

## **OPTIMIZATION OF PIT SLOPE DESIGN AT BANKO BARAT PIT 2 IN 2016, PT BUKIT ASAM (PERSERO) TBK, TANJUNG ENIM MINING UNIT, SOUTH SUMATRA PROVINCE**

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### **ABSTRACT**

Slope stability is generally a critical concern in maintaining daily mining operations, as instability can disrupt activities and result in material losses or even fatalities. In designing an open-pit mine, it is essential to conduct slope stability analysis to ensure both safety and economic efficiency. This study focuses on optimizing slope stability analysis at PT Bukit Asam (Persero) Tbk, specifically in the Banko Barat Pit 2 area, using the Bishop Simplified method. The analysis was conducted using GeoSlope 2007/Slope W software to design and optimize a safe excavation slope by incorporating secondary data obtained from PT Bukit Asam, including mining design parameters (slope geometry) and the physical and mechanical properties of the rock, such as density, cohesion, and internal friction angle. The optimization results indicated that cross-sections A-A', C-C', and D-D' could accommodate an additional 3 benches. Cross-section B-B' was also optimized by adding 3 benches downward. The safety factor (SF) values for the first and second optimization scenarios showed stable slope conditions. However, for the third optimization (overall slope), the SF values indicated a marginal or risky condition. Cross-section E-E' could be optimized by adding 5 benches downward, and all five cross-sections remained in a stable condition.

**Keywords:** safety factor, slope stability, Bishop Simplified method, optimization, GeoSlope 2007/Slope W software

### **1. INTRODUCTION**

#### **1.1 Background**

PT Bukit Asam Tbk (PTBA) is one of Indonesia's largest state-owned coal mining companies, operating primarily through open-pit mining at its Tanjung Enim Mining Unit in South Sumatra. As part of its large-scale operations, PTBA utilizes both conventional mining methods—such as excavator and dump truck combinations—and advanced systems like the Bucket Wheel Excavator (BWE), which support continuous mining in several pits (Isdianti, Ibrahim, & Setiawan, 2022).

One of the major challenges in open-pit coal mining is ensuring slope stability, especially in highwall conditions where any slope failure may endanger personnel safety, damage equipment, and hinder

production targets. Numerous factors influence slope stability, including mining geometry, rock mechanics properties (e.g., cohesion, internal friction angle), hydrological conditions, and geostructural discontinuities (Agbelele, Kinsley, & Sam, 2024; Li et al., 2022).

In Banko Barat Pit 2, slope instability has been reported at various disposal and production areas, prompting several studies that evaluate the performance of different slope configurations using limit equilibrium methods (Sepriadi & Adiwarmanto, 2024). Slope analysis using the Morgenstern–Price method identified marginal safety factors in several highwall zones, necessitating adjustments in slope geometry and excavation sequences. Ramadhan, Toha, and Purbasari (2021) further demonstrated that disposal slope optimization, especially through proper

sequencing and geometry refinement, could significantly improve safety without sacrificing economic performance.

In addition to analytical methods, real-time monitoring systems such as Slope Stability Radar (SSR) have been deployed to observe deformation on active slopes. Rahmatullah et al. (2024) documented deformation rates of up to 27 mm/hour at Banko Barat Pit 2, indicating critical conditions in some slope segments and underlining the value of integrating observational data with numerical analysis for continuous risk assessment.

Among the available modeling tools, GeoStudio 2007's SLOPE/W module has become a standard in Indonesian mining geotechnics, especially when used with classical methods like Bishop Simplified and Fellenius. Yuliansyah (2016) applied this tool to assess slope performance in Banko Barat Pit 1 and concluded that stability conditions are highly sensitive to changes in material strength and geometry. Later studies supported these findings by comparing different methods such as Bishop, Janbu, and Morgenstern-Price for better decision-making (Simanjuntak, Fahraini, & Indriawati, 2020).

Furthermore, environmental concerns in reclaimed post-mining areas such as Air Laya have raised the importance of slope erosion resistance, sediment control, and soil stability as integral parts of long-term slope management (Isdianti et al., 2022; E3S Web of Conferences, 2020). Slope design must not only prevent immediate failure but also support reclamation goals and minimize future geotechnical hazards.

This study seeks to analyze and optimize slope stability at Banko Barat Pit 2, PTBA, using the Bishop Simplified method through GeoStudio 2007/SLOPE/W. By applying slope geometries, physical and mechanical

properties of rock (density, cohesion, angle of internal friction), and industry-proven design principles, this research aims to identify stable configurations that ensure operational safety, environmental sustainability, and economic viability in line with PTBA's long-term mining plans..

## **2. RESEARCH METHODS**

### **Research methodology**

#### **2.1 Research Place**

This research was conducted at the coal mining company PT Bukit Asam (Persero) Tbk., specifically within the Exploration and Geotechnical Work Unit of the Tanjung Enim Mining Unit. The study took place over approximately one month and one week, from July 25 to September 5, 2016. All field activities were carried out at Banko Barat Pit 2, located in Tanjung Enim, South Sumatra Province, Indonesia..

#### **2.1 Tools and Materials**

##### **2.1.1 Tools used**

The tools and software used in this study, both during data collection and data processing, include:

1. Microsoft Excel – Used for processing and calculating geotechnical laboratory test data such as physical and mechanical properties.
2. GeoSlope 2007/SLOPE/W software – Utilized to analyze and model the most optimal excavation slope design based on calculated safety factor (SF) values for each designed slope section.

##### **2.1.2 Materials used**

This study relied entirely on secondary data provided by PT Bukit Asam (Persero) Tbk, which included:

1. Laboratory test results of physical and mechanical rock properties from Banko Barat Pit 2, tested in September 2014 at the Geotechnical Soil Mechanics Laboratory of PTBA.
2. Lithology and stratigraphy data of the Banko Barat Pit 2 area.

3. Mining plan maps of the Banko Barat Pit 2 site.
4. Cross-sectional design drawings (penampang) of Banko Barat Pit 2, and regional rainfall data.

These datasets were processed using GeoSlope 2007/SLOPE/W, producing outputs including:

- Slope geometry profiles in Banko Barat Pit 2.
- Simulation parameters for both single slopes and overall slopes.
- Final slope design alternatives for Banko Barat Pit 2.

## **2.2 Experimental Design**

### **2.2.1 Fixed Variables**

The fixed variables in this study included:

- Slope geometry, such as slope height, bench width, and slope angle.
- Physical and mechanical rock properties, including:
  1. Unit weight ( $\gamma$ ) – representing the rock's physical property.
  2. Cohesion ( $c$ ) and internal friction angle ( $\phi$ ) – representing the mechanical strength properties of the slope materials.

### **2.2.2 Independent Variables**

The independent (changing) variables in this research consisted of:

- Safety factor (SF) – affected by variations in slope geometry, especially bench height during slope simulation and design modeling using GeoSlope 2007/SLOPE/W.
- Slope stability analysis – influenced by changes in the SF values resulting from the slope geometry variations.

### **2.2.3 Dependent Variable**

The main outcome or dependent variable in this study is the optimized slope design, determined from the combination of fixed and independent variables that result in safety factors

meeting or exceeding stability criteria (generally  $SF \geq 1.3$  for static conditions).

## **2.3 Experimental and Testing Procedures**

This study consists of five main stages: (1) preliminary study, (2) field observation, (3) data collection and processing, (4) data analysis and interpretation, and (5) report compilation. The detailed procedures are described below:

### **2.3.1 Preliminary Study**

This initial stage involved a literature review to gather fundamental theories and supporting data related to slope stability analysis in open-pit coal mines. References were obtained from scientific journals, company reports, textbooks, and previous research relevant to slope optimization, geotechnical investigation, and limit equilibrium methods. This stage helped to define the research problem and determine the appropriate analytical method to be applied in the case of Banko Barat Pit 2.

### **2.3.2 Field Observation**

A field investigation was conducted at Banko Barat Pit 2, located within the Tanjung Enim Mining Unit of PT Bukit Asam (Persero) Tbk., South Sumatra Province. The site visit included visual inspections of the mine topography, slope conditions, access roads, and active excavation areas. Cross-sectional locations were determined based on strike direction and slope morphology to accurately represent actual field conditions.

### **2.3.3 Data Collection and Processing**

#### **A. Data Collection**

The study used secondary data obtained from the Exploration and Geotechnical Unit of PTBA, including:

1. Mine planning maps and cross-section data of Banko Barat Pit 2

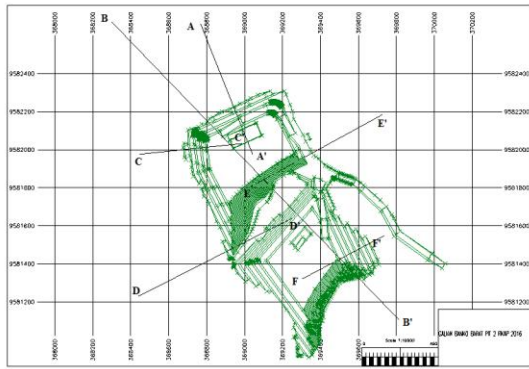


Figure 2.1 Mining Plan Map of Banko Barat Pit 2, Year 2016 (Source: PT Bukit Asam (Persero) Tbk, Mine Planning Department)

2. Geotechnical cross-sections derived from mine plans, with six (6) key sections selected for analysis

Table 2.1 Coordinates of Cross Sections in Banko Barat Pit 2 Area

NO.	Cross Sections	Coordinates	
		X (East)	Y (North)
1	A	368769	9582661
	A'	369042	9581976
2	B	368298	9582674
	B'	369813	9581106
3	C	368446	9581977
	C'	368987	9582033
4	D	368439	9581228
	D'	369251	9581641
5	E	369024	9581802
	E'	369728	9582186
6	F	369302	9581320
	F'	369736	9581549

- Lithological and stratigraphic data describing subsurface conditions and rock layering
- Hydrogeological information, where pore water pressure was assumed as one-third saturation for slope simulation
- Loading conditions, including static loading (650 kPa from heavy equipment) and dynamic loading from seismic activity (0.02 g)
- Failure surface estimation, assuming circular failure in homogeneous

material based on observed geology and topography

- Physical and mechanical properties of each layer, obtained from laboratory tests including direct shear, triaxial, and UCS, such as: Cohesion ( $c$ ); Internal friction angle ( $\phi$ ); and Wet density ( $\gamma_w$ ). The physical and mechanical properties of rock materials in the Banko Barat Pit 2 area were obtained from laboratory testing conducted by the Geotechnical Soil Mechanics Laboratory of PT Bukit Asam (Persero) Tbk. The tests included direct shear, triaxial, and unconfined compressive strength (UCS). These properties are critical for determining slope stability and are used as input parameters for modeling in GeoSlope 2007/SLOPE/W. The table below summarizes the cohesion ( $c$ ), internal friction angle ( $\phi$ ), and wet density ( $\gamma_w$ ) for each geological layer.

Table 2.2 Physical and Mechanical Properties of Each Layer

NO	LAPISAN	MATERIAL	C	$\phi$	$\gamma_w$
			kPa	°	kN/m <sup>3</sup>
1	TOP SOIL	Silty Claystone	18.615	21.34	17.39
2	OVERBURDEN A1	Clayey Silstone	21.95	30.05	19.395
3	SEAM A1	Coal	200	30	11.8
4	INTERBURDEN A1-A2	Silty Clayey Sandstone	31.48	32.45	19.37
5	SEAM A2	Coal	200	30	11.8
6	INTERBURDEN A2-B1	Clayey Silstone	20.37	25.3	20.09
7	SEAM B1	Coal	200	30	11.8
8	INTERBURDEN B1-B2	Clayey Silstone	22.175	22.76	20.405
9	SEAM B2	Coal	200	30	11.8
10	INTERBURDEN B2-C	Clayey Silstone	30.11	22.5	21.625
11	SEAM C	Coal	200	30	11.8
12	UNDER C	Sandy Clayey Silstone	17.29	24.1	21

Source: Geotechnical Soil Mechanics Laboratory, PT Bukit Asam (Persero) Tbk, 2016

## B. Data Processing

- Physical and mechanical property

data were organized in Microsoft Excel for calculation.

2. Geotechnical sections were modeled using GeoSlope 2007/SLOPE/W, with each layer assigned its corresponding strength parameters.
3. Three slope analyses were performed:
  - Existing (2016) mine plan overall slope configuration
  - Simulation of single slopes for Overburden and Interburden materials
  - Optimization of slope geometry based on varying bench heights (8 m, 9 m, 10 m) and 45° slope angle (1:1)
4. The obtained safety factor (SF) values were exported into Excel for comparative analysis and decision-making on optimized designs.
5. The results included SF values for both single slopes and overall slopes for each of the six cross-sections.

#### 2.3.4 Data Analysis and Interpretation

This stage involved analyzing the results from GeoSlope simulations by comparing the safety factor values with geotechnical standards (typically  $SF \geq 1.3$  for static conditions). The results were interpreted based on material strength, slope geometry, and loading conditions. The goal was to identify slope configurations that are both safe and efficient for mining operations.

#### 2.3.5 Report Compilation

In the final stage, all findings from field observations, data analysis, and literature review were compiled into a research report. Visual aids such as diagrams, tables, maps, and graphs were used to present the results clearly. The report summarizes the optimized slope designs for Banko Barat Pit 2 and includes recommendations for implementation in the mine's operational planning.

#### 2.3.6 Analysis of Test Parameters

The test parameters used in this research were derived from triaxial tests conducted on soil and rock samples obtained from the field. The triaxial test was employed to determine the key geotechnical parameters: cohesion ( $c$ ), density ( $\gamma$ ), and internal friction angle ( $\phi$ ) of the material samples from the Banko Barat Pit 2 area.

In the triaxial test, cylindrical samples of soil and rock were subjected to controlled axial loads under confined pressure until failure occurred. The results obtained—values of cohesion, internal friction angle, and density—were then used as input parameters for the slope stability analysis.

These geotechnical parameters were incorporated into the GeoSlope 2007/SLOPE/W software alongside the cross-sectional data of the mine's design in Banko Barat Pit 2. The analysis simulated slope geometries using various bench heights of 8, 9, and 10 meters, with the aim of identifying the most stable and optimal slope configuration.

By analyzing each geotechnical cross-section using this method, the safety factor (SF) for each design alternative was calculated. The simulation results were used to evaluate the slope stability and to determine whether further slope optimization could be implemented.

Ultimately, the optimized slope designs obtained through this analysis are expected to serve as valuable references for PT Bukit Asam (Persero) Tbk in future mine planning and operational decision-making at Banko Barat Pit 2.

### 3. RESULTS AND DISCUSSION

#### 3.1 Research Results

##### 3.1.1 Site Conditions

The study was conducted in the Banko Barat Pit 2 area of PT Bukit Asam (Persero) Tbk, where land clearing had been completed as of August 2016. The terrain is generally undulating with

elevations ranging from 65 to 102 meters above sea level. Slope design and optimization were carried out by analyzing geotechnical sections based on six cross-sections obtained from the 2016 mine plan. Stable slope geometry depends heavily on the physical and mechanical properties of each lithological layer, groundwater conditions, berm width, equipment loads, and slope angles.

### 3.1.2 Geotechnical Cross-Section

Six cross-sections were used as reference points in the analysis.

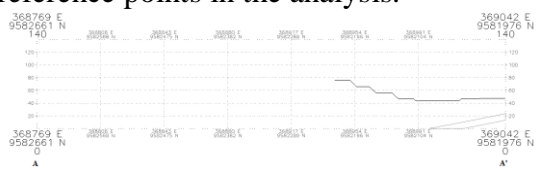


Figure 3.1 Cross-Section A-A'

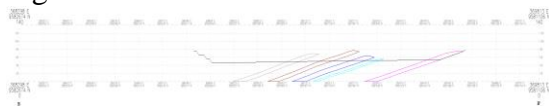


Figure 3.2 Cross-Section B-B'

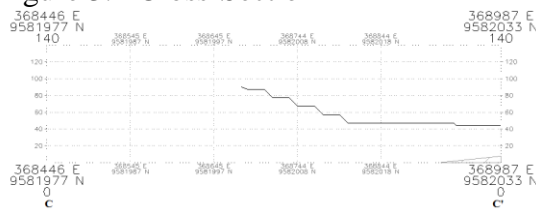


Figure 3.3 Cross-Section C-C'

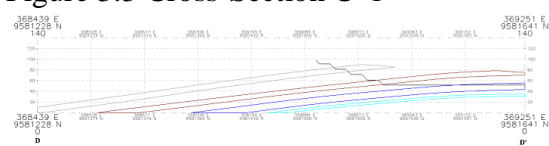


Figure 3.4 Cross-Section D-D'

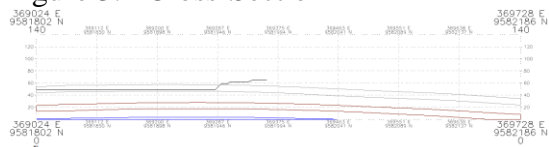


Figure 3.5 Cross-Section E-E'

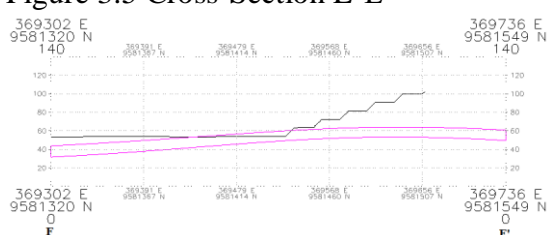


Figure 3.5 Cross-Section F-F'

### 3.1.3 Physical and Mechanical Properties

Laboratory tests provided key input parameters including cohesion (C), internal friction angle ( $\phi$ ), and wet density ( $\gamma_w$ ) as shows in Table 2.2.

### 3.1.4 Physical and Mechanical Properties

The area comprises overburden, coal seams, and interburden materials with specific identifiers such as Suban Marker and Petai Marker. Each layer was characterized by its color, texture, composition, and typical partings. Seam B1, for instance, contains a single clay parting, while Seam A1 has three partings with varying clay compositions.

### 3.1.5 Hydrology

Pore water pressure was assumed at 1/3 saturation. Analysis showed that lower pore pressures correlate with higher safety factors (SF).

Table 3.1 Pore Water Pressure at One-Third Saturation

Slope Height (m)	Crest Height (Top) (m)	Crest Height (Bottom) (m)	$\Delta H = H_a - H_b$ (m)	Pore Water Pressure (m)
8	40	32	8	37.33
9	40	31	9	37.00
10	40	30	10	36.67

### 3.1.6 Single Slope Analysis

Simulations using GeoSlope 2007/Slope W across all layers and various slope geometries (1:1, 1:2, 1:3) revealed that most layers were stable at 8 m and 9 m heights, except “Under C” and parts of “IB B1-B2” where SF dropped below safe thresholds under steep conditions. See Table 3.2 for full SF values.

Table 3.2 SF Single Slope Analysis

Height Bench (m)	OB A1		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,547	2,106	2,555
9	1,258	2,083	2,528
10	1,351	1,951	2,386

Height Bench (m)	IB A1-A2		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,997	2,652	3,198
9	1,840	2,587	3,128
10	1,727	2,417	2,943

Height Bench (m)	IB A2-B1		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,346	1,826	2,206
9	1,244	1,794	2,171
10	1,172	1,681	2,050

Height Bench (m)	IB B1-B2		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,345	1,793	2,160
9	1,115	1,745	2,108
10	1,163	1,632	1,986

Height Bench (m)	IB B2-C		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,585	2,077	2,495
9	1,455	1,998	2,406
10	1,368	1,867	2,252

Height Bench (m)	UNDER C		
	Slope ( $\alpha$ ) 1:1 (45°)	Slope ( $\alpha$ ) 1:2 (26,6°)	Slope ( $\alpha$ ) 1:3 (18,4°)
8	1,181	1,615	1,979
9	0,964	1,595	1,957
10	1,035	1,498	1,853

### 3.1.7 Existing (2016) Slope Conditions

The slope configurations in the 2016 mine plan yielded SF values ranging from 1.272 to 2.025 across all sections, indicating that current designs were stable under assumed conditions. For example, Section C–C' achieved an SF of 1.926, and Section E–E' reached 2.025. These values provided the baseline for optimization.

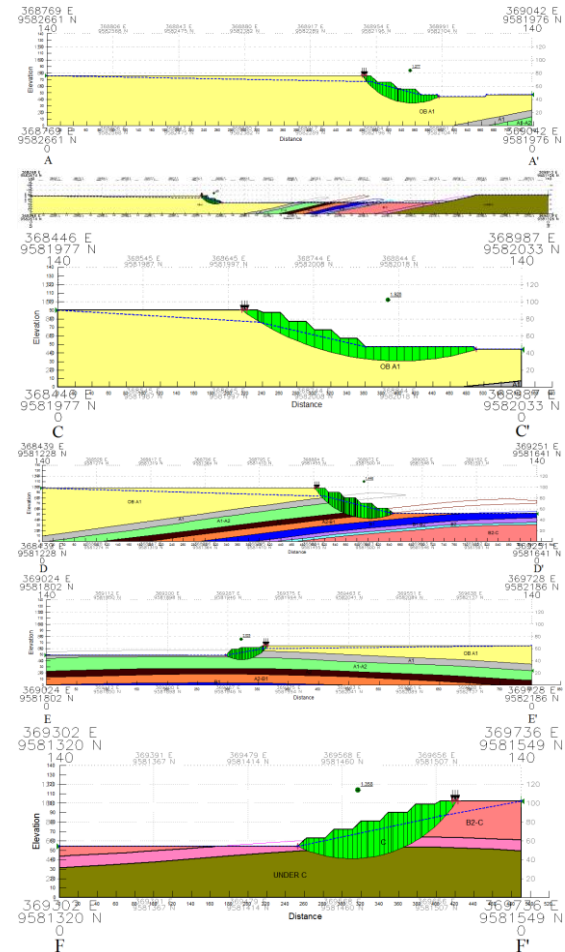


Figure 3.1 Factor of Safety (FoS) of the 2016 Mine Plan in Banko Barat Pit 2 Based on Six Cross-Sections

### 3.1.8 Slope Optimization Results

Using the results of single slope simulations, optimization was done using 9 m bench height and 1:1 slope angle. Optimization results per cross-section:

1. A–A': 3 additional benches; final SF = 1.266–1.246 (stable)
2. B–B': 3 benches; SF = 1.217 (third bench: marginal)
3. C–C': 3 benches; SF = 1.386–1.249 (stable)
4. D–D': 3 benches; SF = 1.685–1.293 (stable)
5. E–E': 5 benches; SF = 1.925–1.370 (stable)
6. F–F': 1 bench; SF = 1.210 (marginal) – due to presence of weak “Under C” layer.

These results demonstrate that most slopes in Banko Barat Pit 2 can still be optimized safely by adding benches, except in areas dominated by low-strength materials (e.g., “Under C”).

### 3.2 Discussion

The slope stability at Banko Barat Pit 2 is largely governed by lithological conditions and slope geometry. The simulation results using the Bishop Simplified method indicate that safe designs must consider both bench height and angle to accommodate variations in cohesion, friction angle, and pore pressure.

Layers with high cohesion (e.g., coal seams) consistently exhibited higher SF, while weak layers like “Under C” posed stability risks. Optimization by increasing bench height to 9 m was successful for most cross-sections, with safety factors remaining above the minimum requirement of 1.3 under static conditions. However, critical zones such as Section F–F’ demonstrated the need for conservative slope designs or reinforcement due to poor mechanical properties. The approach used in this study provides practical insight for slope design decision-making and future mine planning in similar geological conditions.

## 4. CONCLUSION

### 4.1 Conclusion

Based on the results and discussions from the slope optimization study in Banko Barat Pit 2, the following conclusions can be drawn:

1. Slope stability is highly influenced by several factors, including the physical and mechanical properties of each geological layer (cohesion  $c$ , internal friction angle  $\phi$ , and wet density  $\gamma_w$ ), hydrological conditions (pore water pressure), loading and vibration from mining equipment, slip surface determination, and slope geometry (height, angle, and berm width).

2. The optimal slope geometry determined from single slope simulations is a bench height of 9 meters with a slope angle of 1:1 ( $45^\circ$ ). The berm width varies between 20 to 25 meters, depending on local topography and operational requirements.
3. For the modeling process—whether in single slope, current mine plan, or optimized slope analysis—the material condition was assumed to be at one-third saturation, meaning the piezometric line was set at one-third of the slope face height. This approach reflects moderate pore pressure, influencing the factor of safety (FoS) in the analysis.
4. Evaluation of the 2016 mine plan slope design in all cross-sections showed that all slopes are in a stable condition, with FoS values ranging from 1.272 to 2.025, indicating the existing designs are safe under current operating conditions.
5. The slope optimization analysis demonstrated the following findings:
  - A–A’, C–C’, and D–D’ sections can be extended by three additional benches downward and remain stable.
  - B–B’ can also be extended by three benches, but only the first two levels remain stable, while the third (overall slope) results in a marginal FoS.
  - E–E’ section can be extended by five additional benches and maintains stability.
  - F–F’ section can only be extended by one additional bench, but results in a marginal safety condition due to weak underlying materials.

### 4.2 Suggestions

Based on the results and discussion of the slope optimization study in Banko Barat Pit 2, it is recommended that:

1. Further slope optimization can still be

implemented in several cross-sections by adding more benches downward, especially where the post-optimization FoS remains in the stable range.

2. Continuous monitoring of pore water pressure, geotechnical parameters, and operational conditions is essential to validate the assumptions made in the simulation, particularly in critical sections such as  $F-F'$ , where stability is sensitive to geological variability.
3. It is advisable to periodically re-evaluate the slope stability as mining progresses, ensuring long-term safety and economic efficiency in line with operational changes and updated geotechnical data.

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