilakukan, diketahui bahwa nilai faktor keamanan pada lereng penelitian sebesar 4,192 untuk kondisi lereng alami dan 3,967 untuk kondisi lereng jenuh air. Adapun nilai faktor keamanan untuk lereng tersebut diketahui masih memiliki kondisi yang sangat aman sehingga diperlukan maksimalisasi desain tambang agar material penambangan yang diambil bisa seoptimal mungkin. Rancangan geometri lereng yang paling tepat untuk wilayah penelitian tertentu memerlukan sudut lereng tunggal sebesar 80°, tinggi 10 m, dan lebar 3 m, sehingga menghasilkan kemiringan keseluruhan sebesar 68°. Berdasarkan hasil rekomendasi ini, nilai faktor keamanan yang diperoleh yakni 2,076 untuk kondisi natural dan 2,050 dalam kondisi jenuh air.

Kata Kunci: *Faktor keamanan; geometri lereng; kestabilan lereng; longsor*

INTRODUCTION

The escalating requirement for energy resources is mostly driven by the nation's demands, specifically within the industrial and economic sectors. Limestone and its associated derivatives products hold significant importance as essential commodities within the category of Group C minerals, as they are in high demand by both the state, industries, and society. The primary operations conducted throughout the limestone mining procedure involve the utilization of excavators for blasting and excavation purposes [1]. The issue of slope safety is a matter of increased concern in the context of maintaining the long-term viability of mining activities. Zwageri et al [2] propose that the implementation of active mining operations leads to various hazards and uncertainties in slope environments. A problem of concern that might result from this matter refers to the occurrence of mine slope landslides, which can take place at any point during mining operations [3]. Regular monitoring of slope stability is crucial in decreasing the risk of slope failure. Additionally, it is essential to point out that the safety of workers is closely associated with the stability of slopes during the mining operation [4]. To enhance industrial efficiency, it is essential to consider the safety of workers carefully.

The safety factor value is a parameter that investigates and evaluates the stability of a slope. The previously mentioned value is obtained through the analysis of the physical and mechanical characteristics and geometric configuration of a slope[5]. Obtaining greater accuracy in the results required a more comprehensive assessment, particularly concerning the study of the geological characteristics of the area. The amount of potential failure on a mining slope is influenced by the presence of several geological structures in the form of discontinuity areas [6]. One method applied to ensure slope stability is the implementation of direct geotechnical studies [7]. This work requires acquiring a comprehensive understanding of slope design optimization, with particular consideration given to the recovery of material volume. The practice called slope geometric redesign is undertaken to achieve secure circumstances for the slope and optimize the extraction of raw materials for production purposes [8]. The research employed several methodologies, notably the Rock Mass Rating (RMR) classification developed by Bieniawski in 1989 [9], the Geological Strength Index (GSI) proposed by Hoek et al. in 1998 [10], the Slope Mass Rating (SMR), kinematic analysis, and the Morgenstern limit equilibrium approach.

Some researchers performed a study on slope stability utilizing the RMR [11-12,14-15], SMR [11,13], Kinematic analysis [12-14], GSI [14], and limit equilibrium methods [11,14-15]. Nevertheless, the technique is employed separately to examine slope stability at tuff mines [11], road [12], gold mines [13], and limestone mines [14]. Prasetyo et al [15] investigated the correlation between the RMR value and the Safety Factor on coal mine slopes. Nevertheless, applying these four methodologies for analyzing slope stability in coal final walls remains limited. The main goal of this study is to investigate the geotechnical factors, specifically focusing on analyzing the stability of slopes near the final wall zone using four methods. This research aims to generate a slope geometric design that could be an essential reference for slope design.

LITERATURE REVIEW

Regional Geology

In accordance with the Regional Geological Map of the Bogor Sheet [16], the Jakarta and Seribu Islands Sheet [17] and the physiographic zone division proposed by [18], the area under consideration is categorized into four major zones: the Bogor Zone, the Jakarta Coastal Plain, the Bandung Zone, and the Southern Mountain Zone of West Java. Based on a synthesis of data from [16-17,19], the stratigraphy of the studied region exhibits a classification that includes various formations, particularly the Jatiluhur Formation (Tmj), Klapanunggal Formation (Tmk), Mount Dago Basalt (Tmpb), Serpong Formation (Tpss), Alluvial Fan (Qav), and Alluvial Deposits (Qa).

The geological features observed in this region consist of anticlines located within the southeastern portion of the Klapanunggal Formation, accompanied by a northwest-to-southeast trending axis[16]. In addition, a strike-slip fault was identified that intersects the Klapanunggal Formation in a northwest-to-southeast direction. The fault displays a thrust lineament with similar features to a strike-slip fault. Furthermore, a weak zone across the geological structure was identified, conducting in a northeast-to-southwest direction, in which compression takes place from the northeast to the southwest.

Rock Mass Classification

Rock mass refers to the connection between the physical properties of rock material and the presence of discontinuities. The fundamental principle dealing with intact rock masses is that rocks initially exist in a state of homogeneity and integrity, subsequently experiencing a reduction in strength due to the presence of areas characterized by discontinuities. Various classes of rock masses exist, involving:

1. Rock Mass Rating (RMR)
   The Rock Mass Rating (RMR) is a geomechanical categorization system that utilizes empirical methods and incorporates rock mass weighting procedures. The RMR technique uses various parameters, namely Intact Rock Strength, Rock Quality Designation (RQD), Spacing of Discontinuities, Condition of Discontinuities, Groundwater Condition, and Orientation of Discontinuities [9].
2. Geological Strength Index (GSI)
   The Geological Strength Index (GSI) is a system used to categorize rock formations by assigning their numerical values. This classification system was developed to facilitate analysis of rock mass behavior and failure potential, drawing upon the failure criteria established by Hoek and Brown [20]. The technique mentioned above is employed to obtain an approximation of the structural strength of the fractured rock formation.
3. Slope Mass Rating (SMR)
   Slope Mass Rating (SMR) is the utilization of the RMR value to estimate the appropriate slope angle for stripping slopes. This study aims to assess the Slope Mass Rating (SMR) value, which serves the purpose of assessing the qualifications of rock masses, as modified by the Rock Mass Rating (RMR) concept [21].

Kinematic Analysis

The application of kinematic analysis is widely used in examining slope stability. Using discontinuity and joint orientation information in applying kinematic analysis is an essentially valuable methodology for understanding various types of failure. Kinematic analysis, alternatively referred to as a geometric approach, requires studying the angular interactions between discontinuity planes in order to assess the potential for failure and identify the specific failure mode inside a consolidated rock mass. Using kinematic analysis provides the objective of identifying potential failure modes or movements in a rock slope, disregarding the influence of shear strength and resistance. Rock landslides can be classified into four categories based on their characteristics and mechanisms, as defined by Hoek and Bray [22]. These types include plane, wedge, topple, and slump sliding.

Slope Stability

Arief [23] defines a slope as a topographic element on the Earth's surface that exhibits a specific degree of inclination relative to the horizontal plane. A slope might be considered stable when it reaches an acceptable safety factor. As stated by Bowles[24], a classification of safety factor values can be performed by studying the resulting range of values, as demonstrated in Table 1.

Tabel 1. The safety factor value, as defined by Bowles[24]

Factor of Safety Values	*Slope Condition*
FoS < 1.07	*Unstable Slopes*
1,07< *FoS* < 1,25	*Critical Slopes*
FoS > 1,25	*Stable Slopes*

Slope Geometry

The subject of slope geometry involves quantifying several variables, including the height, width, and slope of a wall and the azimuth of a slope. Hustrulid [25] conducted a study about the geometry of a slope, which is a significant determinant of its stability. The term "mine slope" corresponds to its geometric structure, which incorporates three primary elements: bench configuration, interramp slope, and overall slope.

METHOD

The study has been divided into four distinct phases of implementation, which encompass the initial preparation, data collection, data processing, and data analysis. These phases focus on the use of rock mass classification data, kinematic analysis, slope stability assessment, and the generation of recommendations for slope geometry redesign. In short, primary data is acquired by directly observing and measuring geological formations, particularly joints, in the field. Collecting primary data requires utilizing the scanline sampling technique to evaluate groundwater conditions. Furthermore, we integrate secondary data sources consisting of regional geology maps, mine progress maps, peak ground acceleration data, rock physical data, and rock mechanical data. The data under consideration refers to the compressive strength of undamaged rock and the weight measurement of the material component. The necessary mechanical data includes the cohesion value (c) and internal friction angle (ϕ) obtained from the processing results in Roclab software. The methodology is visually represented in Figure 1.

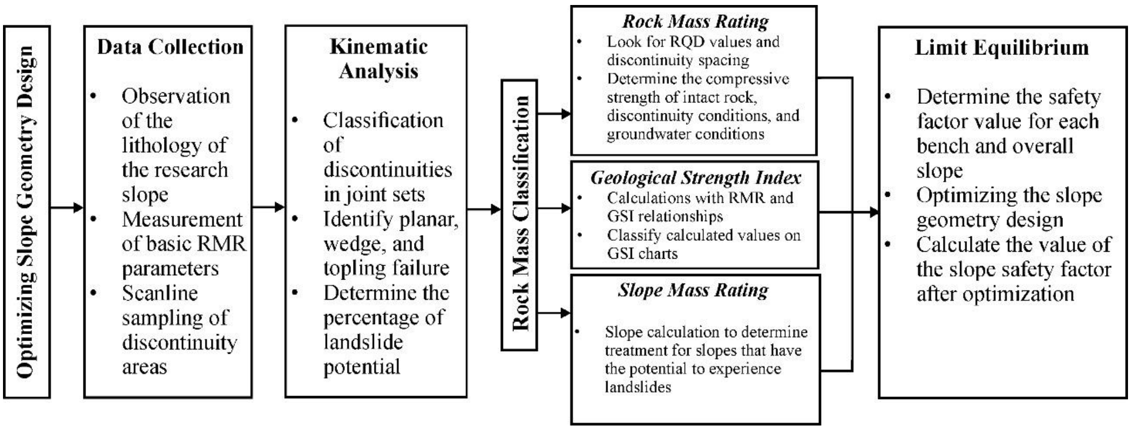


Figure 1. Research phases.

RESULTS AND DISCUSSION

Geological Research Area

The current study endeavor was conducted in the raised mining region of PT. Solusi Bangun Indonesia Tbk, which are at the Narogong Factory. The research slope, functioning as the ultimate boundary and border of the company's Industrial Use Permit (IUP), covers approximately 210 meters in length. The research site has a particular limestone lithology, associated with the Klapanunggal Formation. This formation comprises sandy limestone, marl, glauconitic quartz sandstone, and green sandstone [18]. In terms of regional geological conditions, it is critical to consider the evolving geological structure identified as the discontinuity area. The geological structure observed in the research area is a complex assemblage of deformations occuring on Java island through the Late Miocene period.

The study data collecting site reveals a geological feature characterized by a fracture in the rock, oriented in a west-east direction. This local geological structure is commonly defined as a homocline within the research data collection area. The correlation between lithology and slope stability lies in the fact that lithology represents a significant internal component that impacts the stability of a slope. The lithological composition of a given region is closely associated with each area's particular features and influences processes such as weathering and deformation. The research site exhibits slopes characterized by limestone lithology, with a moderate degree of weathering and a relatively low amount of slope body deformation. Thus, the slopes at this particular site exhibit predominantly favorable stability characteristics. Still, certain areas demonstrate lower degrees of stability, primarily resulting from internal geological variables, such as the presence of structural joints. The lithological units in the research area consist of limestone originating from the Klapanunggal Formation (Figure 2).

Rock Mass Classification

The rock masses classification needs the utilization of data obtained from performed measurements. The measurement took place on a total of four occasions across three different levels throughout the chosen research region. The results of the scanline mappings indicated that there were a total of 29 joints on scanline 1, 31 joints on scanline 2, 12 joints on scanline 3, and 27 joints on scanline 4.

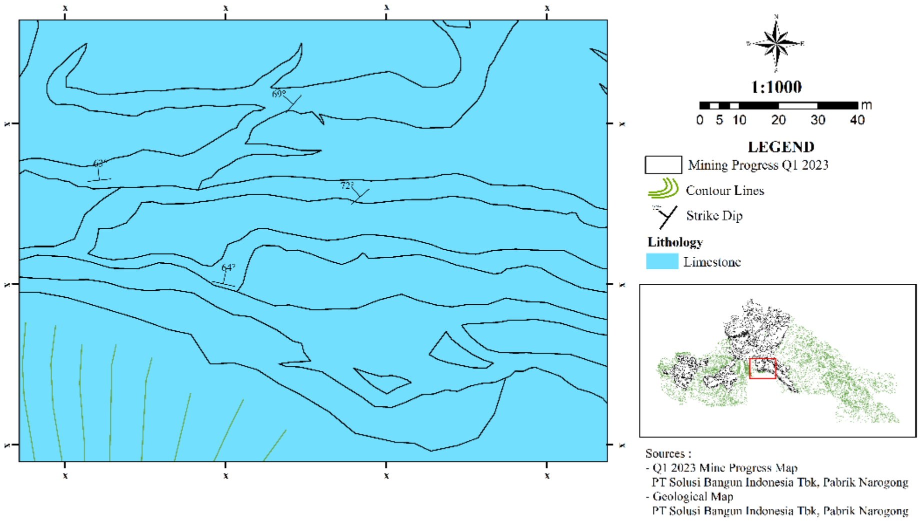


Figure 2. Local geological map of the research area.

Rock Mass Rating (RMR)

The Rock Mass Rating (RMR) methodology incorporates the processing and weighing of five parameters: the compressive strength of intact rock, the spacing of discontinuity areas, the RQD value, the discontinuity conditions, and the groundwater conditions. Following performing a weighting procedure based on Bieniawski [26] RMR classification, it was determined that level 1 presented an overall RMR value of 70. Similarly, scanline 2 of the second level generated a value of 62, scanline 3 of the second level ended with a value of 67, whilst the third level showed a value of 70. If the calculation of the mean value was performed, the resulting value was 67.25. Further details can be observed in Table 2.

Table 2 The weighting of Rock Mass Rating (RMR) for the specific research area.

Bench	***Parameters***				
	Intack Rock Strength	***RQD***	***Spacing of Discontinuities***	***Condition of Discontinuities***	***Groundwater Condition***
Bench 1 Scanline 1	*Limestone* 11,37 Mpa	99,51	0,99 m	*Continuity discontinuity <1 m, rough surface roughness, none aperture, no infilling material, moderately weathered*	*Wet*
Total Rating	**2**	**20**	**15**	**26**	**7**
Bench 2 Scanline 2	*Limestone* 11,37 Mpa	98,32	0,51 m	*Continuity of discontinuity 1-3 m, rough surface roughness,*	*Wet*

Bench	*Parameters*				
	Intack Rock Strength	*RQD*	*Spacing of Discontinuities*	*Condition of Discontinuities*	*Groundwater Condition*
				aperture <0.1 mm, no infilling material, moderately weathered	
Total Rating	**2**	**20**	**10**	**23**	**7**
Bench 2 Scanline 3	*Limestone* 11,37 Mpa	99,68	1,24 m	*Continuity of discontinuity 1-3 m, rough surface roughness, no aperture, no infilling material, moderately weathered*	*Wet*
Total Rating	**2**	**20**	**15**	**24**	**7**
Bench 3 Scanline 4	*Limestone* 11,37 Mpa	99,68	0,83 m	*Continuity discontinuity <1 m, rough surface roughness, no aperture, no infilling material, moderately weathered*	*Wet*
Total Rating	**2**	**20**	**15**	**26**	**7**

Based on the aforementioned observation, it may be concluded that the rock mass forming the slope falls into rock mass class II (Good). According to the conclusions of [9], it can be noticed that rock mass class number II demonstrates an average duration of stability of one year, accompanied by an overall spatial extent of 10 meters. In addition, the rock mass in this classification shows a cohesive value ranging from 300 to 400 kilopascals, along with a friction angle within the range of 35 to 45 degrees.

Geological Strength Index (GSI)

The current research adopts the approach proposed by Hoek et al [27] to determine the Geological Strength Index (GSI) value, which is calculated from the Rock Mass Rating (RMR) value. The present computation refers to the value of Hoek et al [27], in which the average value of the Rock Mass Rating (RMR) has been identified as 67.25. In addition, the Geological Strength Index (GSI) value for the slope under investigation has been determined to be 62.25. The rock mass under the research region presents a blocky configuration, which is characterized by a non-uniform but connected distribution of rocks. This result is typical for limestone with massive or thickly bedded [28]. These rocks are predominantly cube-shaped and are formed by the intersection of three sets of discontinuities. The surface quality of the rock exhibits a satisfactory level of roughness. Still, there are indications of weathering or minor weathering affecting the overall state of the rock.

Slope Mass Rating (SMR)

The method used applies four categorizations to determine the maximum value of the slope angle. The SMR classification employed in this study corresponds to calculations based on the methodologies proposed by [29-31]. This method could be used to evaluate the stability level of a rock slope [32]. The research area generated recommendations on safe stripping slope angles for limestone quarry slopes based on the given values. The SMR values referring to the slopes in the research area are shown in Table 3.

Table 3. Slope Mass Rating (SMR) value for each level on the slope.

Material Type	***SMR (°)***				
	Classification	***Bench 1***	***Bench 2***	***Bench 3***	***Average***
Limestone	Laubscher, 1975 [29]	65	65	65	65
	Hall, 1985[30]	70,5	67,25	70,5	69,41
	Orr, 1992[31]	80,68	75,06	80,68	78,8

According to the Romana [33] approach, the Slope Mass Rating (SMR) value was calculated and was determined as 59.75. The aforementioned value belongs to the classification of class III (41-60), incorporating regular slopes, stable slope stability on some slopes, and the possibility of landslides, specifically those that result from joints or wedge landslides. In the context of slope analysis, the most common type of reinforcement is systematic stabilization, as shown in the case studies given in this research. The recommended supports are toe ditch, wire mesh, and spot/systematic bolting. Blanco-Fernandez et al. [34] propose combining wire mesh and bolting for slope stabilization, specifically designed to improve the material's resistance against existing landslides.

Kinematic Analysis

Kinematic analysis to explore non-circular failure or slide. The mentioned potential has the form of a wedge type, which is located on scanline 4. An illustration of this can be noted in Figure 3. The findings of this study reveal that, by kinematic analysis processing on four scanlines, evaluations have been performed to evaluate three types of landslide potential: planar sliding, wedge sliding, and toppling sliding. The results demonstrated that only one of the scanlines satisfied the criteria for landslides as defined by Hoek and Bray[22].

Slope Stability

Based on the slope geometry measurements performed, the slope can be divided into three sections. The single slopes have heights measuring 7.56 m, 8.64 m, and 8.97 m, corresponding angles of 49°, 60°, and 64°. Likewise, the length of the single slopes is 11.84 m and 18.73 m. The elevation of the slope has been estimated at 37.34 meters, while the angle of inclination of the slope has been estimated at 29 degrees. Figure 4 illustrates the different heights associated with each level.

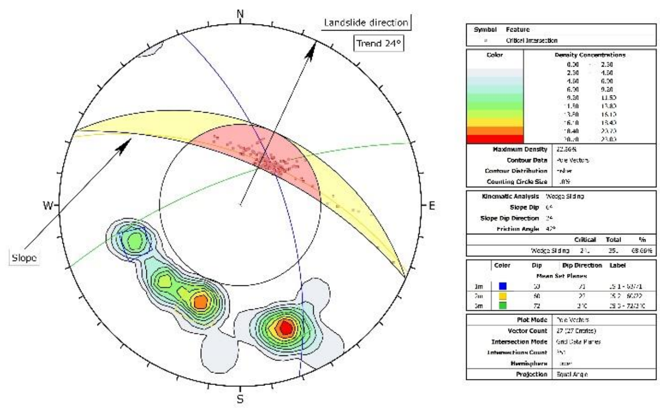


Figure 3. Wedge sliding kinematics on scanline 4

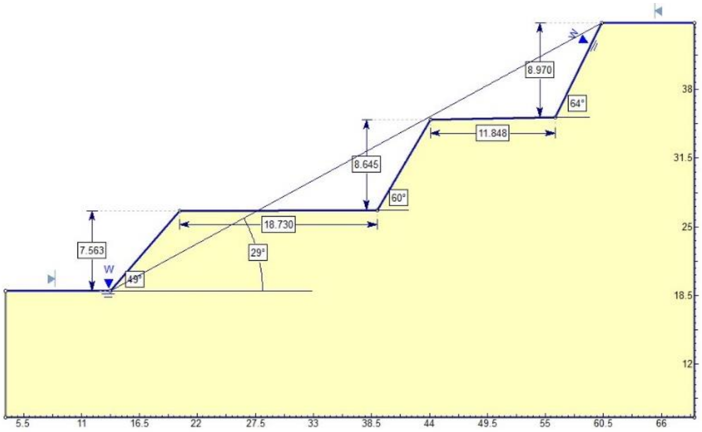


Figure 4. Actual of slope geometry

The completed analytical results obtained from the application of the limit equilibrium approach using Slide software indicate differences in values between natural slopes and water-saturated slopes. The study demonstrated that the observed slope stability indicated a safety factor value of 4.192 under natural conditions (Figure 5a) and 3.952 over saturated conditions (Figure 5b). According to Romana's [33] analysis of the safety factor value with the FK criterion, the slope under investigation might be stable. The slope has a significant impact on the safety factor. The force of gravity is the primary factor that causes movement on the slope, which is directly influenced by the angle of inclination [35-36]. Similarly, decreasing the incline angle enhances the safety factor of the slope [37]. Furthermore, the level of safety is strongly correlated with the shear strength of the probable failure plane, as stated by Hoek and Bray [22]. The prospective failure plane's shear strength is influenced by cohesion (c) and friction angle (ϕ). An increase in the shear strength will increase the safety factor.

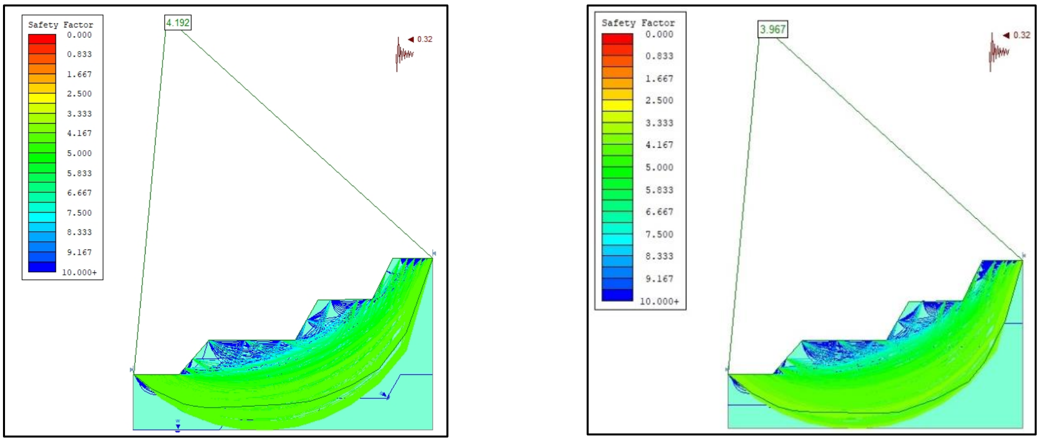
Slope Geometry Design Optimation

According to the slope stability analysis findings, the research site indicates a stable slope condition. The stability of the slope relies on favorable values of the limestone rock mass, with RMR of 67.25 [26], GSI of 62.25 [28], and the impact of minimum seismic activity, specifically 0.32 [38]. As noted by Beyabanaki[39], groundwater conditions significantly impact slope stability. This study assessed the groundwater depth at the research site based on real field conditions and when the groundwater is saturated. The slope conditions can be classified as safe based on by slope safety factor values of 4.912 (under natural conditions) and 3.952 (under saturated conditions). Thus, optimizing the slope remains quite feasible.

In terms of evaluating the geometric characteristics of the slope, the optimization process involved setting the height of each level at 10 m, constructing a single slope angle of 80˚, determining a bench width of 3 m, and obtaining an overall slope angle of 68˚. These recommendations are summarized below and can be shown in design models, such as Figure 6.

The slope stability safety factor for the final wall overall slope design in the research area was determined based on the recommended values. The Morgenstern-Price method has been applied to calculate the safety factor. Figure 7a was employed for natural slopes, resulting in a safety factor of 2.076. For water-saturated slope conditions, Figure 7b was utilized, resulting in a safety factor of 2.050.

The stability or safety condition of the slope geometry design can be evaluated based on the safety factor value established by Bowles [24]. On evaluating the method of optimizing natural resources to maximize production operations, it is observed that the proposed slope geometry designs coincide with both geotechnical and economic principles.



(a) (b)

Figure 5 The values of slope safety factors under two different scenarios: natural conditions (a) and water saturation (b).

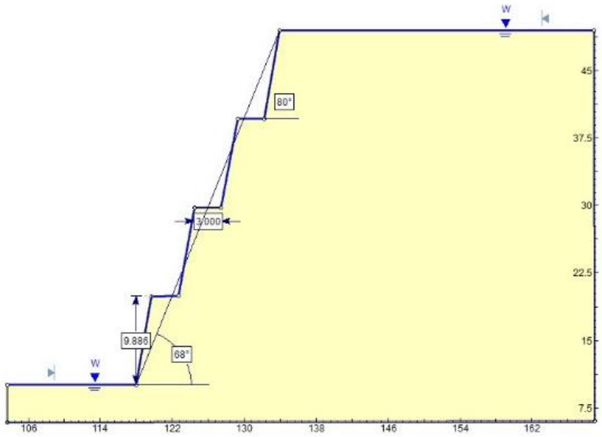
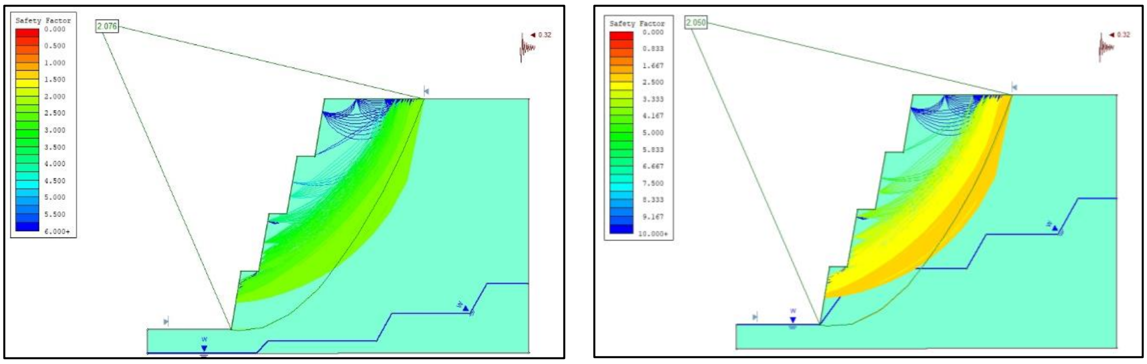


Figure 6. Recommendation for slope geometry design.



(a) (b)

Figure 7 The safety factor values that arise from the redesign of slopes under both natural (a) and water-saturated (b) conditions.

CONCLUSION

The average value for the three slope levels, as determined by the Rock Mass Rating (RMR) classification, was RMR 67.25. The rock mass was classified as II, representing an excellent rock description. The research region reveals a blocky structure in terms of its Geological Strength Index (GSI) condition. A cohesive configuration of disturbed rock characterizes this structure, whereas the individual blocks connect one another and form a mass. The blocks under consideration reveal a dominant cube shape and are formed by an intersection of three distinct sets of discontinuities. The

Slope Mass Rating (SMR) values for each level were calculated from the studies conducted by Laubscher at a slope of 65°, Hall at an inclination of 70°, and Orr at an angle of 80°. The slope has an SMR value of 59.75 and is classified as class IIIa. Based on the kinematic study conducted by Hoek and Bray in 1981, the research slope implies the possibility of a wedge-type landslide, especially on the third level, with a major landslide direction towards the northeast. The research performed on the present slope suggests the safety factor in natural conditions is 4.192, while under saturated conditions, it is 3.967. The optimal slope geometry design for the defined research area requires a single slope angle of 80°, a single height of 10 m, and a single width of 3 m, which leads to an overall slope of 68°. The suggestions above give a safety factor value of 2.076 in natural conditions and 2.050 under saturated conditions.

ACKNOWLEDGMENT

The authors express gratitude to PT. Solusi Bangun Indonesia Tbk, Narogong Factory, for granting permission to study in the mining area.

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