

## RESEARCH ARTICLE

## Analysis of the Factor of Safety (FS) in Slope Stability Against Blasting Activities at Pit X, South Kalimantan

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### Abstract

Blasting is used to break hard rock in mining, but the vibrations can destabilize the slope through the resulting soil vibrations. The resulting blasting vibration must be in a safe condition, especially the stability of the mine slope around the blasting. This study aims to analyze the value of the slope factor of safety (FS), blasting soil vibration, and the influence of soil vibration on the value of the factor of safety (FS). The research method involves data collection followed by slope stability analysis utilizing the Bishop Simplified Method within Slide software and blasting vibration analysis using regression models to determine Maximum Horizontal Acceleration (Amax). The study results showed that the value of FS varied based on location and geological conditions. The A-A' section in the upper western part of the mine has the highest FS value of 2.36, while the C-C' cross-section in the lower eastern part of the mine has the lowest FS value of 1.16. Analysis of soil tremors in Amax values showed the highest values in August and the lowest at the end of October. The Amax value has an effect on the decrease in the FS value based on the blasting distance. The B-B' cross-section has the largest influence, the A-A' and C-C' cross-sections have a fairly small influence, and the D-D' cross-section has no influence.

**Keywords:** Blasting, Ground Vibration, Slope Factor of safety (FS), Slope Stability

### 1. Introduction

Blasting activities are widely used in mining to break down hard rock and facilitate material extraction. The primary reasons for choosing this method include its relatively low operating costs and adaptability to varying field conditions, which make it an efficient and convenient choice for many mining operations. However, blasting can also generate ground vibrations, which may have unintended consequences on the surrounding environment. Ground vibrations are waves generated from an energy source, such as blasting, that propagate through the ground and can potentially destabilize structures, including mine slopes (Amaliya et al., 2016; Mahda and Yuliadi, 2022).

The stability of slopes in mining is influenced by several factors, including slope geometry, rock structure, groundwater levels, and the external forces acting on the slope (Das and Sivakugan, 2017). Vibrations from blasting activities can cause ground shaking, which, in turn, impacts the stability of slopes in areas close to the blast zone (Frank, 2003). If these vibrations exceed safe levels, they may induce slope instability, increase the risk of landslides, and compromise the safety of workers and equipment operating near these areas (Agnesty et al., 2018; Pratiwi et al., 2022). Given the potential risks, evaluating the factor of safety of slopes subjected to blasting activities is critical to ensuring that mining operations adhere to good mining practices (Bowles, 1989).

### 2. Geological Setting

The study area for this research is located within the Barito Basin, positioned on the western side of the Meratus Mountains, South Kalimantan (Figure 1). This mountain range is an ophiolite belt, isolated from plate convergence zones since the Paleogene period, with uplift beginning in the Late Miocene and continuing through the Pliocene-Pleistocene, creating a natural boundary for the Barito Basin (Heryanto, 2010). The geological structure of the region divides South Kalimantan into two main parts: a western plain and an eastern plain.

The research site is positioned explicitly along the boundary between the Meratus Mountains and the western plains, intersecting with the Warukin Formation. This formation, dating from the Miocene to Pliocene, consists predominantly of quartz sandstone and claystone, with coal interbeddings, which were deposited in a fluvial environment and span approximately 400 meters in thickness (Figure 2) (Heryanto and Sanyoto, 2007).

In slope stability analysis, the factor of safety (FS) is a widely used metric for determining whether a slope can maintain stability under varying conditions (Das and Sivakugan, 2017). The SF represents the ratio between resisting forces (shear strength) and driving forces (shear stress) acting on a slope (Bowles, 1989). If the SF value surpasses a critical threshold, typically set at 1.25, the slope is considered stable, while SF values below this threshold indicate potential instability (Hoek and Bray, 1981). Bowles, (1989) categorizes SF values into stable, critical, and unstable based on the SF values obtained and the corresponding landslide risk.

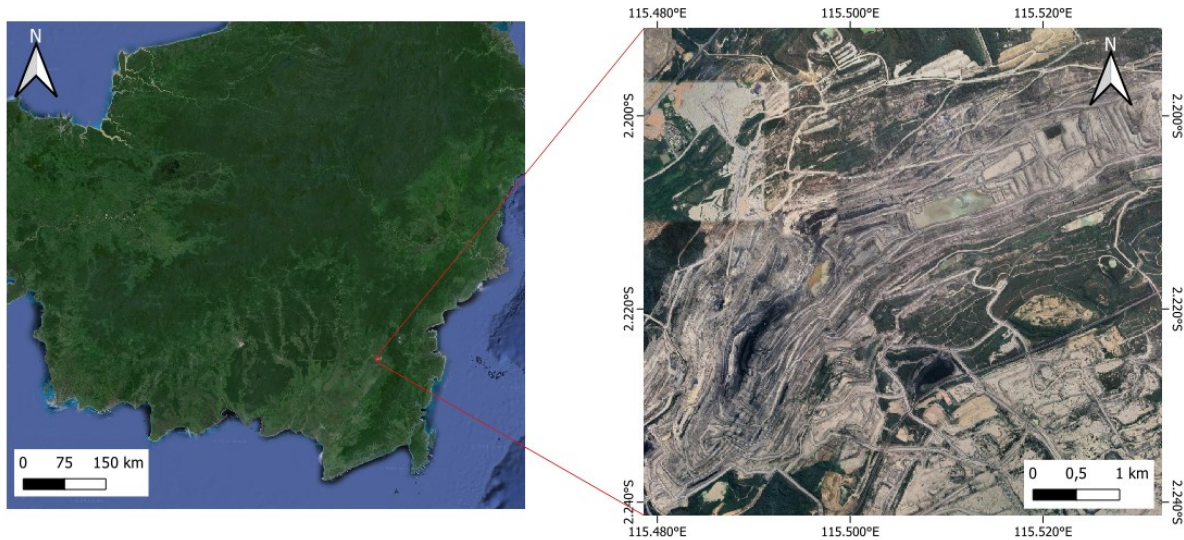


Fig. 1. The Location for the Study is in South Kalimantan

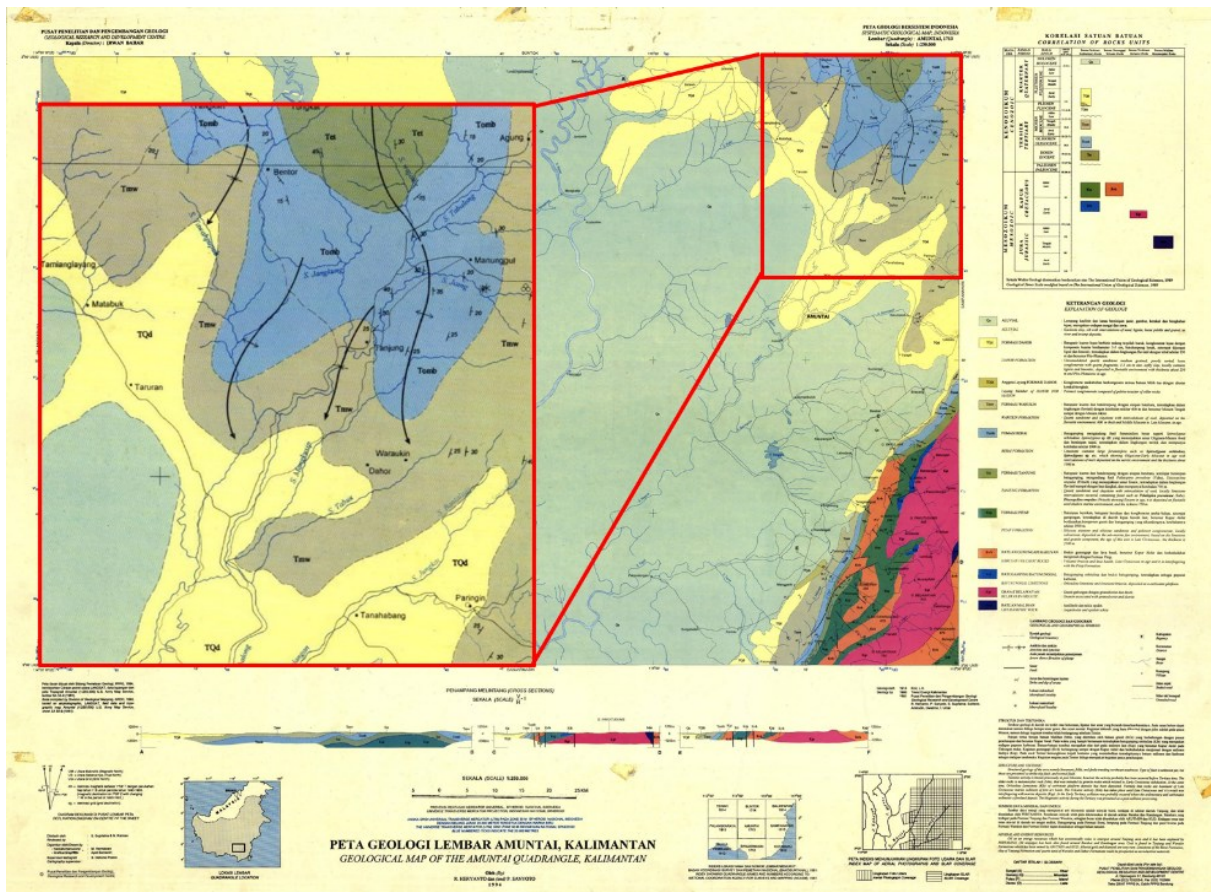





Fig. 2 The Geological Map of Study Location (Heryanto and Sanyoto, 2007)

Calculating SF is also crucial in slope stability analysis. The Bishop Simplified Method, a form of the slice method, is commonly applied. It divides a slope's sliding plane into segments and assesses forces within each slice (Hoek and Bray, 1981). Further research by Hoek and Brown (2002) contributed to understanding fracture behavior within rock masses, refining calculations used in assessing SF for slopes with complex geological structures.

The vibrations generated by blasting activities significantly affect slope stability. These vibrations, or

ground waves, propagate through rock and soil, potentially damaging nearby structures (Agnesty et al., 2018). The primary characteristics of these waves include peak particle velocity (PPV), frequency, and amplitude, which collectively influence the vibration's impact on surrounding slopes. The PPV, often measured in millimeters per second (mm/s), reflects the highest speed reached by particles in the vibration wave and is used alongside the frequency to calculate the maximum horizontal acceleration, or Amax, of a blast. Amax is an essential parameter in SF analysis for

Table 1. Mechanical properties of rocks in the study area. Data sourced from the Geotechnical Department of the mining company.

Material	Color	Unit Weight (kN/m <sup>3</sup> )	Type Strength	UCS (kPa)	m	s	a	GSI
Claystone		19.9 - 24.5	Generalized Hoek-Brown	800 - 10190	0.45391 - 1.89057	0.00055 - 0.1998	0.5021 - 0.9995	32 - 64
Coal		12.3 - 22.9	Generalized Hoek-Brown	2170 - 10500	1.0671 - 2.1798	0.00042 - 0.00387	0.50573 - 0.52234	30 - 50
Sandstone		19.9 - 23.7	Generalized Hoek-Brown	1140 - 7410	0.74365 - 1.64974	0.01035 - 0.19801	0.50308 - 0.99507	38 - 68

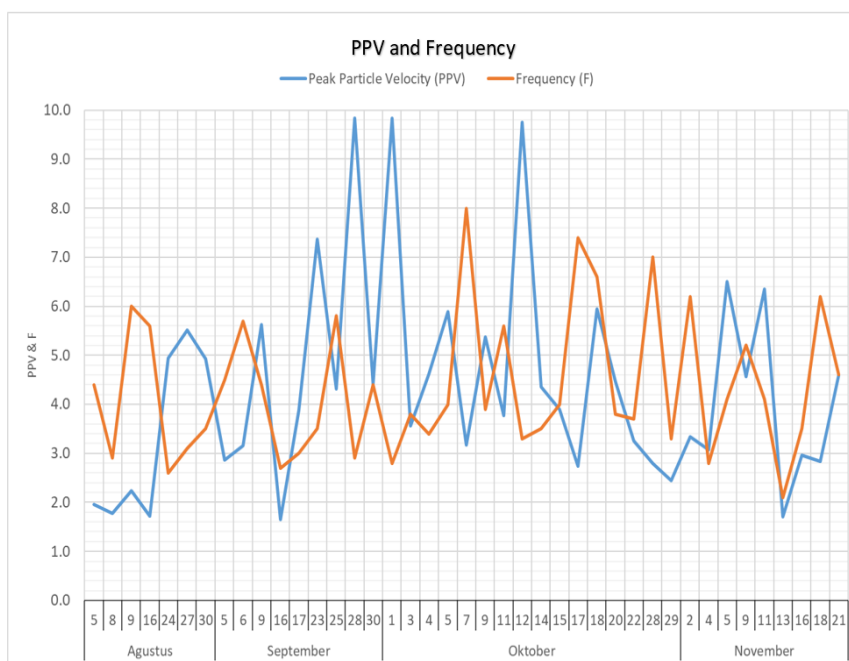


Fig. 3. The recorded PPV (Peak Particle Velocity) and frequency values in the study area

slopes subjected to blasting, helping to quantify how these external forces impact slope stability (Frank, 2003).

Previous research by Mahda and Yuliadi (2022) established that blasting vibrations influence slope stability in this region. However, their study primarily focused on general stability assessments without quantifying the specific degradation of the Factor of Safety (FS) relative to horizontal acceleration changes. This study addresses this gap by integrating the Maximum Horizontal Acceleration (Amax)—derived from Peak Particle Velocity (PPV) and frequency using regression models—directly into the stability analysis. Furthermore, this research distinguishes itself by statistically analyzing the correlation between increasing Amax values and the reduction of FS across specific geological cross-sections in Pit X, thereby providing a more precise determination of safe blasting distances.

### 3. Data

This study uses comprehensive spatial, geotechnical, and vibration datasets to assess slope stability to blasting activities at Pit X in South Kalimantan.

#### 3.1 Spatial and Topographical Data

**Aerial Imagery:** High-resolution aerial images were utilized to identify geomorphological features and human-made structures. These images assist in defining surface morphology and potential areas of concern around the mining site.

**Digital Elevation Model (DEM),** DEM data of the study area enabled precise slope and elevation calculations,

essential for creating slope class maps and understanding topographical influences on slope stability.

#### 3.2 Geotechnical and Geological Data

**Rock Unit Data:** The geological survey identified and categorized rock units based on engineering geological properties. These units were classified by lithological composition (e.g., sandstone, claystone), directly affecting material behavior under stress (Table 1).

**Material Properties:** Uniaxial Compressive Strength (UCS). UCS tests provided compressive strength values, which are critical indicators of rock stability under load.

**Geological Strength Index (GSI),** GSI values were calculated for various rock types to understand structural quality and assess excavatability according to Tsiambaos and Saroglou (2010), impacting overall slope stability.

**Bulk Density and Weathering Condition:** Bulk density measurements and weathering classifications informed how material mass and durability might affect slope resilience during blasting activities.

#### 3.3 Blasting and Vibration Data

**Blastmate Device Data:** Vibration data were collected using blastmate devices positioned at critical points around the blast site. These devices recorded (Figure 3):

**Peak Particle Velocity (PPV),** PPV data, measured in millimeters per second (mm/s), indicate the highest velocity of particles induced by blast waves, which correlates with potential slope disturbance.

Frequency Measurements: The frequency of blast-induced vibrations provided additional insight into the impact on different soil and rock strata. In conjunction with PPV, the frequency was used to assess the severity of blast waves on slope stability.

Distance Measurements: Distances from blast points to measurement sites were recorded to calibrate PPV values across various slopes, forming a regression model to predict PPV at differing proximities.

#### 4. Methodology

This study involves several critical analyses to assess the stability of slopes against blasting activities.

##### 4.1 Geomorphological Analysis

The geomorphological analysis of the study area yielded two keymaps: a map of geomorphological features and a map of slope class. Aerial imagery data were processed to identify geomorphological features and anthropogenic structures that could affect morphological formations within the area. The slope class map was prepared using DEM data in QGIS software and classified according to Van Zuidam's classification.

##### 4.2 Geotechnical and Geological Analysis

For the engineering geological map, the rock units were categorized as engineering geological units with properties including surface weathering, bulk density, Uniaxial Compressive Strength (UCS), and Geological Strength Index (GSI). The engineering geological units and their technical properties are crucial for understanding how slope stability might be affected by various geological conditions.

##### 4.3 Factor of safety (FS) Analysis for Slope Stability

SF analysis was conducted using the Slide software to evaluate the stability of slope geometry within four cross-sections: A-A', B-B', C-C', and D-D'. The SF calculation is based on the Bishop simplified method (Das and Sivakugan, 2017), represented by the following equation:

$$FS = \frac{\sum(C' b_n + (W_n \cos a_n - u_n b_n) \tan \theta)}{\sum W_n \sin a_n} \quad (1)$$

where FS is factor of safety,  $C'$  is cohesion,  $b_n$  is the width of the  $n$ th slice,  $W_n$  is the weight of the  $n$ th slice,  $a_n$  is the angle of the  $n$ th slice,  $u_n$  is pore water pressure of the  $n$ th slice, and  $\theta$  is internal friction angle.

Slope stability classification refers to the criteria established by Bowles (1989), where an FS value greater than 1.25 is classified as stable, a value between 1.07 and 1.25 is considered critical, and a value less than 1.07 indicates an unstable slope condition.

##### 4.4 Analysis of Blasting Vibrations on Slope Stability

To evaluate the impact of blasting, data on rock material strength, UCS, and GSI were analyzed to determine compatibility with blasting excavation. The PPV and frequency data recorded by blastmate devices positioned at specific points were used to assess vibration impact. PPV

(measured in mm/s) inversely relates to distance, enabling PPV for each cross-section to be calculated by generating a regression graph showing the relationship between PPV and blasting distance according to Wang (2019):

$$y = 43.693e^{-0.004x} \quad (2)$$

where  $y$  is the recorded PPV and  $x$  is the distance from the blast point.

##### 4.5 Calculation of Maximum Horizontal Acceleration

The maximum horizontal acceleration ( $A_{max}$ ) was calculated based on PPV and frequency ( $F$ ) using the equation derived from Frank (2003):

$$A_{max} = \frac{2\pi \cdot PPV \cdot F}{386.4} \quad (3)$$

where  $PPV$  is Peak Particle Velocity and  $F$  is frequency (Hz)

Incorporating these methods and equations allowed for a thorough assessment of slope stability and vibration impact across different sections of the study area, contributing valuable insights into safe blasting practices in the mining environment.

#### 5. Results and Discussion

##### 5.1 Geomorphological Analysis

The geomorphological assessment classified the research area's slopes into different categories, primarily "steep" (16°–35°) and "very steep" (35°–55°), according to Van Zuidam's classification (1985) (Figure 4). Notably, the lower part of the mining site displayed gentler slopes, while the upper section exhibited more severe gradients, especially in areas prone to landslides. This differentiation guided the selection of slope cross-sections and highlighted key morphological features, such as natural escarpments and constructed water management zones (Figure 5).

##### 5.2 Geotechnical and Geological Analysis

The geotechnical properties of the rock masses were evaluated through the Geological Strength Index (GSI) and Uniaxial Compressive Strength (UCS) values. These indicators were fundamental in identifying rock units with variable stability levels (Figure 6):

Sandstone-claystone interbedding, Constituted about 30% of the study area, characterized by a GSI of 45.84 and UCS of 3023.24 kPa, indicating relatively high stability.

Coal-claystone interbedding, representing approximately 10% of the site, had lower mechanical stability (GSI 41.46, UCS 5837.89 kPa) and exhibited weaker cohesion.

Claystone-coal interbedding, The dominant unit (60% of the area), with a GSI of 52.70 and UCS of 3026.47 kPa, primarily in highly weathered states, contributing to the lowest stability values observed.

These rock units exhibited varying cohesion and internal friction levels, significantly influencing overall slope resilience.

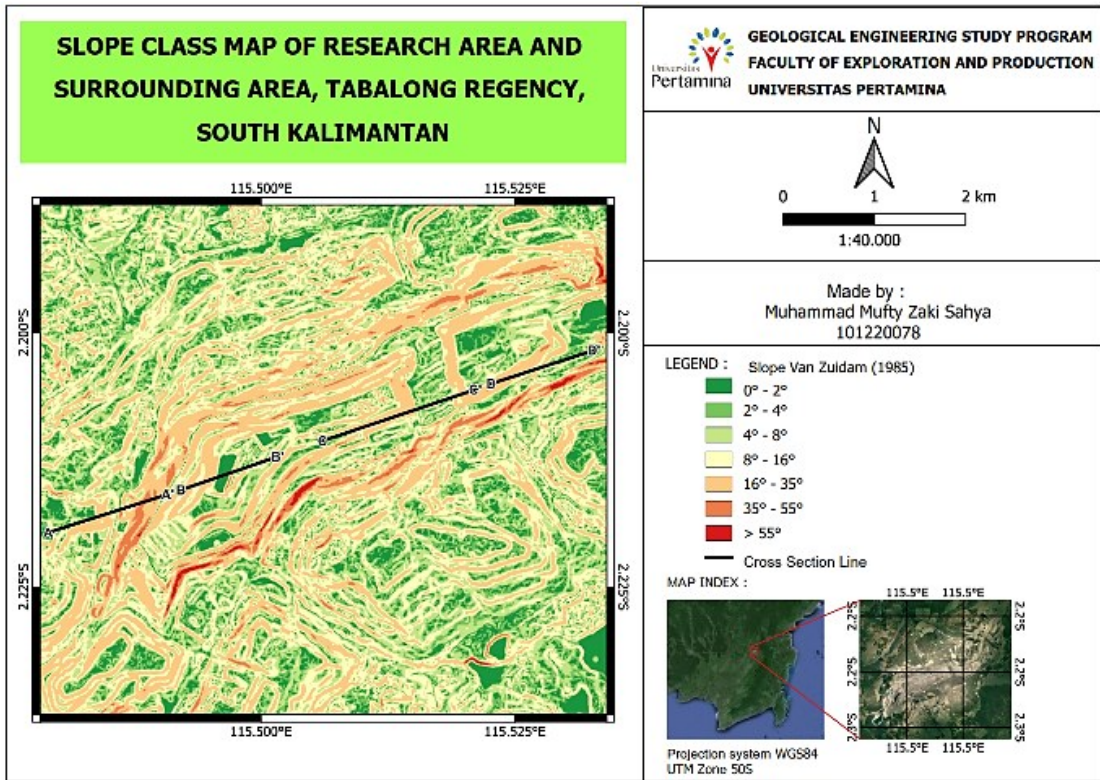


Fig. 4. Slope Class Map of Research Area

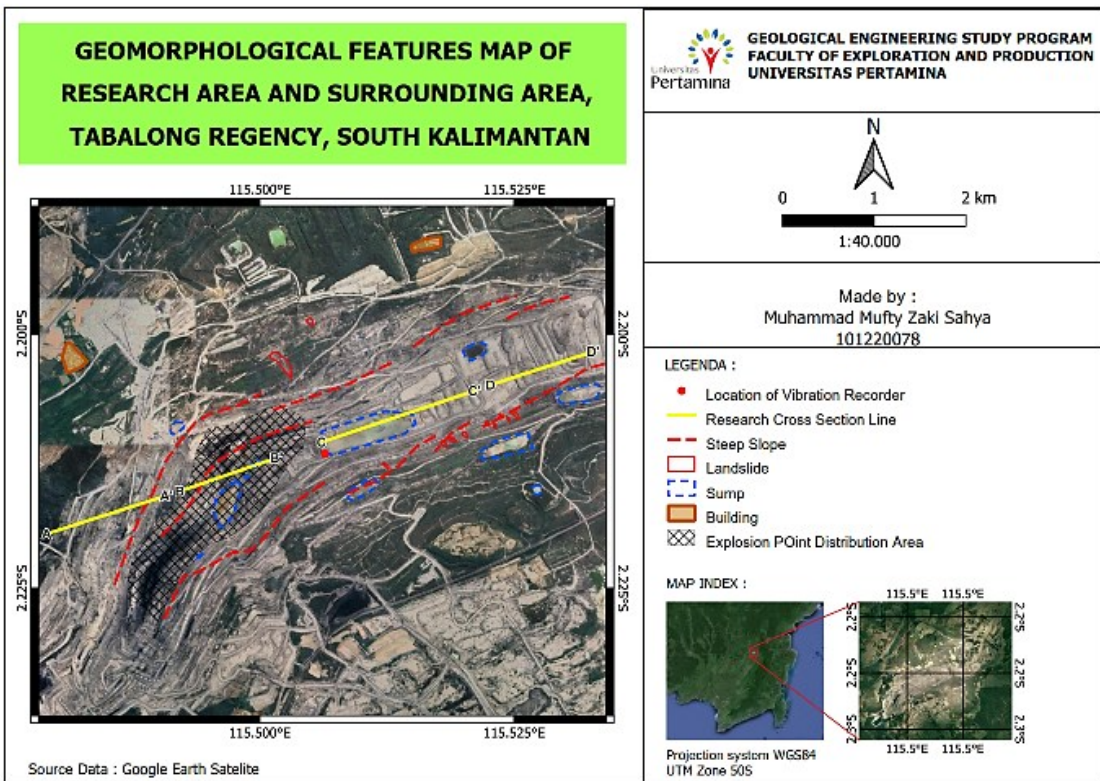


Fig. 5. Geomorphological Features Map of Research Area

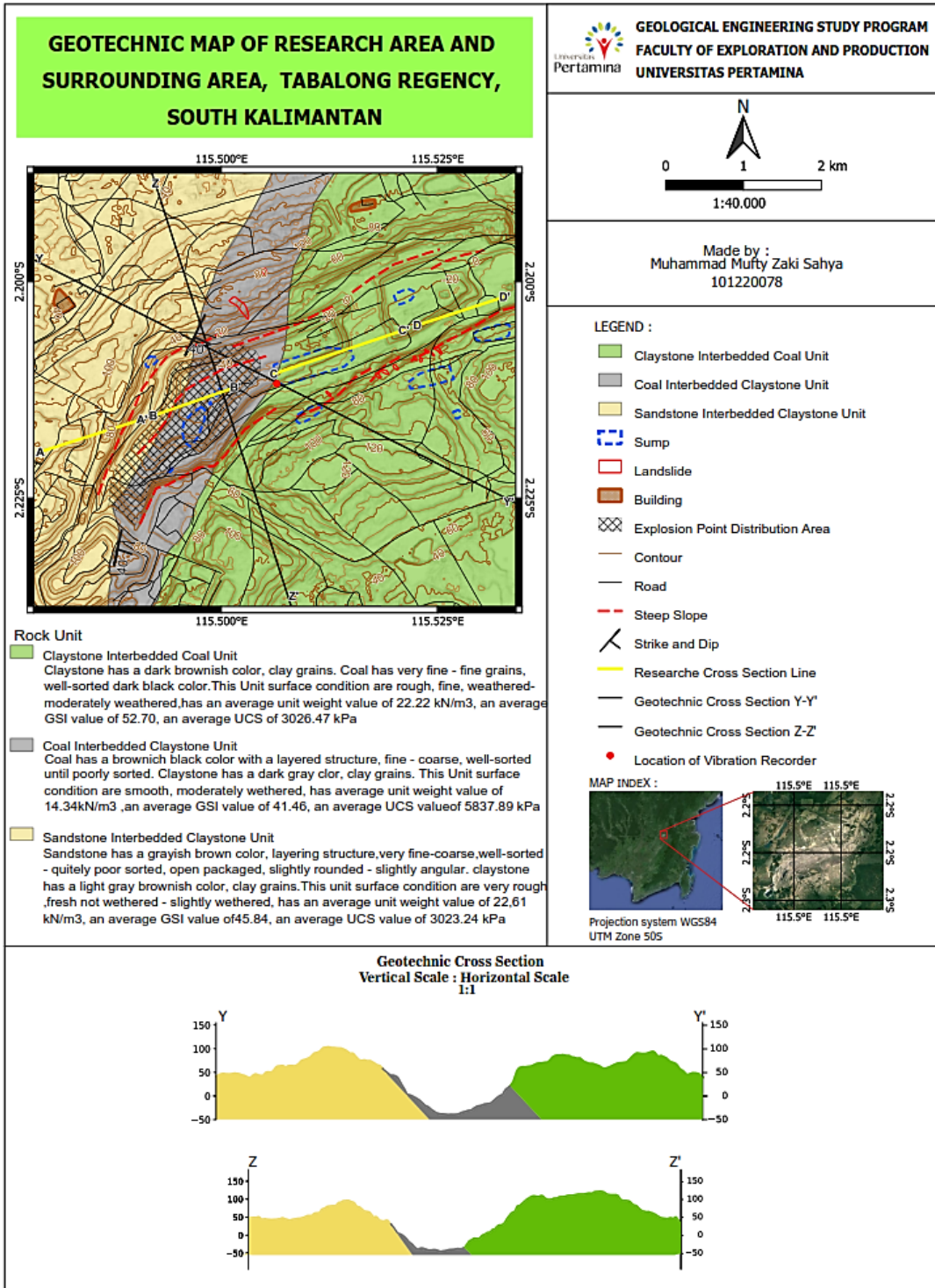


Fig. 6. Engineering Geological Map of Research Area

### 5.3 Factor of safety Analysis

The Factor of safety (FS) was calculated for four cross-sections (A-A', B-B', C-C', D-D') using the Bishop Simplified Method to assess stability:

Cross-section A-A', SF = 2.36, classified as stable. This section is dominated by sandstone and claystone, materials with high mechanical strength, and has a relatively gentle slope. The water table is deep, around 80 meters, which enhances stability (Figure 7).

Cross-section B-B', SF = 1.55, indicating stable but lower resilience than A-A'. The slope is steeper, with interbedded claystone and coal, which have lower strength than sandstone. The groundwater table is moderately deep, contributing to a slightly reduced stability (Figure 8).

Cross-section C-C', SF = 1.16, classified as critical. This section has a steep gradient and is predominantly composed of weaker claystone interbedded with coal. The water table is shallow at approximately 5 meters, increasing the risk of instability, especially in adverse weather (Figure 9).

Cross-section D-D', SF = 1.32, showing moderate stability. This section contains claystone with a gentle slope but a shallow groundwater level (5 meters), which introduces a variable risk factor. Stability is affected by the moderate strength of the claystone layers (Figure 10).

This analysis highlights that steep gradients, shallow groundwater, and lower-strength materials like claystone and coal increase slope vulnerability, especially in cross-sections like C-C'.

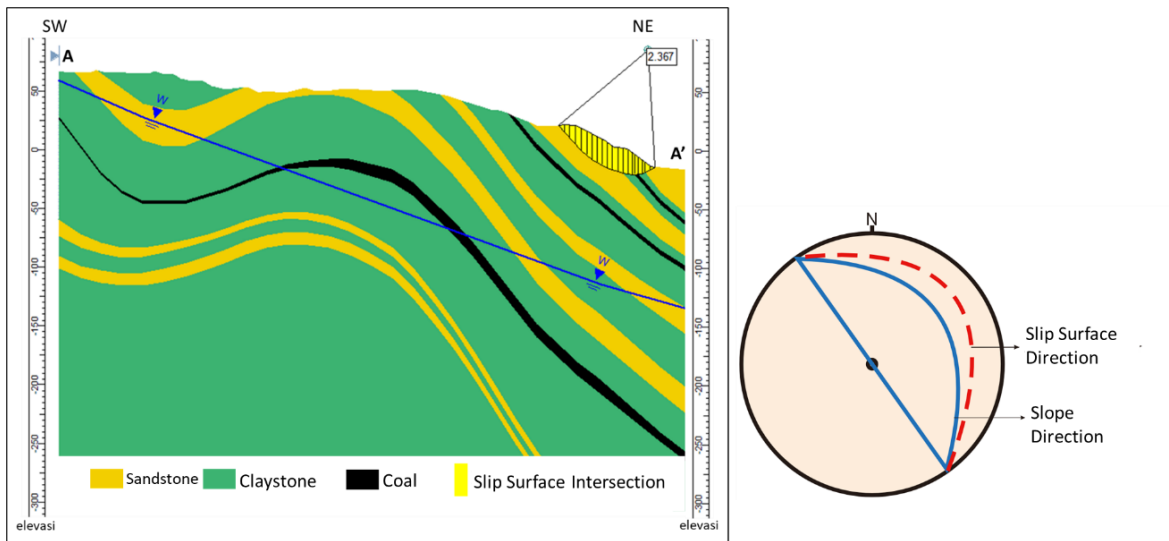


Fig. 7. The factor of safety for cross-section A-A'

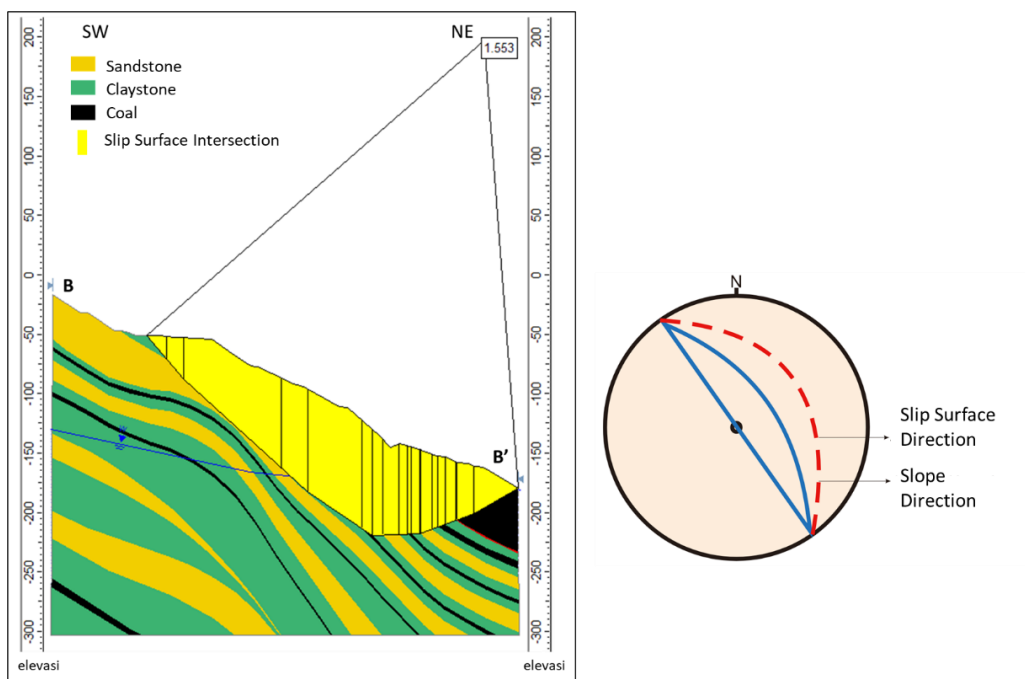


Fig. 8. The factor of safety for cross-section B-B'

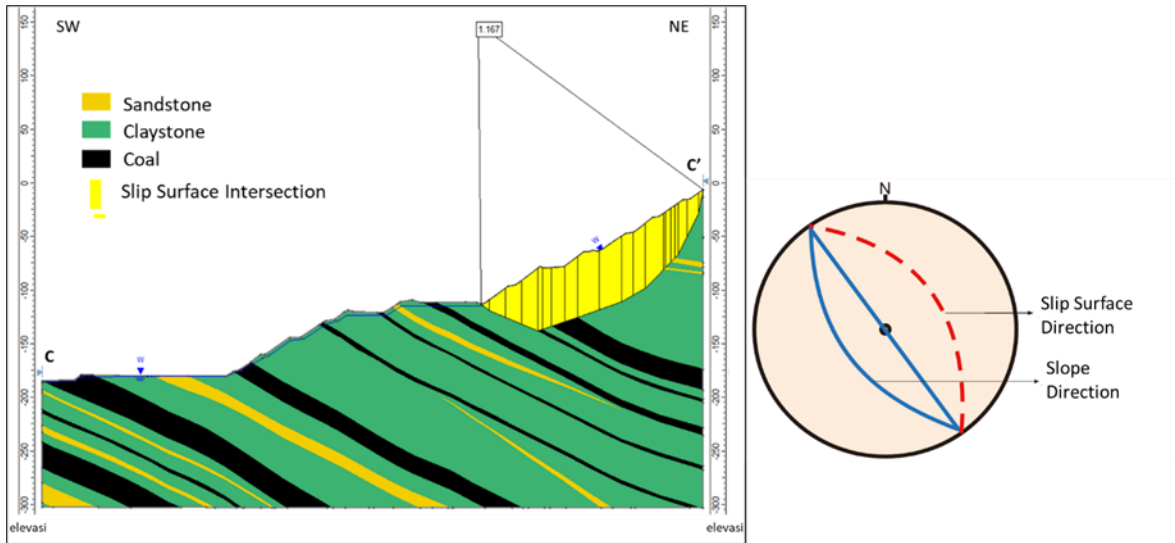


Fig. 1. The factor of safety for cross-section C-C'

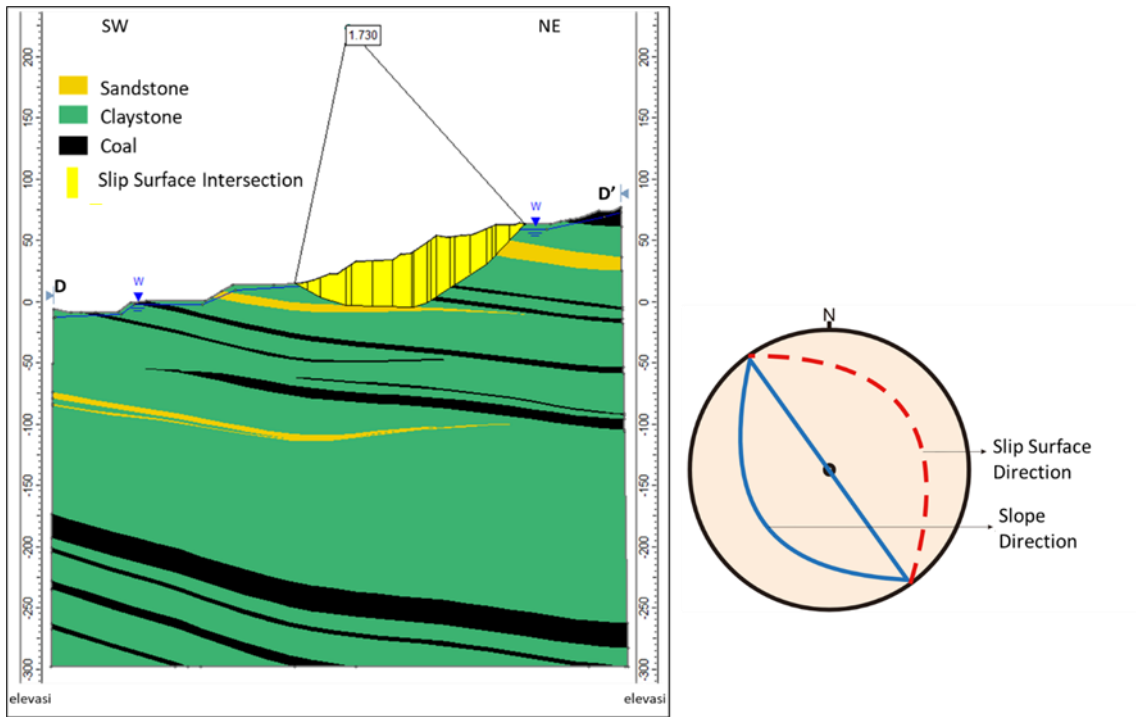


Fig. 2. The factor of safety for cross-section D-D'

### 5.4 Amax Analysis

The Amax analysis involves calculating peak particle velocity (PPV) values for each cross-section based on its distance from the blast source, using Wang's (2019) model (Figure 11).

Based on this model, PPV values were calculated for each slope cross-section and, along with frequency data, were used to determine Amax values. The maximum horizontal acceleration (Amax) for each cross-section was computed using the equation.

While each cross-section demonstrated a similar pattern in the relationship between distance and Amax—

where closer proximity to the blast source yields higher PPV and Amax values—the exact values vary due to differences in slope composition, gradient, and proximity. The highest Amax values were recorded in August, while the lowest occurred at the end of October. Each cross-section showed varying Amax values (Figure 12).

Cross sections A-A', C-C', and D-D' recorded very low Amax values, each less than 0.0001. Cross-section B-B' had a notably higher Amax of approximately 0.01. These Amax values will subsequently be incorporated into the slope stability analysis for each respective cross-section to assess blasting impact on slope safety.

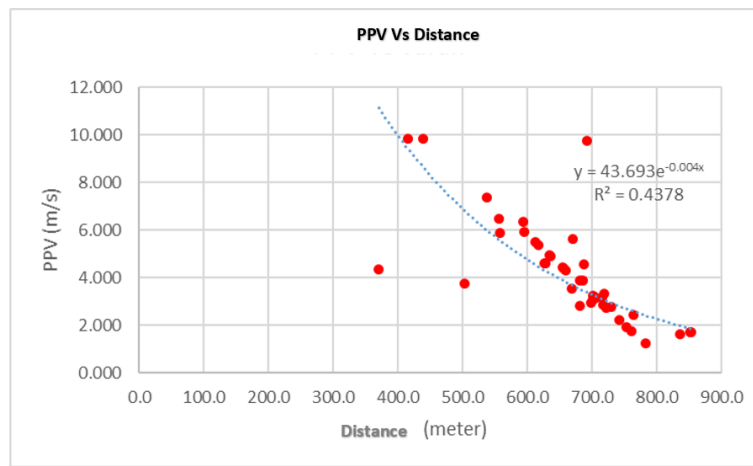


Fig. 11. Relation between PPV and blasting distance in research area

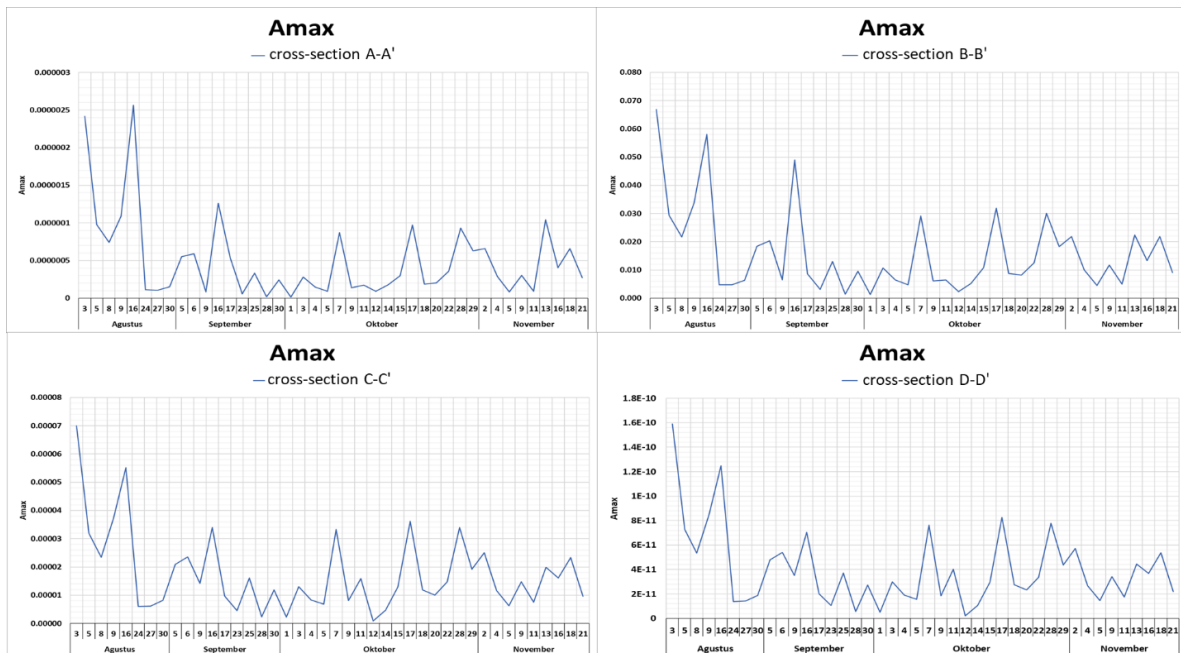


Fig. 12. Value of Amax every cross-section

### 5.5 Factor of safety Analysis with Amax

The evaluation of slope stability under blasting vibration conditions is based on the resulting Safety Factor (FS) values after incorporating Amax as a horizontal seismic load. The classification of these FS values adheres to the criteria established by Bowles (1989), where a slope is considered stable if  $FS > 1.25$ , critical if  $1.07 \leq FS \leq 1.25$ , and unstable if  $FS < 1.07$ .

The Factor of safety (FS) values relative to Amax varied across each cross-section, demonstrating distinct stability behaviors based on distance from blasting and Amax impact (Figure 13).

Cross-section A-A', The SF ranged from 2.366 to 2.367, remaining within the stable slope class. This minimal change reflects a small Amax value due to the greater distance from the blast source, resulting in a very minor decrease in SF. A clear pattern of SF reduction with increasing Amax is observed, with a high determination coefficient ( $R^2$ ) of 0.93, indicating that 93% of the SF reduction is attributable to increases in Amax.

Cross-section B-B', SF values ranged from 1.35 to 1.60, also within the stable class. Here, the SF shows a more substantial variation than A-A', due to a higher Amax resulting from the closer blast proximity. A consistent pattern of SF decline with increasing Amax is evident, with an  $R^2$  of 0.98, meaning that the rise in Amax explains 98% of the SF reduction.

Cross-section C-C', With an SF range of 1.163 to 1.164, this section falls within the critical slope stability class. The slight variation in SF is due to a lower Amax value, reflecting the greater distance from the blast source. Nevertheless, an SF decrease pattern with increasing Amax is observed, with

an  $R^2$  of 0.95, suggesting that 95% of the SF reduction correlates with the Amax increase.

Cross-section D-D', The SF remains constant at 1.73, indicating stability. Due to the very low Amax at this cross-section, located farthest from the blast source, no significant pattern of SF reduction with Amax is observed. The determination coefficient here is 0.85, implying that 85% of the SF is unaffected by changes in Amax.

The obtained Safety Factor (FS) values were evaluated against the geotechnical stability standards recommended by Bowles (1989). According to these guidelines, a slope is considered stable if the FS is 1.25. The results indicate that while Cross-sections A-A', B-B', and D-D' meet the regulatory compliance for stability, Cross-section C-C' ( $FS = 1.16$ ) falls below the required safety threshold, classifying it as a critical slope that necessitates immediate mitigation measures.

This analysis highlights that SF values in cross-sections closer to the blast (such as B-B') are more sensitive to Amax changes. At the same time, those farther away (like D-D') show minimal impact, emphasizing the influence of distance on stability under blasting conditions. This finding supports previous studies by Canima and Heriyadi (2019) regarding the critical limit of ground vibrations on slope stability.

The stability analysis reveals a complex interaction between geotechnical properties, hydrogeological conditions, and blasting induced vibrations. For instance, the critical instability observed in Cross-section C-C' ( $FS = 1.16$ ) is not solely driven by blasting activities but is fundamentally largely attributed to the presence of weak claystone-coal interbedded lithology combined with a

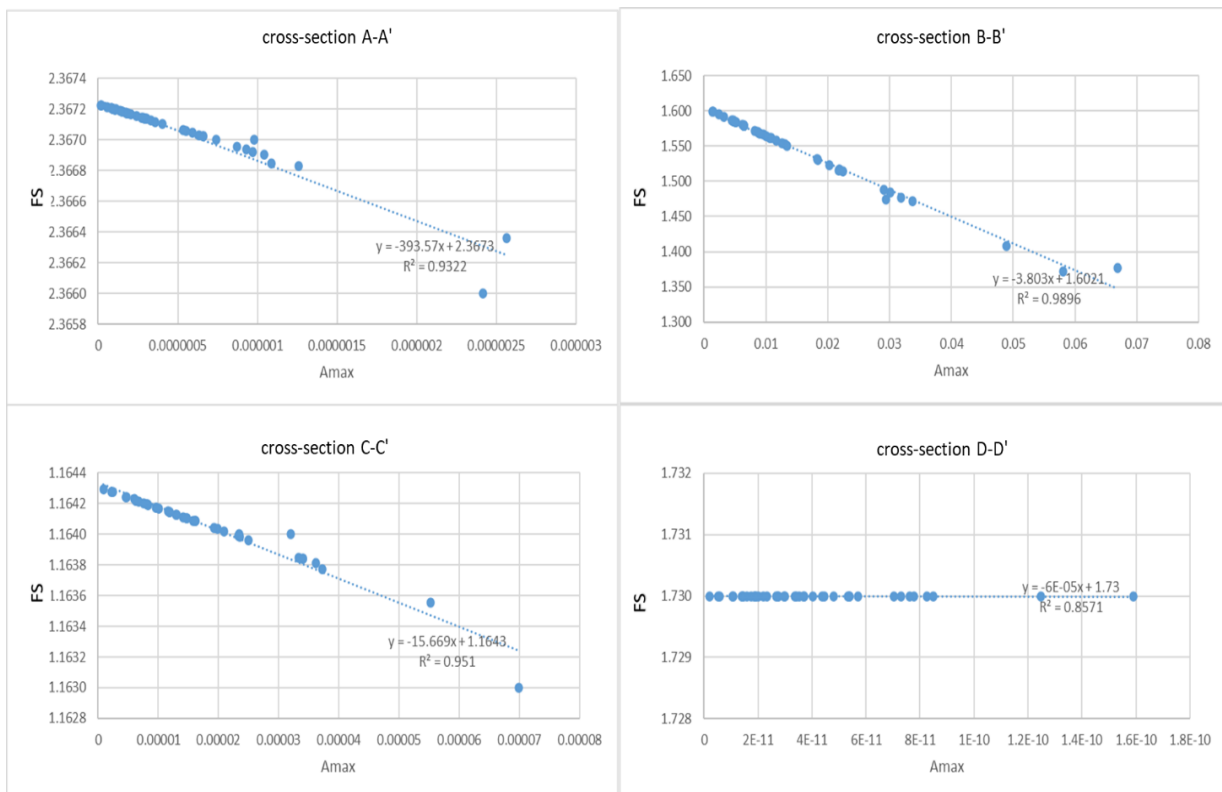


Fig. 13. Factor of safety Value with Amax

shallow groundwater table (approximately 5 meters depth). The high pore water pressure reduces the shear strength of these materials, making the slope highly sensitive to external disturbances. Consequently, even minor ground vibrations (low Amax) from blasting can act as a trigger mechanism, accelerating potential failure in this already vulnerable geological setting.

The findings of this study align with previous research by Mahda and Yuliadi (2022), which established that blasting vibrations generally degrade slope stability in mining environments. However, while previous studies primarily focused on qualitative stability assessments, this research contributes to quantitative novelty by establishing a direct statistical correlation between Maximum Horizontal Acceleration (Amax) and the degradation of the Factor of Safety (FS). Specifically, this study demonstrates that for slopes in close proximity to the blast source (e.g., cross-section B-B'), the increase in Amax accounts for up to 98% ( $R^2=0.98$ ) of the reduction in FS. This distinct contribution offers a more precise predictive model for determining safe blasting distances compared to general stability assessments, allowing for more targeted geotechnical mitigation strategies.

## 6. Conclusions

**Factor of safety Distribution:** The analysis across cross-sections A-A', B-B', C-C', and D-D' showed that slope stability varies with slope geometry, lithology, and groundwater depth. Cross-section A-A' was the most stable, with an SF of 2.36, while C-C' was the least stable, with an SF of 1.16, falling into the critical category.

**Amax Variations:** Amax values peaked in August and dropped by the end of October. Cross-sections A-A', C-C', and D-D' recorded minimal Amax values due to their distance from the blast site, while B-B' had the highest Amax due to its proximity.

**Amax Impact on Factor of safety :** The study confirmed that Amax values significantly impact SF reduction, especially for cross-sections closer to the blast, like B-B'. Sections farther from the blast, such as A-A' and D-D', exhibited minimal or no SF changes due to low Amax values.

Based on these findings, specific practical recommendations are proposed for mining operations. First, strict vibration monitoring and controlled blasting techniques are required for areas with steep slopes and proximity to blast sites, such as cross-section B-B', where slope stability is highly sensitive to Amax increases. Second, for critical slopes like cross-section C-C', which suffer from shallow groundwater levels (5 meters), dewatering programs must be prioritized before any blasting activities to increase the intrinsic Factor of Safety. Finally, utilizing the derived regression model ( $y = 43.693e^{-0.004x}$ ), mine engineers should establish a minimum safe distance buffer that maintains Peak Particle Velocity (PPV) within limits that do not reduce the Factor of Safety below the critical threshold of 1.25.

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