*International Journal of Research in Engineering and Science (IJRES)*
*ISSN (Online): 2320-9364, ISSN (Print): 2320-9356*
*www.ijres.org Volume 14 Issue 7 ǁ July 2026 ǁ PP. 60-69*

# Integrated Rock Mass Characterization and Slope Stability Assessment of Andesitic Rock Slopes in Watusampu, Central Sulawesi, Indonesia

F. Riansyah[1)], Zeffitni [2)] S. Nurdin[3*)]
[1]*Master Student at the Department of Civil Engineering, Tadulako University, Indonesia*
[2]*Department of Geology Engineering, Tadulako University, Indonesia*
[3]*Department of Civil Engineering, Tadulako University, Indonesia*

***Abstract***
*Open-pit mining activities in Watusampu, Palu City, are highly vulnerable to mass movement hazards due to alterations in slope geometry and local seismicity along the Palu-Koro Fault system. This study aims to evaluate the physical-mechanical properties of andesite rocks and overall slope stability by integrating petrographic analysis, porosity testing, Unconfined Compressive Strength (UCS) testing, 2D Electrical Resistivity Tomography (ERT) subsurface modeling, and limit equilibrium analysis using Bishop's simplified method via Rocscience Slide 6.0 software. Petrographic results reveal that the lithology is dominated by massive andesite with a hypocrystalline texture, composed of plagioclase, quartz, pyroxene, biotite, and hornblende, and shows localized intensive weathering. Laboratory tests across 6 stations yielded varying porosity values and UCS values ranging from* $392{,}19\ kg/cm^2\ hingga\ 1.279{,}42\ kg/cm^2$*, which qualifies the rock as suitable for light to medium foundation materials, while the 2D ERT imaging confirms the presence of high-resistivity compact andesite layers and subsurface weathered zones. Furthermore, stability analysis correlating Geological Strength Index (GSI) values of 37–54 shows contrasting behaviors under the two control scenarios; under static conditions, the slope is highly stable and safe with a Safety Factor (FS) of 1.76 and a Probability of Failure (PoF) of 0%, whereas under dynamic conditions incorporating a 0.7 gal seismic load, the FS drops drastically to an unsafe 0.29 while the PoF surges to 100%. Consequently, the current mine slope geometry is secure under normal operational conditions but highly susceptible to catastrophic failure during strong earthquake shocks, making slope redesign and advanced monitoring technologies such as SMR, LiDAR, and deformation radar highly recommended for long-term risk mitigation.*
**Keywords:** *Andesite, Uniaxial Compressive Strength, 2D ERT, Bishop Method, Safety Factor, Probability of Failure.*

---

Date of Submission: 13-07-2026 Date of Acceptance: 24-07-2026

---

## I. INTRODUCTION

Palu City, the capital of Central Sulawesi Province, is situated within the Palu valley plain and Palu Bay area. Geographically, the region comprises five distinct topographic features: mountains, valleys, rivers, bays, and oceans, with elevations ranging from 0 to 700 meters above sea level. Covering a total area of 395.06 km2, Palu City borders Donggala Regency to the west and north, Sigi Regency to the south, and Parigi Moutong Regency to the east. Elongated from north to south, Palu City's topography is characterized by lowlands, undulating terrain, and highlands.

Volcanic or extrusive rocks form directly on Earth's surface [3, 6]. Volcanic igneous rocks generally form when magma cools rapidly (e.g., during volcanic eruptions), resulting in finer-grained constituent minerals. These volcanic rocks can be identified through their texture, structure, and mineral composition. The texture provides insights into the cooling process of the magma, and the rock structure characterizes whether the formation is intrusive or extrusive, whereas the mineral composition correlates with the rock color and its magmatic origin [4]. Common volcanic igneous rocks include basalt, dacite, and andesite. Andesite rock itself is typically massive, hard, and resistant to rainfall-induced weathering [5].

Based on the aforementioned context, in order to optimize the utilization of rock potential and conduct a comprehensive slope stability analysis, the authors focused on this specific study area. Because this research area currently lacks a Mining Business License (IUP), this study aims to provide baseline primary and secondary data derived from field observations and laboratory testing to assist future investors planning mining activities in this region. Therefore, this study evaluates the physical and mechanical properties, as well as the slope stability, of the Watusampu andesite rocks in Palu City. To determine the mechanical properties of the andesite igneous rock, unconfined compressive strength testing was conducted. Meanwhile, petrographic analysis and porosity testing were utilized to identify its physical properties. Additionally, the LEM-Bishop method was applied alongside geophysical research methods, which have been successfully implemented in various case studies for open-pit mining pit geometry planning and slope stability analysis [7].

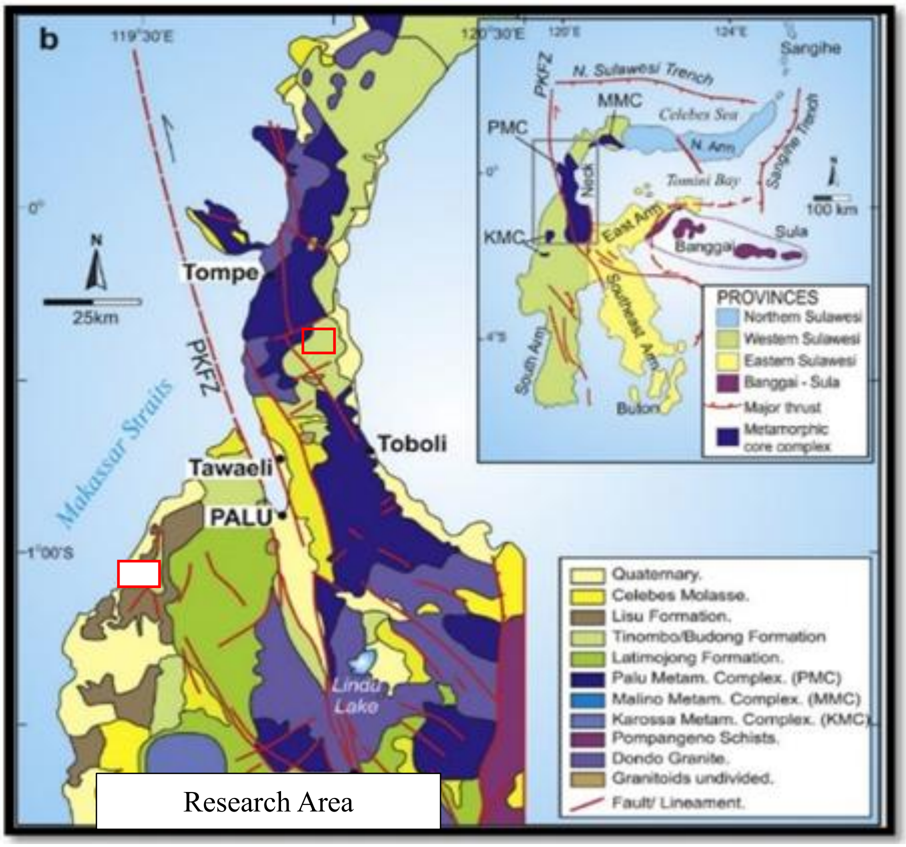


**Figure 1:** Regional Geological Map of the Palu Area and Surroundings, with the Position of the Research Area

## II. METHOD

This research applied a combined methodology integrating qualitative and quantitative fieldwork and laboratory analyses. To ensure a systematic workflow, the execution was structured into several primary stages: preparation, field data acquisition, laboratory analysis, data interpretation, and final report compilation. Geological mapping was conducted via field observations and data collection, including geomorphological, lithological, and structural geological data. Field documentation was recorded for each geological condition, and rock outcrops were characterized along with their relationships to the surrounding rock formations. Furthermore, geophysical measurements were carried out to obtain subsurface geological information. The research steps included map interpretation, station point determination, observation station quantification, geological data logging, rock sampling selection, and subsurface geological data acquisition

The data and samples obtained from the field were subsequently processed and analyzed through the following methods:

- Petrographic Analysis: Aimed at microscopically identifying the rock type, texture, mineral composition, alteration mineral content, and wallrock characteristics.
- Physical Properties Analysis (Porosity): Measured the ratio of void space (pore volume) to the total rock volume to determine the pore space characteristics and potential water content within the rock.
- Unconfined Compressive Strength (UCS) Testing: Implemented to evaluate the mechanical properties and rock strength capacity under compressive loads.
- Slope Stability Analysis: Evaluated the stability of the mine slope using the Limit Equilibrium Method (LEM) with the Bishop simplified variation.
- Subsurface Modeling: Processed geoelectrical data using Res2Dinv version 3.5 software to generate 2D subsurface resistivity cross-sections.

During the final synthesis stage, all laboratory results were comprehensively integrated to derive the primary conclusions:

- Petrographic Data Synthesis: Optical properties of minerals were utilized for definitive rock naming and to identify alteration/mineralization zones.
- Rock Physical Properties Synthesis: Yielded quantitative data regarding bulk density, specific gravity, water content, degree of saturation, porosity, and void ratio.
- Mechanical Properties and Slope Stability Synthesis: Integrated the dimensions, cross-sectional area, and maximum load from the UCS tests into the Bishop method analysis to determine the Safety Factor (FS) of the mine slope.
- Geoelectrical Synthesis: Correlated subsurface resistivity models with surface geological data to clarify the lithological conditions and subsurface structures in the study area.

## III. RESULTS

### 3.1. GEOLOGICAL CONDITIONS OF THE RESEARCH AREA

Administratively, the study area is located in Watusampu Village, Ulujadi District, Palu City, Central Sulawesi Province. Geographically, it is situated between coordinates 00°49’30” to 00°49’00” South Latitude and 119°48’00” to 119°48’30” East Longitude. As an initial step in slope stability evaluation, a thorough understanding of baseline mapping—including morphological characteristics, lithological characteristics, and sampling point representation—is required. The evaluation of local geological conditions in this section is based on three main working maps at a scale of 1:2,000, compiled from field surveys, satellite imagery, and digital topographic maps.

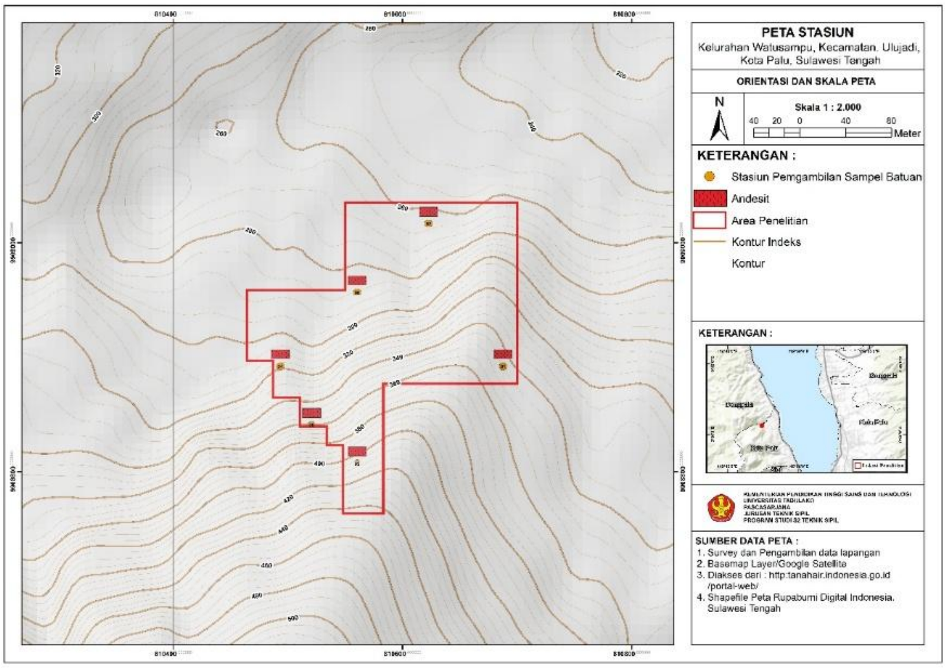


**Figure 3.1** Map of the research area in the Watusampu region

Based on field data analysis using physical methods from 6 observation stations, the rock quality was determined through petrographic observations and porosity testing. The results are as follows:

**Petrographic Observations**

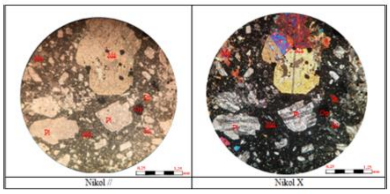


**Figure 4.4**
Thin Section St 01 Andesite Porfiri

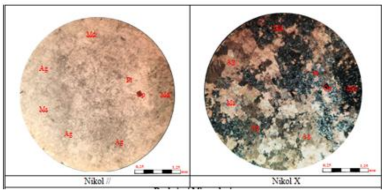


**Figure 4.5**
Thin Section St 02 Andesit

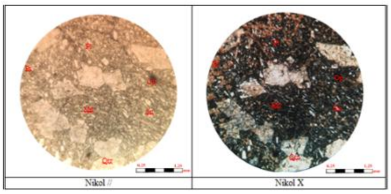


**Figure 4.6**
Thin Section St 03 Andesit

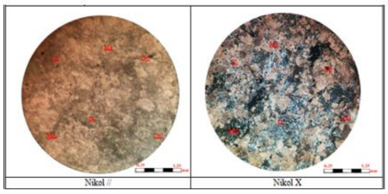


**Figure 4.7**
Thin Section St 04 Andesit

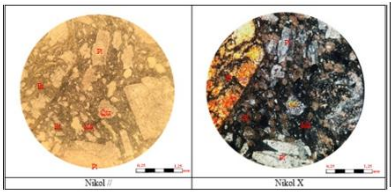


**Figure 4.8**
Thin Section St 04 Andesit

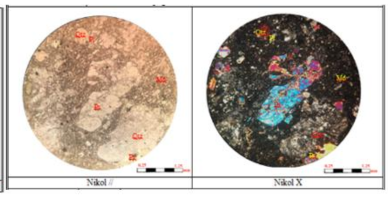


**Figure 4.9**
Thin Section St 04 Andesit

## 3.2. Porosity Test Results

Porosity data were obtained by weighing samples in their natural, saturated, and oven-dried conditions to calculate the void volume relative to the total rock volume. The tabulated laboratory results for each andesite rock sample are presented in Table 3.1:

**Table 3.1** Porosity values of the andesite rocks

| No | Sample ID | % Porosity | Remarks |
|---|---|---|---|
| 1 | Andesite 1 | 0.30 | Stasiun 01 |
| 2 | Andesite 2 | 0.34 | Stasiun 02 |
| 3 | Andesite 3 | 1.35 | Stasiun 03 |
| 4 | Andesite 4 | 0.24 | Stasiun 04 |
| 5 | Andesite 5 | 0.46 | Stasiun 05 |
| 6 | Andesite 6 | 0.16 | Stasiun 06 |

As shown in Table 3.1, the rock porosity values from station 01 to station 06 ranged from 0.16% to 1.35%. Referring to Table 2.7, this porosity quality classifies the rock within the "very poor" category.

**Hasil Pengujian Kuat Tekan Batuan Uniaxial**

Mechanical testing was performed to evaluate the rock's resistance against external compressive loads. This test utilized the Unconfined Compressive Strength (UCS) method on representative andesite rock samples from each observation station. The parameters, including dimensions, bulk density, maximum load, and compressive strength values, are detailed in Table 4.2 and summarized in Table 3.3.

**Table 3.2** Uniaxial compressive strength test values of andesite rock

| No | Weight (g) | Dimensions | | | Density(gram/cm3) | Cross-sectional Area($cm^2$) | Maximum Load(KN) | Compressive Strength(kg/cm2) |
|---|---|---|---|---|---|---|---|---|
| | | Length (cm) | Width (cm) | Height (cm) | | | | |
| **1** | 461.8 | 5.46 | 5.6 | 5.31 | 2.84 | 30.57 | 260 | 867.27 |
| **2** | 420.2 | 6.03 | 5.75 | 4.58 | 2.64 | 34.67 | 435 | 1,279.42 |
| **3** | 476.4 | 6 | 5.85 | 5.45 | 2.49 | 35.1 | 135 | 392.19 |
| **4** | 449.8 | 5.39 | 5.05 | 5.88 | 2.81 | 27.21 | 250 | 936.89 |
| **5** | 409.2 | 5.5 | 5.21 | 5.41 | 2.64 | 28.65 | 230 | 818.62 |
| **6** | 432.6 | 6.13 | 5.72 | 4.6 | 2.68 | 35.06 | 420 | 1,221.56 |

**Table 3.3** Summary of physical and mechanical property values of uniaxial andesite rock

| PARAMETER | | Unit | SAMPLE | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 |
| | **PETROGRAPHY** | | | | | | | |
| **PHYSICAL PROPERTIES** | Muscovite | % | √ | √ | | √ | | |
| | Pyroxene | % | √ | | √ | | √ | √ |
| | Plagioclase | % | √ | √ | | √ | √ | √ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Sanidine | % | √ | | √ | | | |
| | Opaque | % | √ | √ | √ | √ | | √ |
| | Augite | % | | √ | | | | |
| | Chlorite | % | | √ | | √ | | |
| | Biotite | % | | | | | √ | |
| | Quartz | % | | | √ | √ | √ | √ |
| | Groundmass | % | √ | √ | √ | √ | √ | √ |
| | POROSITY | | | | | | | |
| | Very Poor | % | √ | √ | √ | √ | √ | √ |
| | **COMPRESSIVE STRENGTH** | | | | | | | |
| **MECHANICAL PROPERTIES** | Medium Foundation | $Kg/cm^2$ | √ | √ | √ | √ | √ | √ |
| | Light Foundation | $Kg/cm^2$ | √ | √ | √ | √ | √ | √ |
| | Floor Covering / Sidewalk | $Kg/cm^2$ | √ | √ | √ | √ | √ | √ |
| | Curbstone / Milestone | $Kg/cm^2$ | √ | √ | √ | √ | √ | √ |
| | Decorative Stone or Wall Cladding | $Kg/cm^2$ | | | √ | | | |

Based on the range of compressive strength values obtained, the Watusampu andesite exhibits potential for use as decorative stone, light to medium foundation materials, pavement/sidewalk tiles, and wall cladding, which are suitable for single-story buildings and road construction applications.

## 3.3. Slope Stability Analysis

The study area is characterized by surface soil interbedded with weathered rock, with a thickness not exceeding 10 meters, overlying competent andesite, which serves as the baseline material for the slope stability analysis (Figure 3.14). From an engineering perspective, the local andesite has an average bulk density of 2.66 $g/cm^3$ (see Table 3.2).

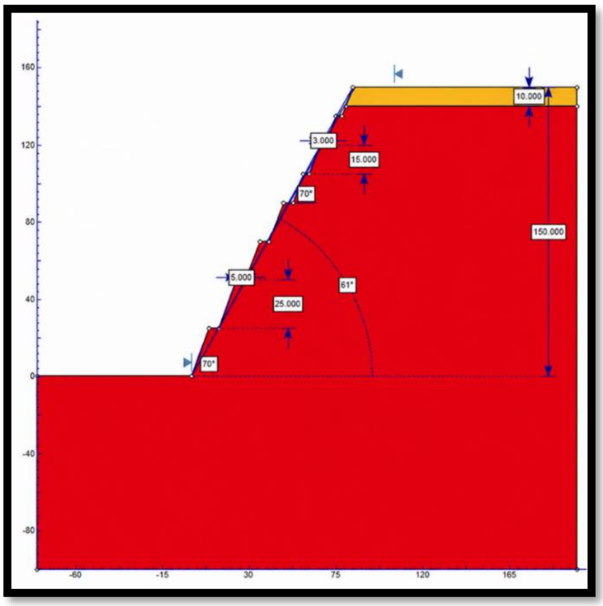


**Figure 3.19** Slope geometry on andesite lithology at the research location.

The slope Safety Factor (FS) is calculated by comparing the shear strength of the material against the acting shear stresses along the failure plane. The interpretation of FS in this study refers to the prevailing ministerial regulations for overall slopes (see Table 3.4).

**Table 3.4** Factor of safety and mining slope probability values according to the Decree of the Minister of Energy and Mineral Resources (KepMen. ESDM) Number 1827 K/20/MEM/2018 concerning Guidelines for Implementing Good Mining Principles, App. II Guidelines for Technical Mining Management

| Slope Type | Consequence of Failure (CoF)* | Acceptance Criteria | | |
|---|---|---|---|---|
| | | Static Factor of Safety (FS) (min) | Dynamic Factor of Safety (FS) (min) | Probability of Failure (max) PoF ($FS \leq 1$) |
| Single Slope | Low to high | 1.1 | None | 25-50% |
| Inter-Ramp | Low | 1.15-1.2 | 1.0 | 25% |
| | Medium | 1.2-1.3 | 1.0 | 20% |
| | High | 1.2-1.3 | 1.1 | 10% |
| Overall Slope | Low | 1.2-1.3 | 1.0 | 15-20% |
| | Medium | 1.3 | 1.05 | 10% |
| | High | 1.3-1.5 | 1.1 | 5% |

Dynamic parameters incorporated seismic loads in accordance with SNI 1726:2012 and its amendments, referencing the 2017 Indonesian Seismic Source and Hazard Map, with a peak ground acceleration (PGA) exceeding the 10% probability in 50 years (Figure 3.15). This dynamic analysis accounts for the fact that rock slopes are primarily affected by vibrations, particularly those induced by earthquakes [1]. Within the study area, a seismic coefficient of 0.7 gal corresponds to the PGA value used to evaluate slope stability.

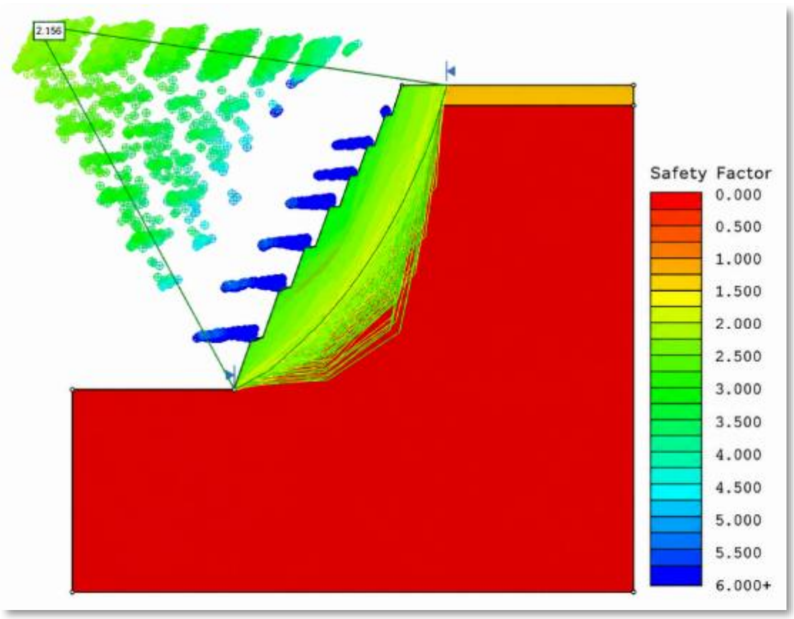


**Figure 3.20** FS analysis result model for GSI Andesite 01 under static conditions

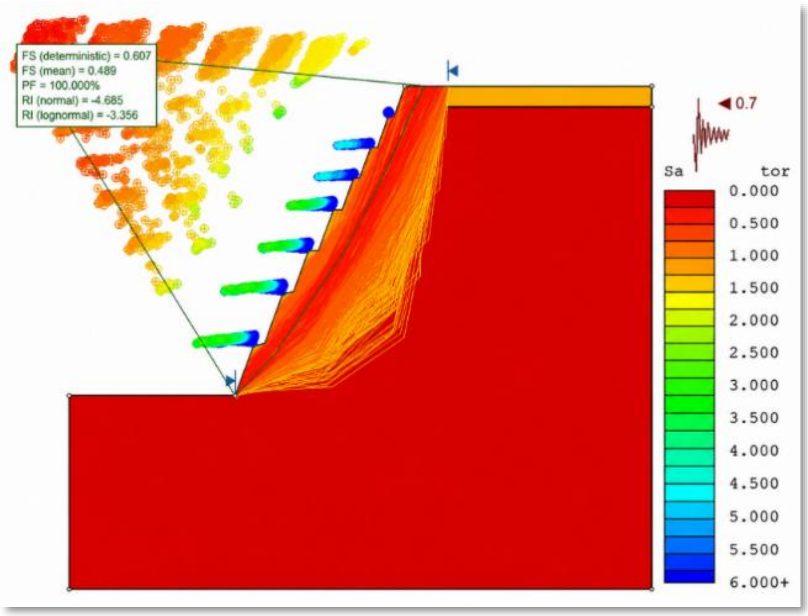


**Figure 3.21** FS analysis result model for GSI Andesite 02 under dynamic conditions

**Table 3.5** Results of factor of safety (FS) determination under dynamic slope conditions

| Slope Type | GSI Value | Dynamic FS (min) | Dynamic PoF (%) |
|---|---|---|---|
| Overall slope | 37 | 0.211 | 100 |
| | 40 | 0.288 | 100 |
| | 45 | 0.433 | 100 |
| | 50 | 0.607 | 100 |
| | 54 | 0.744 | 99.89 |

The slope stability analysis under dynamic conditions yielded FS values ranging from 0.21 to 0.75 (where the required standard is >1.1), with the Probability of Failure (PoF) reaching 100%, indicating that the slope is unsafe and unstable. The observed trend shows that the FS value is directly proportional to the increase in the Geological Strength Index (GSI) value.

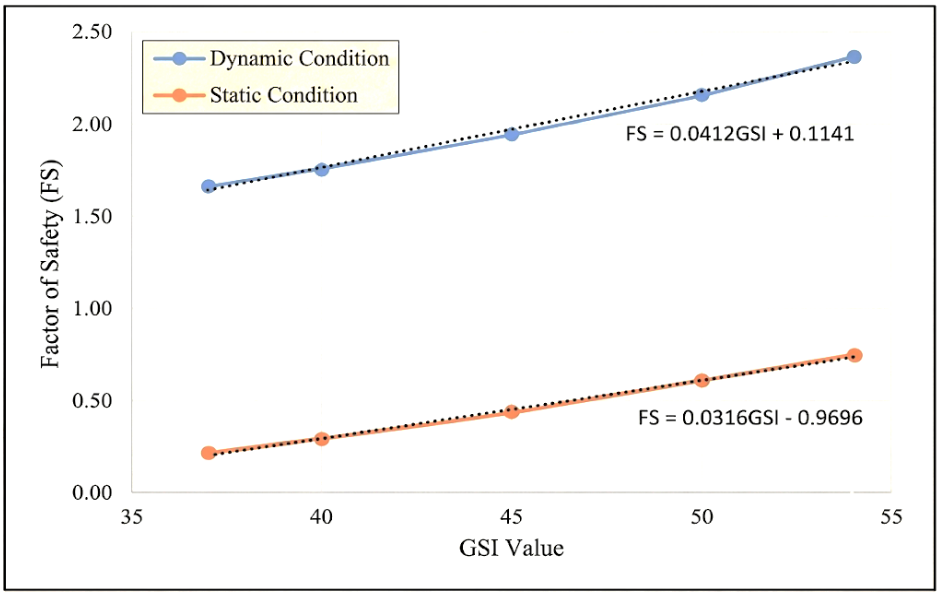


**Figure 4.22** Correlation graph between Geological Strength Index (GSI) value and Factor of Safety (FS) on the overall slope under static and dynamic conditions.

It can be concluded that a higher GSI value results in a higher calculated FS. Although the correlation does not form a perfectly straight line, the data trend indicates a proportional relationship between the two parameters. Therefore, a statistical regression analysis was applied to model the relationship between these variables, aiming to support decision-making by identifying optimal analysis outcomes across variations in GSI values.

**Table 3.6** FS determination results under dynamic slope conditions

| GSI Value | FS statis (min) Cal. | FS statis (min) Obs. | FS statis (min) error (%) | FS dinamis (min) Cal. | FS dinamis (min) Obs. | FS dinamis (min) error (%) |
|---|---|---|---|---|---|---|
| 37 | 1.64 | 1.66 | 1.31 | 0.2 | 0.21 | 5.71 |
| **40** | **1.76** | **1.75** | **0.46** | **0.29** | **0.29** | **2.17** |
| 45 | 1.97 | 1.94 | 1.22 | 0.45 | 0.43 | 4.29 |
| 50 | 2.17 | 2.16 | 0.83 | 0.61 | 0.61 | 0.56 |
| 54 | 2.34 | 2.36 | 1.03 | 0.74 | 0.74 | 0.98 |

The final decision-making process was based on identifying the minimum error between the modeling data (observed data) and the calculated data. It is evident that the lowest error value occurs at a GSI value of 40 for the andesite rock.

**Table 3.7** Results of FS value determination

| Slope Type | Static FS (min) | Dynamic FS (min) | Probability of Failure (FS≤1) Dynamic |
|---|---|---|---|
| Overall slope | 1.75 | 0.29 | PoF 100% |

Based on the comprehensive analysis, the slope in the study area is considered stable under normal conditions. However, if triggered by strong earthquake shocks, localized to widespread slope failure can occur. A severe earthquake leading to slope failure would pose significant consequences and high severity, including severe injuries or fatalities among mine workers, infrastructure damage exceeding 50%, production downtime surpassing 24 hours, loss of unrecoverable reserves, and environmental degradation extending beyond the mining perimeter into neighboring residential settlements.

### 3.4. 2D Electrical Resistivity Tomography (ERT) Results

a. Resistivity Characteristics of ERT Line 1 (Orientation: N45°E):

The geoelectrical resistivity measurement for ERT Line 1 was conducted along an N45°E profile using a Wenner-Schlumberger electrode configuration with a unit electrode spacing of 7 meters, yielding a total profile length of 140 meters. The inversion resistivity cross-section at the 4th iteration, with an absolute error of 3.3%, shows resistivity values varying from 417 to >1,467 Ω·m across an elevation range of 300 to 360 meters above sea level. Based on the cross-section interpretation (Figure 3.10), the rock mass along this profile can be classified into two primary units: the Weathered Andesite Zone and the Massive Andesite Zone.

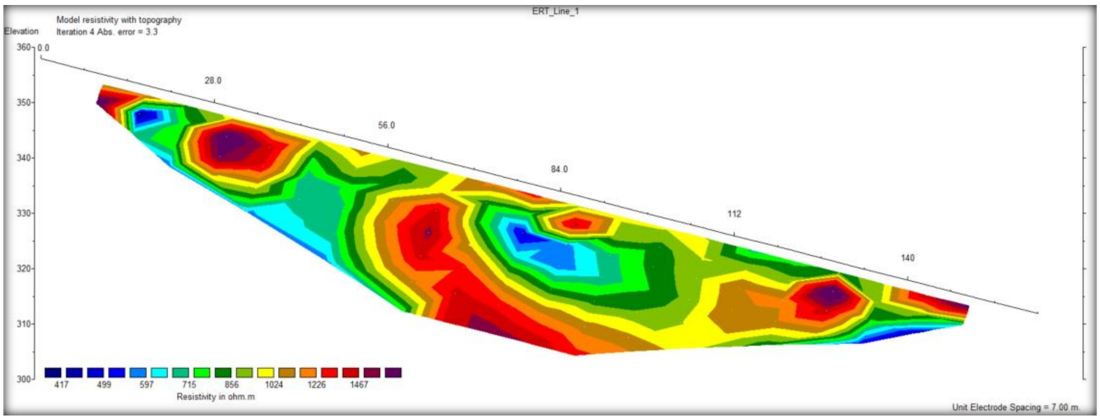


**Figure 3.15** Resistivity cross-section of ERT Line 1 model in N45°E direction (Iteration 4, Abs. error = 3.3%)

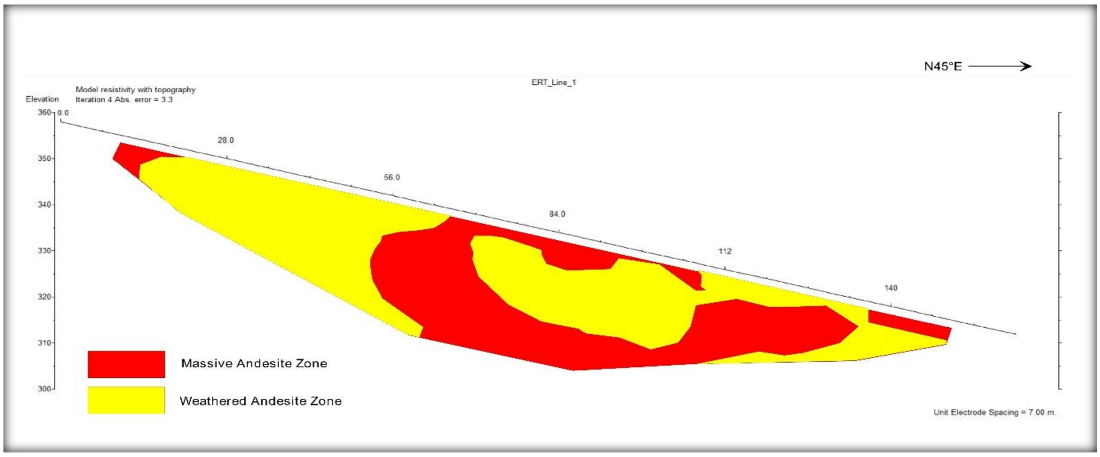


**Figure 3.16** Rock zonation interpretation of ERT Line 1 in N 145°E direction

The Weathered Andesite Zone is characterized by relatively low-to-medium resistivity values (±417–856 Ω·m), dominating the upper and peripheral sections of the profile, particularly within the 0–56 meter segment at elevations of 340–360 meters. This lower resistivity reflects the intensive weathering of the rock, which increases porosity and pore water content, thereby enhancing electrical conductivity [8]. This zone correlates directly with surface outcrops consisting of disaggregated andesitic material with low hardness and fractures filled with secondary minerals.

b. Resistivity Characteristics of ERT Line 2 (Orientation: N143°E):

RT Line 2 was conducted along an N143°E profile using a 7-meter electrode spacing and a total length of 140 meters. The inversion at the 2nd iteration produced an absolute error of 13.1%, which is higher than Line 1 but remains acceptable given the complex local topography. The cross-section displays resistivity values ranging from 565 to >3,125 Ω·m at elevations between 230 and 290 meters.

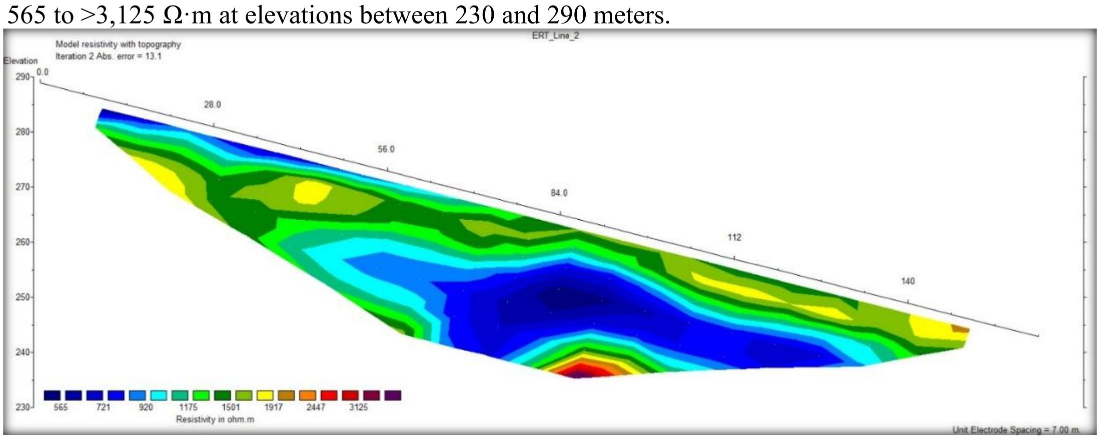


**Figure 3.17** Resistivity cross-section of ERT Line 2 model in N143°E direction (Iteration 2, Abs. error = 13.1%)

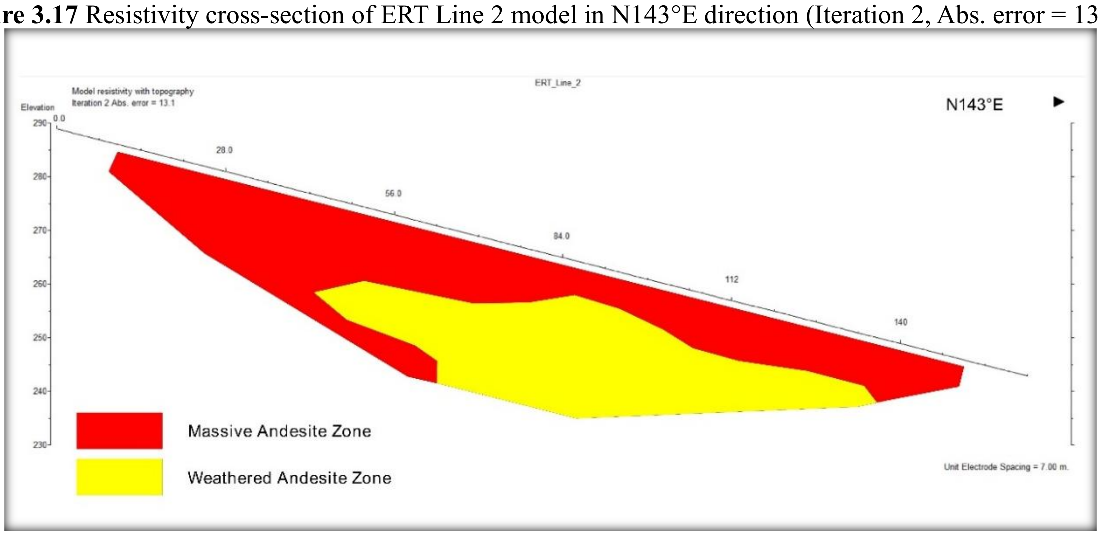


**Figure 3.18** Rock zonation interpretation of ERT Line 2 in N143°E direction

Unlike Line 1, Line 2 exhibits a more distinct resistivity contrast between the upper and lower sections. The Massive Andesite Zone dominates the upper portion of the profile (elevations of 260–290 meters), with resistivity values ranging from>1,917 to >3,125 Ω·m. This dominance suggests that fresh andesite outcrops are closer to the surface along Line 2, likely due to higher erosion rates that stripped away the weathered overburden.

c. Korelasi Hasil Geolistrik dengan Kondisi Geologi dan Implikasinyaterhadap Kestabilan Lereng

Cumulatively, the interpretation of both ERT profiles provides a representative subsurface model of the open-pit mine. The correlation between the intersecting Line 1 and Line 2 demonstrates that the distribution of the weathered zone is non-homogeneous and is governed by structural and topographical patterns. On Line 1, the weathered zone is thicker on the west-southwest side and thins toward the northeast, indicating more intensive weathering on slopes facing the valley or exposed to major weathering agents. Conversely, on Line 2, the weathered zone is detected at a greater depth beneath the upper massive rock, indicating potential paleo-weathering or a weathered zone buried by prior geomorphic processes. These findings estimate the weathered zone thickness to be between 5 and 20 meters, depending on the slope position, with maximum thickness at the center of Line 2, correlating with typical fracture networks in andesite that act as pathways for meteoric water infiltration, accelerating hydrolysis and oxidation [2].

## IV. CONCLUSION

In conclusion, integrating surface geological mapping, rock physical and mechanical properties, and subsurface 2D ERT modeling provides a comprehensive geotechnical assessment of the study area. This integrated synthesis forms the foundation for evaluating the stability of the mine slope under both static operational conditions and seismic activity. The core conclusions are summarized as follows:

**Local Distribution of Andesite Rock:**
The local lithology is naturally dominated by in situ massive andesite, boulders, cobbles, and surface debris in the form of gravelly sand (*tasirtu*). Petrographically, the rock is classified as Andesite Porphyry with a massive hypocrystalline texture, composed mainly of plagioclase, quartz, pyroxene, biotite, hornblende, sanidin, and muscovite. Outer outcrop zones show intensive weathering driven by hydrolysis and oxidation processes.

**Rock Physical and Mechanical Characteristics:**
- Physical Properties: Laboratory tests across 6 stations show varying porosity values with an average material bulk density of 2.66 g/cm³
- Mechanical Properties: Based on UCS testing, the Watusampu andesite exhibits compressive strength values ranging from 392.19 kg/cm² to 1,279.42 kg/cm².

These values qualify the rock as compliant with natural stone quality standards for construction, making it suitable for light-to-medium foundation materials and coarse construction aggregates.

**Mine Slope Safety Factor (Bishop Method):**
Stability analysis of the 150-meter-high overall slope with a 61° angle using Bishop's Simplified Limit Equilibrium Method across GSI values of 37–54 revealed:
- Static Condition: The slope is highly secure, yielding a Safety Factor (FS) of 1.76 and a Probability of Failure (PoF) of 0%, fully satisfying the safety criteria of KepMen ESDM No. 1827 K/20/MEM/2018.
- Dynamic Condition (Seismic Load): Under the dynamic influence of a local 0.7 gal seismic load from the Palu-Koro Fault system, the Safety Factor drops drastically to an unsafe/critical level of 0.29, while the Probability of Failure surges to 100%.
- Implication: The current mine slope geometry is stable under normal operating conditions but highly vulnerable to catastrophic failure if triggered by a high-magnitude earthquake

## REFERENCE

[1]. Arifianti, Y., Sarkowi, M., & Utama, H. W. (2023). Analisis Stabilitas Lereng Berbasis Model Matematis untuk Perencanaan Infrastruktur Perkotaan Berkelanjutan. Jurnal Rekayasa Sipil dan Lingkungan, 7(2), 145–154. https://www.researchgate.net/publication/400263618
[2]. Dearman, W. R. (1991). Engineering Geological Mapping. Butterworth-Heinemann. https://doi.org/10.1016/B978-0-7506-1010-0.50005-7
[3]. Lopresto, C., Leone, C., & De Iorio, I. (2011). Mechanical characterisation of basalt fibre reinforced plastic. Composites Part B: Engineering, 42(4), 717–723. https://doi.org/10.1016/j.compositesb.2011.01.030
[4]. Mulyaningsih, S. (2013). Vulkanologi Lingkungan. Panduan Media.
[5]. Rinawan, R. (2000). Pengantar Praktis Identifikasi Mineral dan Batuan. Laboratorium Geologi Dinamis ITB.
[6]. Sudarmi, S. (2016). Karakteristik Fisik dan Mekanik Batuan Beku Vulkanik sebagai Bahan Konstruksi. Jurnal Sains dan Teknologi Utama, 11(2), 89–98.
[7]. Syafar, Z., Nawir, J., & Sufrianto, S. (2016). Analisis Kestabilan Lereng dengan Metode Bishop pada Penambangan Nikel. Jurnal Geomine, 4(3), 123–128. https://jurnal.fti.umi.ac.id/index.php/JG/article/view/1371
[8]. Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). Applied Geophysics (2nd ed.). Cambridge University Press. https://doi.org/10.1017/CBO9781139167932