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# Application of the LEM-Bishop Based on the Generalized Hoek-Brown Criteria for Assessing the Stability of Rock Slopes at Mining Area of PT. Karya Sopai Sejahtera, Palu City

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**Abstract**

PT. Karya Sopai Sejahtera (PT. KSS) operates in rock mining using an open-pit system in Watusampu, Palu, Central Sulawesi. Excavation alters slope geometry, affecting stability and risking landslides, impacting safety, equipment, and productivity. To address this, a geotechnical study assesses slope stability using the Limit Equilibrium Method (LEM) - Bishop method. Geological surveys and Electrical Resistivity Tomography (ERT) reveal predominantly andesite rock with fresh gray and weathered brown colors, hypocrystalline and equigranular textures, and quartz, pyroxene, biotite, and hornblende minerals. The slope design includes a 150-meter overall height, bench heights of 15-25 meters, widths of 3-5 meters, a single slope angle of 70°, and an overall angle of 61°. Static analysis shows stability (FS 1.94), but dynamic conditions, including earthquakes, reduce FS to 0.43, causing instability (FS < 1.1) with a 100% failure probability. The slope is stable except during strong earthquakes.

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## 1. INTRODUCTION

PT. Karya Sopai Sejahtera (PT. KSS) is a company engaged in the rock mining industry using an open-pit mining system, located in Kelurahan Watusampu, Palu City, Central Sulawesi Province (see Figure 1). Mining activities, such as excavation on a slope, alter the slope geometry, which can lead to changes in the magnitude of forces acting on the slope, potentially disrupting slope stability and ultimately causing landslides [1]. This situation has significant implications for occupational safety, equipment security, and mining productivity. Therefore, a comprehensive geotechnical study of mining is essential, as open-pit mining activities will always face slope stability issues [2]. This can be observed from the mining activities at the PT. KSS site. The absence of a slope stability analysis at the location is concerning if the slope geometry design does not meet safety standards, potentially leading to landslides.

To achieve slope stability, it is crucial to observe engineering geological conditions and determine the factor of safety (FS) using the Limit Equilibrium Method (LEM) [3]. In this context, Bishop's method [4] is popularly applied, having proven to yield safety factor values that closely approximate more precise calculations [5]. The LEM-Bishop method has been successfully used in several cases for slope stability analysis and pit geometry planning [6]. As an effort to attain slope stability in the PT. KSS mining area, this study aims to provide an overview of the rock mechanics properties at the mining site while also evaluating the slope stability levels.

## 2. RESEARCH METHOD

Geological mapping is conducted through field observations and data collection, including geomorphological, lithological, and geological structure data. Photographs are taken to document each geological condition, and rock outcrops are described along with their relationships to surrounding rocks. Subsequently, geophysical measurements are conducted to obtain subsurface rock information. The geophysical data utilized include two-dimensional Electrical Resistivity Tomography (ERT) imaging using the Wenner Alpha configuration. Electrical current is injected into the ground through two current electrodes, and the resulting potential difference is measured using two potential electrodes.

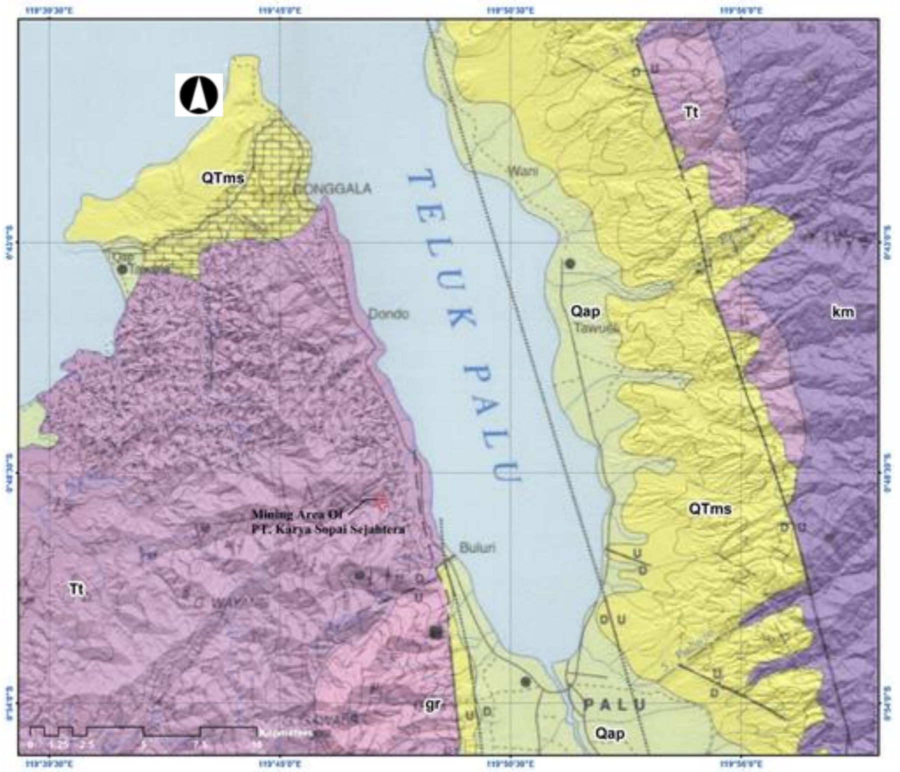


**Figure 1.** Regional Geological Map of the Palu Area and Surroundings, with the Position of PT. KSS

In this study, the Wenner configuration is employed for the measurements. Each electrical current signal and potential difference is processed using Equation (1) to obtain the apparent resistivity values [7].

$$\rho_a = K_W \frac{\Delta V}{I} \qquad (1)$$

where:

| | | |
|---|---|---|
| $\rho_a$ | : | Apparent resistivity (Ohm-m) |
| $K_W$ | : | Geometric Factor Depending on Configuration, $K_W = 2\pi a$ (where a is the distance between the electrodes). (m) |
| $\Delta V$ | : | Potential Difference (mV) |
| I | : | Electric Current (mA) |

The resistivity data modeling follows the inversion problem-solving algorithm [8], using the least squares smoothness-constrained method from the Res2Dinv software. The best inversion modeling results are characterized by the low root mean square (RMS) error, expressed as a percentage, as defined by the following equation:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}\left(\frac{d_i^{cal} - d_i^{obs}}{d_i^{obs}}\right)^2}{N}} \times 100\% \qquad (2)$$

where $N$ is the number of data points, $d_i^{cal}$ is the calculated or predicted data, and $d_i^{obs}$ is the observed or measured data.

Geological and geophysical data will provide information regarding the lithology of rocks in the PT. KSS mining area, which will aid in understanding the materials constituting the slope. Subsequently, the mechanical properties of the slope-forming rocks are estimated using the Generalized Hoek-Brown Criterion [9].

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_i \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a \qquad (3)$$

where $\sigma_1$ is the major principal stress, σ3 is the minor principal stress, $\sigma_{ci}$ is the uniaxial compressive strength of the rock, and $m_i$, $s$, and $a$ are rock mass constants.

The Geological Strength Index (GSI) value is determined from two parameters: the structure rating (SR), which describes the block structure, and the surface condition rating (SCR) [10]. The GSI value ranges from 0 to 100, with a GSI of 100 corresponding to intact rock mass. Subsequently, the constant mbm_bmb is determined from Equation (4), where DDD represents the disturbance factor of the rock mass. The parameters for characterizing the rock mass have interrelated relationships:

$$m_b = m_i\, exp\left(\frac{GSI - 100}{28 - 14D}\right) \qquad (4)$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \qquad (5)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15}\right) - e^{-20/3} \qquad (6)$$

The strength of the rock mass along the shear surface, as expressed, is used to analyze the stability of a slope. Hoek et al. proposed an equivalence between the Generalized Hoek-Brown Criterion and the Mohr-Coulomb criterion to determine the internal friction angle ($\phi'$) and cohesion ($c'$):

$$\phi' = \sin^{-1}\left[\frac{6am_b(s+m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a)+6am_b(s+m_b\sigma'_{3n})^{a-1}}\right] \quad (7)$$

$$c' = \frac{\sigma_{ci}[(1+2a)s+(1-a)m_b\sigma'_{3n}](s+m_b\sigma}{(1+a)(2+a)\sqrt{1+(6am_b(s+m_b\sigma'_{3n})^{a-1})/((1}} \quad (8)$$

where $\sigma'_{3n} = \sigma'_{3max}/\sigma_{ci}$, is related to the application of the Limit Equilibrium Method (LEM) Bishop in determining the Factor of Safety (FS).:

$$\frac{\sigma'_{3max}}{\sigma'_{cm}} = 0.72\left(\frac{\sigma'_{cm}}{\gamma H}\right)^{-0.91} \quad (9)$$

where $\sigma'_{cm}$ is the strength of the rock mass, $\gamma$ is the unit weight, and $H$ is the slope height. The LEM-Bishop method uses static equilibrium conditions and disregards the stress-strain relationship on the slope. In its analysis, it compares the driving forces to the resisting forces on the slope [3].

## 3. RESULTS AND DISCUSSION

### The Geology of Mining Area

The stratigraphy in this area consists of five geological formations (see Figure 1), with only the Tinombo Formation (Tt) present at the research site. Near the metamorphic rock complex to the west of the eastern ridge, the deposits primarily consist of coarse blocks, likely deposited near faults. These rocks transition to finer-grained clastic rocks towards the sea. This layer indicates a middle Miocene age. Additionally, alluvium and coastal deposits (Qap) consist of gravel, sand, silt, and coral limestone, formed in river, delta, and shallow marine environments, representing the youngest sediments in the area. These deposits are likely entirely of Holocene age [11]. The geological structure in this area is controlled by the Palu-Koro Fault. This fault is a segmented strike-slip fault zone system. Following the Mw 7.5 earthquake in 2018, the main track of the Palu-Koro Fault has been identified based on the appearance of surface rupture zones [12].

In the PT. Karya Sopai Sejahtera (PT. KSS) mining area, which ranges from 200 to 410 meters above sea level, the morphology includes mountains and hills transitioning to steep slopes. The hilly to steep slope morphology is part of the Tinombo Formation, dominated by volcanic rocks such as andesite, interbedded with lithologies like slate, sand, and gravel. The exposed lithologies are primarily andesite and sediments, with some areas showing weathering conditions in the andesite. The distribution of sediment deposits and volcanic rock blocks is marked by topographic highs above the plains, with surrounding undulating morphology. These highs indicate differences in the resistance of the constituent rocks.

Lithological observations were made from collected samples. The lithology encountered is andesite, an intermediate igneous rock. The observed andesite appears with fresh gray color and weathered brown hues, showing a hypocrystalline, aphanitic, subhedral-anhedral, and equigranular texture. It has a massive rock structure with a mineral composition of quartz, pyroxene, biotite, and hornblende. In several outcrops, the andesite exhibits intensive weathering. Other outcrops within the mining area also show signs of weathering; however, the extent of weathering in the rock is generally non-uniform due to complex influences both from within the rock itself and external factors such as climate.

Subsequently, a geophysical exploration approach was employed to further investigate and interpret subsurface geological conditions. This technique utilizes 2-D resistivity imaging data. Each measurement line is designated with a code name, referred to as an electrical resistivity tomography line (ERT line). There are three ERT lines, labeled ERT line 1, 2, and 3, each utilizing 24 electrodes.

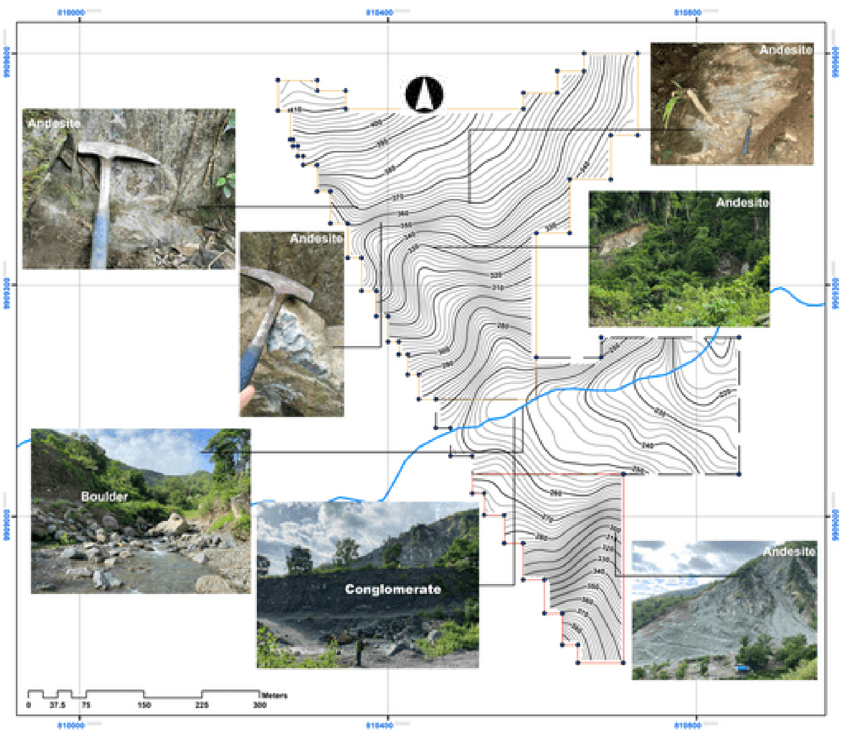


**Figure 2**. Map of Rock Outcrop Distribution in the PT. KSS Mining Area

The ERT measurements were conducted using the Wenner configuration with a 10-meter interval. The orientation of the ERT-01 line is N110°E, the ERT-02 line is N100°E, and the ERT-03 line is N100°E, as depicted in the traverse map (see Figure 3). The ERT line 1 model shows a resistivity range of 21.52 to 9,809.35 Ohm.m (model error 0.92%), the ERT line 2 resistivity model shows a range of 21.93 to 3,060.60 Ohm.m (model error 0.53%), and the ERT line 3 resistivity model shows a range of 36.22 to 1,274.40 Ohm.m (model error 0.58%).

The interpretation of resistivity data is guided by geological conditions and the obtained resistivity values. The investigation site in the PT. KSS mining area is dominated by andesite, with some locations interspersed with boulders and sediments. These conditions form the basis for interpreting the subsurface based on resistivity data from ERT measurements (See Figures 4-6). The investigation depth ranges from 38 to 40 meters along a span of 230 meters.

The ERT line 1 model indicates a layer anomaly predominantly composed of deposits. The surface layer consists of topsoil, sand, and gravel. Medium to high contrast anomalies are interpreted as conglomerates interspersed with boulders. In the lower section of the cross-section, high anomalies are interpreted as a rock layer, which is andesite (see Figure 4).


**Figure 3.** Map of Electrical Resistivity Tomography (ERT) Measurement Lines at PT. KSS Mining Site

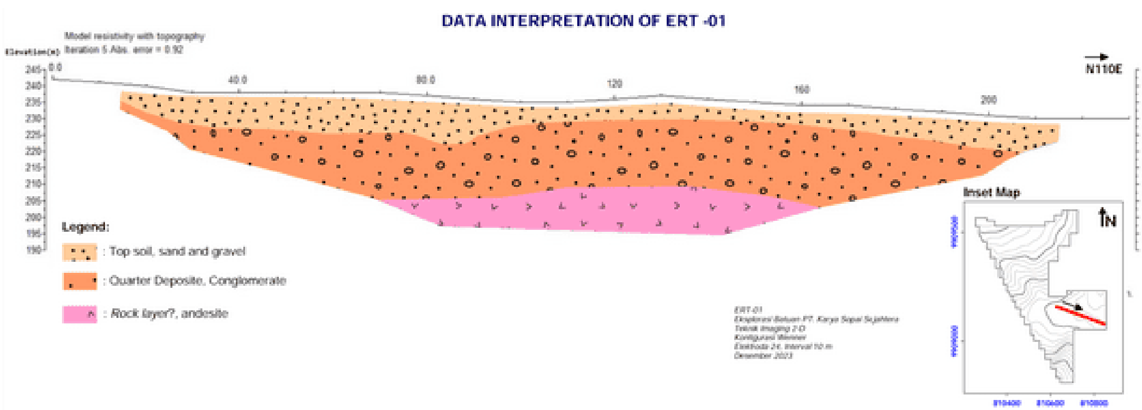


**Figure 4**. ERT-01 data Interpretation

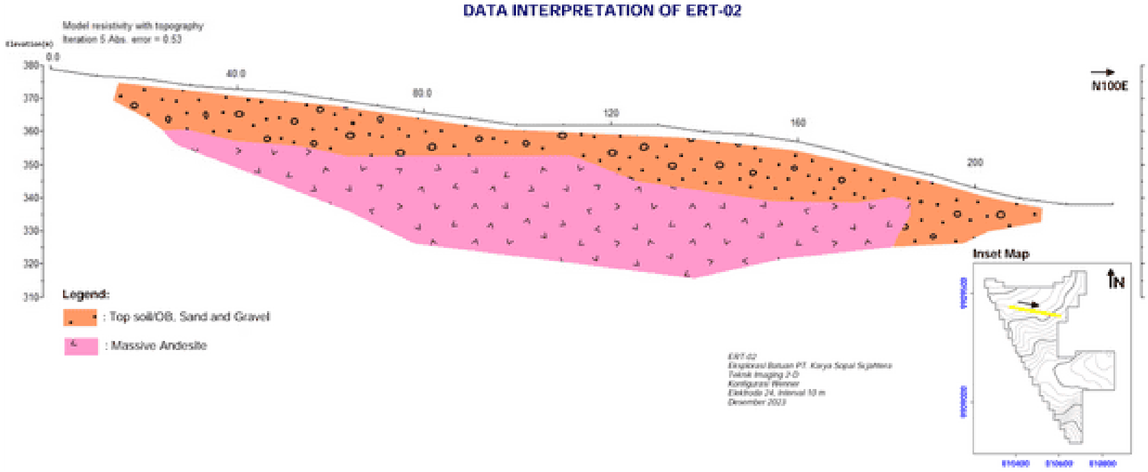


**Figure 5.** ERT-02 Data Interpretation

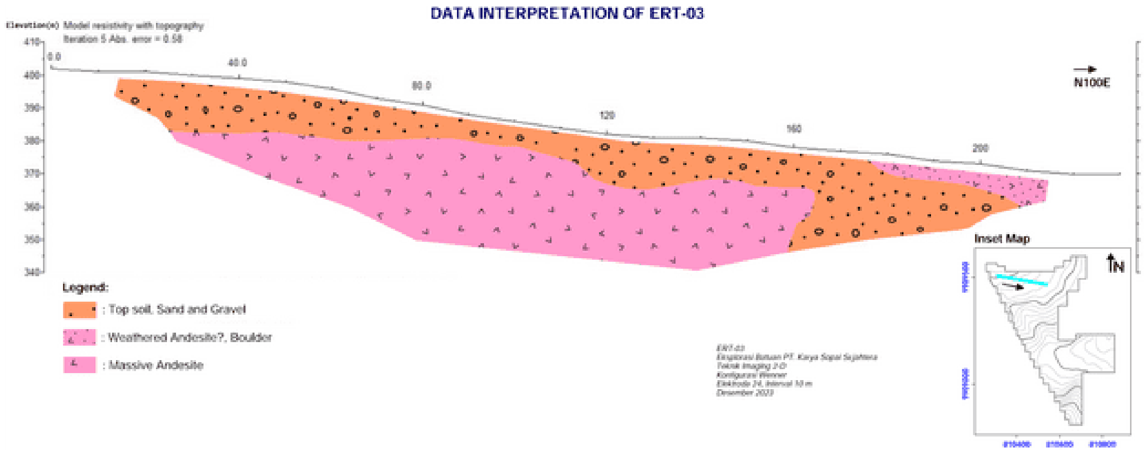


**Figure 6**. ERT-03 Data Interpretation

The ERT line 2 and ERT line 3 models exhibit similar resistivity structure patterns (see Figures 5-6). At the surface, anomalies corresponding to topsoil/overburden (OB), resulting from weathering and interspersed with boulders, are present. The bottom part of the cross-section indicates anomalies associated with massive andesite. This correlates with the northern block, especially towards the northwest and north, indicating prospects for andesite rock. Towards the northeast, the block shows indications of andesite anomalies, although some of the andesite has undergone weathering or is interspersed with deposits and boulders.

## Slope Stability Analysis

Based on geological observations and geophysical investigations, it has been determined that the PT. KSS mining area is predominantly composed of andesite, with some portions consisting of soil and weathered rock, which will serve as material for slope stability analysis. The engineering parameters of andesite at the PT. KSS research location include a unit weight of 2.66 g/cm³. Additionally, the determination of rock mechanics parameters is facilitated by the Rocscience Roclab application. The uniaxial compressive strength (UCS) of the rock was estimated in the field, where the specimen required more than one blow of a geological hammer to fracture, resulting in a UCS value of 75 MPa. The Geological Strength Index (GSI) for soil and weathered rock is classified under disintegrated structure and very poor surface conditions, whereas the andesite is classified under very blocky structure and fair surface conditions (see Table 1).

The slope rock analysis assumes that the slope is controlled by discontinuities, which are either planar or wedge-shaped. Landslides are assumed to occur along these planar or wedge surfaces without the rotation of the block mass. The height of the slope increases its susceptibility to landslides. Greater slope height and angle result in larger volumes of material, thereby increasing the slope's load. Therefore, based on the topography (elevation differences) of the PT. KSS block, the slope geometry study dimensions include an overall height of 150 m, bench heights of 15 m, 20 m, and 25 m, bench widths of 3-5 m, a single slope of 70°, and an overall slope of 61° (see Figure 7).

The factor of safety (FS) of the slope is calculated by comparing the shear strength of the material with the shear force acting along the failure plane. The slope, as depicted, has two layers, and the rock mass strength is determined using mechanical parameters derived from the Hoek-Brown failure criterion. The slope stability assessment is conducted using two schemes: deterministic and probabilistic, under both static and dynamic conditions considering seismic impacts. Each scenario is analyzed using the Bishop method, assuming the absence of a groundwater table in the rock slope.

Dynamic parameters refer to seismic loads according to SNI 1726:2012 and its revisions, based on the 2017 Indonesian Earthquake Source and Hazard Map, with a peak ground acceleration (PGA) corresponding to a 10% exceedance probability over 50 years. This dynamic analysis considers that the stability of the rock slope is primarily influenced by vibrations, especially seismic shocks [13]. In the PT. KSS mining area, the seismic coefficient is 0.7 gal, which correlates with the PGA values. For the pseudo-static analysis, the limit equilibrium approach with a horizontal seismic coefficient is used to evaluate the seismic load's impact on slope stability.

**Table 1**. The estimated rock mechanics values derived from the Generalized Hoek-Brown Criterion

| Parameter Mekanika Batuan | Unit | Score | |
|---|---|---|---|
| | | Soil, Weathered Rock | Andesit |
| Hoek-Brown Classification | | | |
| Uniaxial Compressive Strength ($UCS$)*) | $MPa$ | 35 | 75 |
| Geological Strength Index ($GSI$)*) | - | 23 | 45 |
| Constant $m_i$ | - | 25 | 25 |
| Disturbance Factor $D$ | - | 0.7 | 0.7 |
| | | | |
| Hoek-Brown Criterion | | | |
| Constant $m_b$ | - | 0.364 | 1.218 |
| Constant $s$ | - | 1.42e-5 | 0.0003 |
| Constant $a$ | - | 0.536 | 0.508 |
| | | | |
| Failure Envelope Range | | | |
| Unit Weight $\gamma$**) | $MN/m^3$ | 0.026 | 0.026 |
| Slope Heigh $H$ | $m$ | 10 | 140 |
| | | | |
| Mohr-Coulomb | | | |
| Cohesion $c$ | $MPa$ | 0.061 | 0.910 |
| Friction angle $a$ | $deg.$ | 43.33 | 43.45 |

*) The value is obtained from the field assessment criteria.
**) The value is obtained from tests conducted at the Concrete and Building Materials Laboratory, Faculty of Engineering, UNTAD.

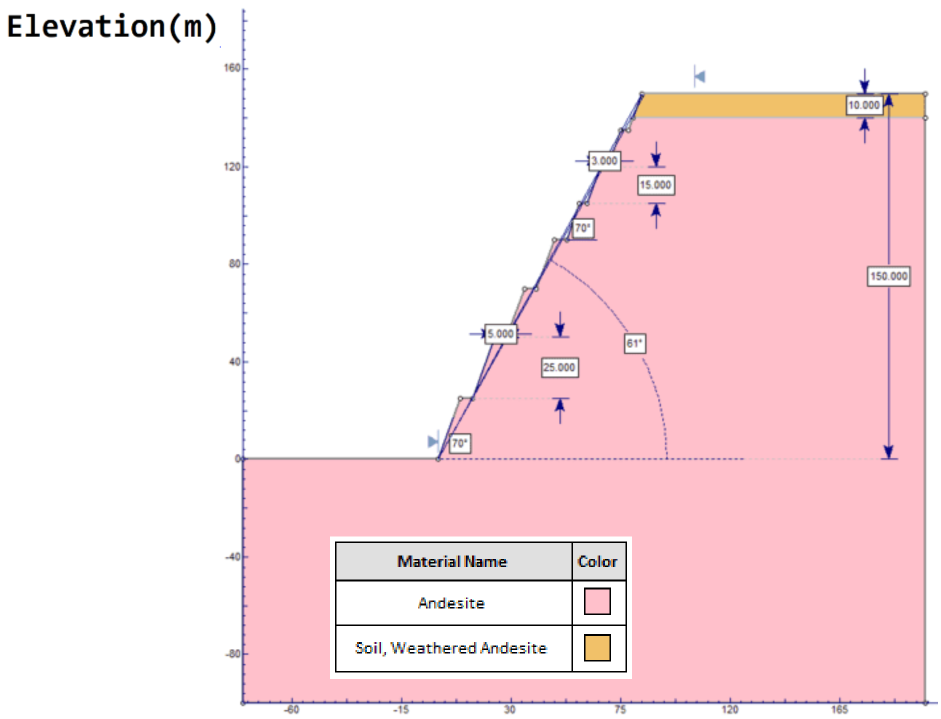


**Figure 7.** The slope geometry model that is analysed

The stability of the slope is interpreted based on the factor of safety (FS) values, where safe and unsafe conditions are referenced from applicable mining regulations in Indonesia. Stability assessment using the Rocscience Slide software shows that under static conditions, the FS value is 1.94, indicating that the slope is safe (FS > 1.1). However, under dynamic conditions, considering seismic shaking with an acceleration of 0.7 gal in this area, the FS value drops to 0.43, which is deemed unsafe, with a landslide probability of 100% (see Figures 8-9). A summary of the slope safety factor assessment results for PT. KSS is provided in Table (2).

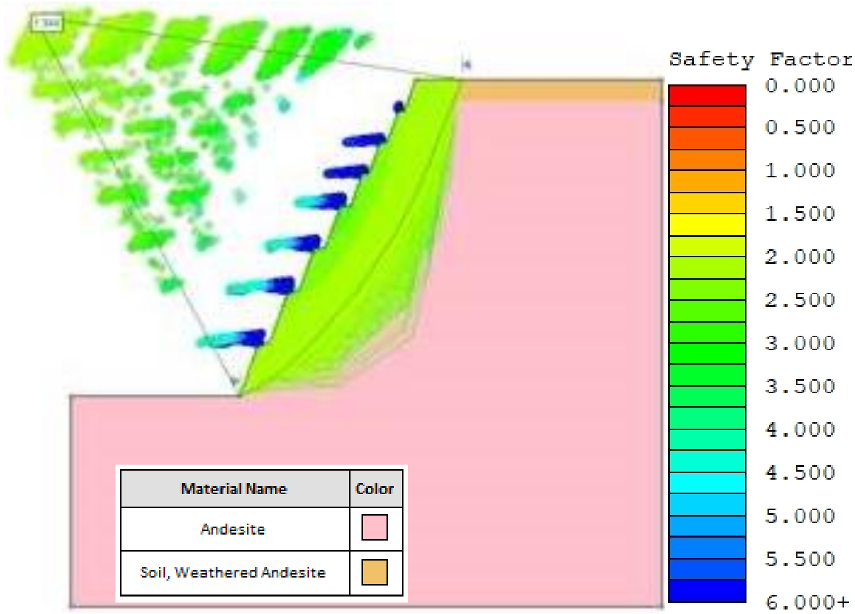


**Figure 8.** The slope stability analysis model under static conditions

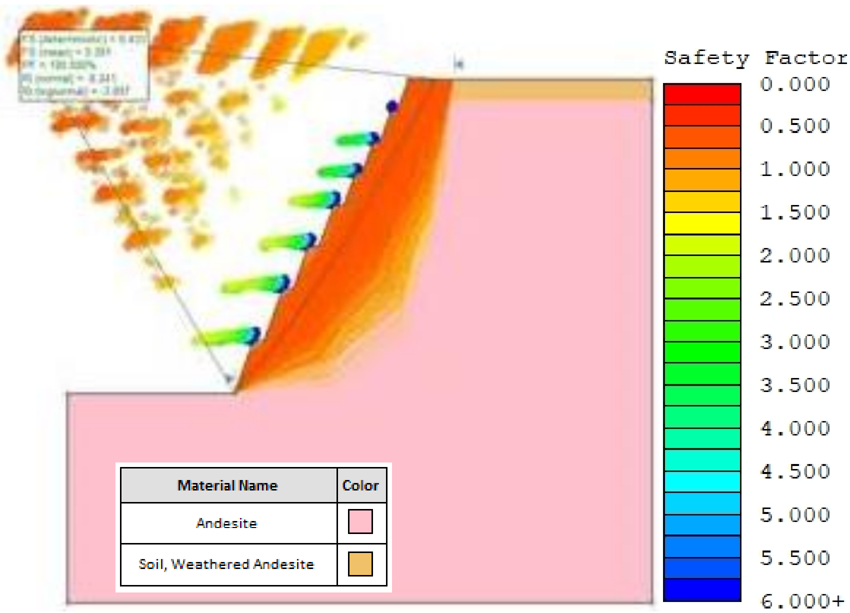


**Figure 9.** The slope stability analysis model under dynamic conditions

**Table 2.** The results of the slope stability analysis

| Type of slope | FS static (min) | FS dynamic (min) | Probability of flood (FS≤1) dynamic |
|---|---|---|---|
| Overall slope | 1.94 | 0.43 | PoF 100 % |

Based on the analysis, the PT. KSS mine slope is considered stable, except in the event of a strong earthquake, which could lead to slope failures in certain areas. A strong seismic event resulting in slope failure would have significant consequences, including severe injuries and fatalities among mine workers, damage to facilities and infrastructure exceeding 50%, production stoppage for more than 24 hours, loss of reserves that cannot be recovered, and environmental damage affecting areas beyond the mining site, including residential areas.

## 4. CONCLUSION

Based on the geological survey results and ERT measurements, the dominant rock type in the PT. Karya Sopai Sejahtera mining area is andesite. The observed andesite exhibits a fresh gray color and weathered brownish hue, with a hypohaline, aphanitic texture, subhedral-anhedral, and equigranular structure, classified as massive rock. The mineral composition includes quartz, pyroxene, biotite, and hornblende. Some outcrops show intensive weathering.

The factor of safety (FS) for the slope, under static conditions, both deterministically and probabilistically, indicates an FS value of 1.94, meaning the slope is safe. However, under dynamic conditions, with seismic shaking having an acceleration of 0.7 gal in the area, the FS value becomes unsafe at 0.43, with a landslide probability of 100%. Therefore, while the slope of the PT. KSS mine is generally stable, it is susceptible to failure in the event of a strong earthquake.

For a comprehensive assessment of rock slope stability, it is advisable to employ additional geomechanical methods such as Slope Mass Rating (SMR), combined with radar technology and LiDAR topographic mapping. These technologies can monitor soil movement vulnerabilities and surface relief changes in detail. Subsequently, identifying geological hazard risk zones and applying best mining practices according to regulations will facilitate effective planning and mitigation measures for landslides in the mining area.

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