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RESEARCH ARTICLE

Geotechnical Insights into Andesite Quarry Slope Stability: A Case Study from Desa Usul, Indragiri Hulu, Riau, Indonesia

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Abstract

This study investigates the slope stability of andesite quarries from a geotechnical and civil engineering perspective, emphasizing geological, geotechnical, and civil engineering factors influencing stability and their implications for mining and infrastructure operations. Andesite is widely used as an aggregate material in construction due to its compliance with Indonesian National Standards (SNI) for aggregate quality. Through comprehensive geotechnical assessments and slope stability analyses, the research concludes that the Andesite quarry slopes exhibit high levels of stability, supporting safe mining practices. Calculated Factor of Safety (FS) values consistently exceed safety thresholds, indicating favorable conditions for resource extraction. Slope simulations using Slide and Geoslope applications confirm the robustness of the slopes, with Safety Factor (FS) values ranging from 1.601 to 2.614. The implementation of open-cut methods, supported by meticulous slope design and blasting techniques, enhances safety and efficiency in mining operations. The study underscores the feasibility and safety of mining activities in the researched area, contributing to the advancement of mining engineering practices in volcaniclastic environments. Effective slope management strategies are essential for ensuring sustainable resource extraction while prioritizing worker safety and environmental integrity.

Keywords: Slope Stability Analysis; Andesite Quarry; Factor of Safety (FS); Geotechnical Assessment

1. Introduction

The demand for high-quality construction materials continues to grow alongside the rapid development of infrastructure, particularly in Indonesia. One critical material in construction is aggregate, which is widely used in concrete production, road construction, and other structural applications. According to the Indonesian National Standards (SNI), aggregates must meet specific criteria for size, strength, and durability to ensure structural integrity and long-term performance in civil engineering projects (SNI 03-1727-1989; SNI 03-2847-2013). Aggregates are categorized into several types, including crushed stone, gravel, sand, and volcanic rocks such as andesite, each with unique applications depending on their properties.

Andesite, a type of volcanic rock, is particularly valued for its strength and durability, making it a preferred choice for producing construction-grade aggregates (Alonso, 1976; Cahyono et al., 2022; El-Ramly et al., 2002). It is commonly used in producing coarse aggregates due to its resistance to weathering and ability to withstand heavy loads, which are essential characteristics for structural concrete, road base layers, and retaining walls. However, successful and safe extraction of andesite requires a comprehensive understanding of slope stability, as instability in quarry slopes poses significant risks to mining operations and nearby infrastructure (Al Heib et al., 2024; Aris Hasibuan and Yustanti, 2023; Darmadi, 2018; Nguembi et al., 2023).

In the mining industry, production efficiency is paramount to achieving planned production targets. Various factors can impede mining or quarry production activities, particularly in upstream mining operations, where failure in mining slopes is a significant concern. Slope failures can result in production losses, increased costs for removing failed material, and potential loss of ore reserves if the pit cannot be mined to its full (Kolapo et al., 2022; Leng et al., 2023; Lu et al., 2024). Therefore, understanding and ensuring slope stability is crucial for the efficiency and safety of mining operations.

The stability of slopes in andesite quarries is influenced by geological, geotechnical, and environmental factors (Ariyanto et al., 2020; Márkus and Rácz, 2024; Ratminah et al., 2021). Geological factors include the lithological characteristics of the rock mass, structural features such as faults and joints, and the presence of geological discontinuities. Geotechnical factors encompass soil properties, including shear strength, cohesion, and internal friction angles, which govern the stability of rock slopes under different loading conditions. Environmental factors such as rainfall, groundwater levels, and seismic activity can also significantly impact slope stability by triggering slope failures and landslides.

This research aims to investigate the slope stability of andesite quarries, focusing on the geological and geotechnical factors affecting stability and the implications for mining operations. By conducting comprehensive geotechnical assessments and slope stability analyses, this study seeks to provide insights into the potential risks associated with mining activities in andesite quarries and propose mitigation measures to enhance safety and productivity. The research area is located in Desa Usul, Kecamatan Batang Gansal, Kabupaten Indragiri Hulu, Provinsi Riau, Indonesia, where active andesite mining operations are ongoing (Fig.1).

Civil engineers involved in mining operations contribute by conducting geotechnical assessments, performing detailed slope stability analyses, and developing solutions for maintaining slope integrity. They apply a combination of engineering principles, soil mechanics, and rock mechanics to assess the load-bearing capacity of slopes, ensuring that they remain stable during resource extraction activities. This process involves understanding the interaction between geological materials and environmental factors, such as rainfall, groundwater conditions, and seismic activity, which can affect the stability of a quarry.

In andesite quarries, civil engineers collaborate with geologists and mining engineers to design open-pit mines that minimize the risk of landslides and other hazards. They utilize advanced computational tools and simulation software, such as Slide and Geoslope, to model the behavior of slopes under various conditions and predict potential failures. These simulations help in determining optimal slope angles, excavation techniques, and drainage systems that reduce the likelihood of slope instability.

Moreover, civil engineers ensure compliance with local and national regulations, such as those outlined by the Indonesian Ministry of Energy and Mineral Resources. Their designs must meet the recommended safety factors to minimize the probability of failure, while also considering the economic feasibility of mining operations. Through these efforts, civil engineers contribute not only to the technical success of mining projects but also to the protection of workers and the preservation of the surrounding environment (Al Heib et al., 2024; Nguembi et al., 2023).

By addressing the challenges posed by slope stability in andesite quarries, this research contributes to the advancement of mining engineering practices and the optimization of resource extraction processes in geological environments characterized by volcanic activity and volcaniclastic deposits. The research area was chosen as a case study due to ongoing andesite rock mining activities nearby, involving numerous offline workers who understand slope stability issues. This analysis aims to support the safety and efficiency of mining operations, ultimately enhancing production efficiency and worker safety.

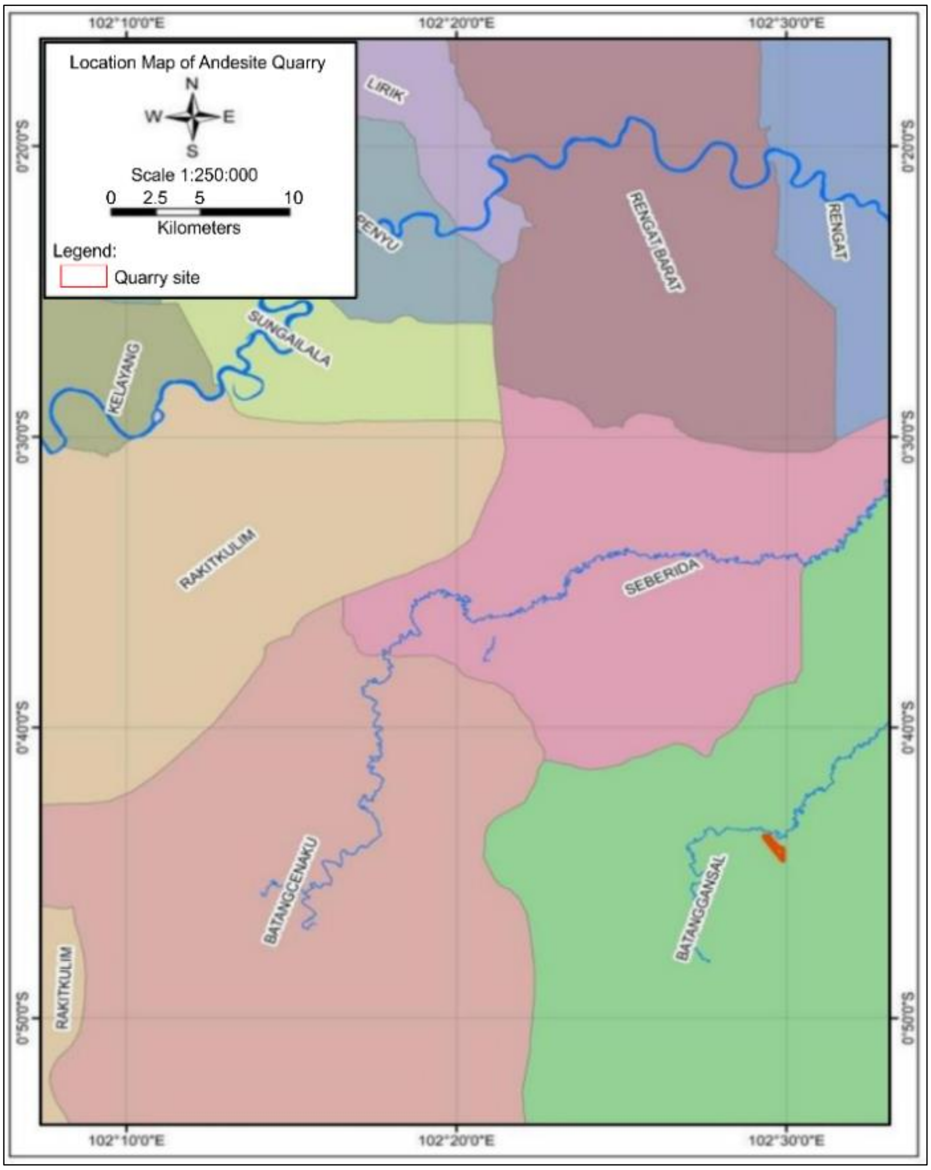

Fig 1. Location of the Andesite Quarry in Desa Usul.

2. Morphology

The general morphology of the area and its surrounding region exhibits a diverse range of landforms, reflecting the complex geological history and environmental processes that have shaped the landscape. The following description provides an overview of the morphological characteristics observed in the study area:

1. Alluvial Plains: These are found along the banks of rivers with a slight gradient ranging from 0 to 3%. As

the rivers flow downstream, they are increasingly influenced by tidal fluctuations, resulting in the formation of marshy floodplains or "rawa lebak."

2. Peatlands : Peatlands are prominent in areas such as Rengat and Kuala Cenaku. These regions feature varying depths of peat deposits, which can significantly affect the topography and hydrology of the area.
3. Transitional Plains : Transitional plains mark the transition zone between alluvial plains and peatlands. This area exhibits undulating terrain with elevations ranging from relatively flat to gently rolling hills.
4. Hills: Hills are characterized by higher elevations compared to the surrounding plains. These hills form complex hillscapes, with elevations ranging from 100 meters to 800 meters above sea level. The slopes of these hills vary from moderate inclines to steep gradients, reflecting the presence of hard volcanic rocks such as andesite and other volcanic materials.

Overall, the morphological characteristics of the study area reflect a dynamic interplay between geological processes, fluvial activity, and tectonic forces (Kausarian et al., 2021, 2023a; Schaetzl and Thompson, 2015; Sreenivasan and Jha, 2022). The presence of diverse landforms underscores the geological complexity of the region, which has implications for various aspects of land use, environmental management, and infrastructure development, including the operation of mining activities within the IUP. Understanding the morphological features of the area is essential for effective land-use planning, resource management, and sustainable development initiatives (Fig. 2).

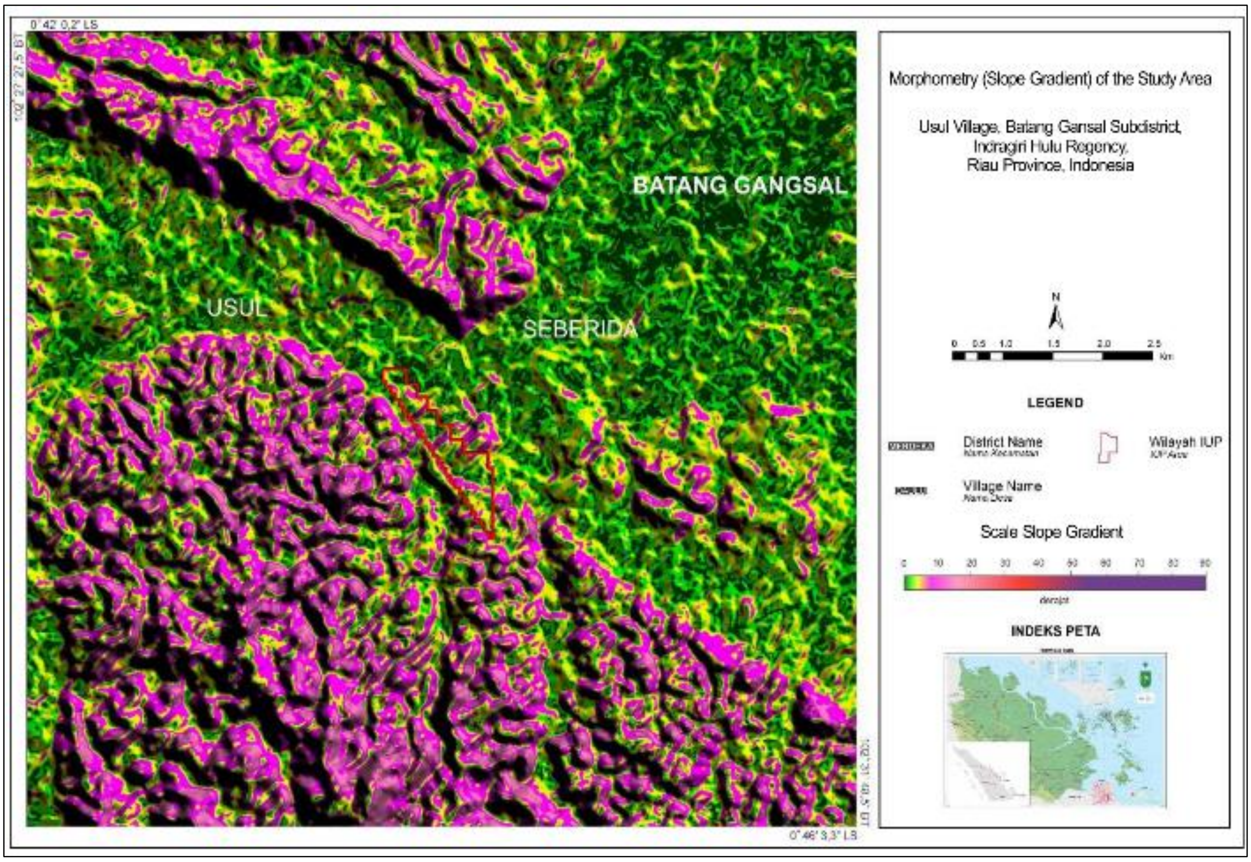

Fig 2. Morphometry in Desa Usul

3. Geological and Research Background

The geological background of the research area plays a fundamental role in understanding the characteristics of the andesite quarry, as well as the slope stability challenges that accompany such operations. Andesite, an igneous volcanic rock, is commonly found in areas of past volcanic activity. It is typically formed through the cooling of lava that contains intermediate amounts of silica, resulting in a medium-grain rock that is widely used in construction for aggregates and road materials.

In Riau Province, the presence of andesite is geologically significant. The region is part of the broader tectonic framework of Sumatra Island, which is influenced by the collision of the Indo-Australian Plate with the Eurasian Plate along the Sumatra Fault Zone. This tectonic activity has led to the formation of various volcanic complexes over geological time, with andesite being one of the prominent rock types. The andesite deposits in this region are typically found in highland areas where volcanic activity historically occurred.

The geological context of the research area, focusing on the Andesite quarry slopes, is crucial for understanding the formation and characteristics of the terrain under investigation. The study area is located within the province of Riau, Indonesia, which is known for its volcanic activity and associated geological features. The presence of Andesite, a volcanic rock formed from the solidification of magma, is indicative of past volcanic eruptions in the region. Andesite is commonly found in tectonic environments characterized by volcanic activity, including both surface and subsurface occurrences such as volcanic necks (Fig. 3).

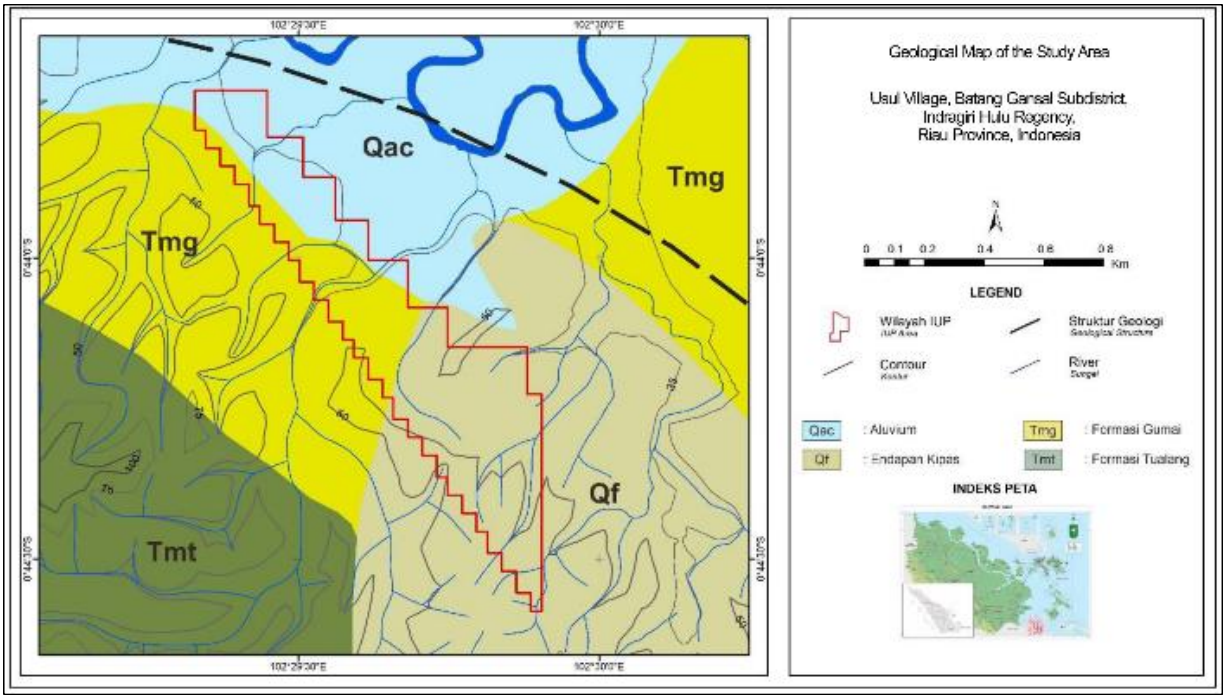

Fig. 3: Geological Map in Desa Usul.

In terms of regional geology, the study area is situated within the larger geological framework of central Sumatra, which is characterized by a complex tectonic history. The Central Sumatra Basin exhibits structural features such as horsts, grabens, and fault systems, which have influenced the deposition and deformation of sedimentary rocks over geological time scales (Heidrick and Aulia, 1993; Kausarian et al., 2023b, 2017; Koesoemadinata, 1981). The region has undergone multiple tectonic phases, including Mesozoic orogeny, Late Cretaceous to Early Tertiary tectonics, and Plio-Pleistocene orogenesis, leading to the development of diverse geological formations.

The lithostratigraphy of the study area comprises several formations, including Aluvium and Coastal Deposits, Fan Deposits, Gumai Formation, and Tualang Formation. These formations represent different depositional environments and geological processes that have shaped the landscape over time. The Alluvium and Coastal Deposits consist of unconsolidated sediments derived from erosion and transportation by rivers and coastal processes. Fan Deposits, on the other hand, represent accumulations of sediment at the base of mountain slopes, often consisting of coarse-grained materials such as sand and conglomerate.

The Gumai Formation primarily consists of shale, mudstone, and limestone, indicating deposition in marine or lacustrine environments. It is characterized by its greenish-gray to brownish-gray coloration and the presence of carbonate minerals. The Tualang Formation, found in the southwestern part of the study area, comprises sandstone and mudstone with interbedded layers of limestone. These sediments were likely deposited in shallow marine environments, reflecting changes in sea level and sedimentation rates over time.

The study area exhibits a diverse range of landforms, including alluvial plains, peatlands, transitional plains, and hills. Elevational gradients vary from 12.5 meters to 350 meters above sea level, indicating significant topographical heterogeneity. Geological mapping reveals the presence of four distinct rock formations: Alluvium and Coastal Deposits (Qac), Fan Deposits (Qf), Gumai Formation (Tmg), and Tualang Formation (Tmt). These formations encompass sedimentary rocks, volcanic materials, and limestone deposits, each with unique lithological characteristics and depositional histories.

Overall, the geological background of the study area provides insights into the formation processes, structural characteristics, and lithological composition of the Andesite quarry slopes. Understanding these geological factors is essential for conducting slope stability assessments, geological mapping, and resource exploration in the research area (Fig. 4).

The geotechnical properties of andesite in Riau Province vary depending on the specific location and formation. Key characteristics include:

- **Unconfined Compressive Strength**: Andesite typically exhibits high unconfined compressive strength, making it suitable for load-bearing applications. Studies indicate that the compressive strength can range from 60 to 150 MPa, depending on mineral composition and porosity (Lenggono et al., 2019).
- **Cohesion and Friction Angles**: The cohesion and internal friction angles of andesite influence its shear strength. Research has shown that the cohesion of andesite can range from 50 to 150 kPa, with friction angles typically between 30° to 40° (Villeneuve and Heap, 2021).
- **Weathering Profiles**: Weathering processes significantly impact the mechanical properties of andesite. The degree of weathering can alter the rock's strength and increase the risk of slope failure. Understanding the weathering profiles is vital for assessing slope stability (Mordensky et al., 2019).

The hydrogeological conditions in the study area are also essential for understanding slope stability. Groundwater movement can influence the stability of slopes by altering pore water pressures and reducing the effective stress on the slopes. The presence of perched water tables or artesian aquifers can exacerbate the risks of landslides, particularly in areas with steep topography (Frans and Nurfalaq, 2019).

The geological context of the Riau Province is critical in the discussion of sustainable quarrying practices. The interaction between geological formations and human activities, such as mining and construction, necessitates careful planning and environmental assessments. Sustainable practices, including reforestation and slope stabilization techniques, are essential to mitigate the environmental impacts associated with quarrying operations (Salgueiro et al., 2020).

Fig 4. Location and Condition of Slopes in the Andesite Quarry Area

4. Result and Analysis

4.1 Slope Stability Analysis Method

The stability of slopes is significantly influenced by the soil's shear strength, determining its ability to resist pressure and potential failure (Carlà et al., 2017; Kolapo et al., 2022; Leng et al., 2023). Slope stability analysis is based on the concept of limit plastic equilibrium, aimed at determining the safety factor against potential landslide occurrences. Fundamental theories governing slope stability employ methods such as the Limit Equilibrium Method, Method of Slice, and Fellenius method. A common approach involves determining the safety factor (F) by comparing the resisting moments to the driving moments induced by applied forces.

$$F = \frac{Rc.Lac}{W.y}$$

Where:

F = Safety Factor

W = Weight of soil (kN)

Lac = Length of Arc (m)

c = Cohesion (kN/m²)

R = Radius of the sliding plane (m)

y = Distance from W to point O (m)

The method used to recommend mining pit slopes in this study is the Limit Equilibrium Method. This method assumes the presence of potential slip planes, where force and moment equilibrium conditions are statically determined (Rao et al., 2024; Sengani and Mulenga, 2020; Timalsina, 2024; Zolkepli et al., 2019). The analysis typically yields the safety factor (SF) against potential landslide planes (Dewi et al., 2022; Ismail et al., 2021; Juliantina et al., 2018).

In accordance with the Ministerial Decree of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018, the recommended slope safety factor (SF) for a single slope is 1.1 with a maximum landslide probability of 50% (Table 1).

Table 1. Slope Safety Factor and Landslide Probability for Mining Slopes (Based on KEPMEN 1827 ESDM, 2018)

Slope Type	Consequences of Failure (CoF)	Static Safety Factor (Min)	Dynamic Safety Factor (Min)	Maximum Probability of Failure (PoF)
Single Slope	Low to High	1.1	1	25-50%
Inter-ramp	Low	1.15-1.2	1	25%
Inter-ramp	Medium	1.2-1.3	1	20%
Inter-ramp	High	1.2-1.3	1.1	10%
Overall	Low	1.2-1.3	1	15-20%
Overall	Medium	1.3	1.05	10%
Overall	High	1.3-1.5	1.1	5%

This table outlines the recommended safety factors and maximum probabilities of failure for different types of slopes in mining operations, based on the Ministerial Decree. It provides guidance for ensuring slope stability and minimizing the risk of landslides.

4.2 Slope Stability Simulation Results

The study on slope stability in the quarry area was conducted at 3 measurement points in each Quarry Block. This was aimed at determining the slope bearing capacity for implementing suitable mining methods in the research area to mitigate any risks during mining activities. The slope stability study involved simulating actual slopes at the mining site using data from drilling, laboratory results, and topography. Slope simulations were carried out using Slide and Geoslope applications to model the slopes for simulation. Slope stability calculations were performed using Bishop and Janbu calculation formulas by creating sliding surfaces on simulated slope areas. Below is the location map used for slope stability measurements in the research area. In Block III, the simulation was conducted on section A-B using drilling data ITB-1 along with its laboratory results (Fig. 5).

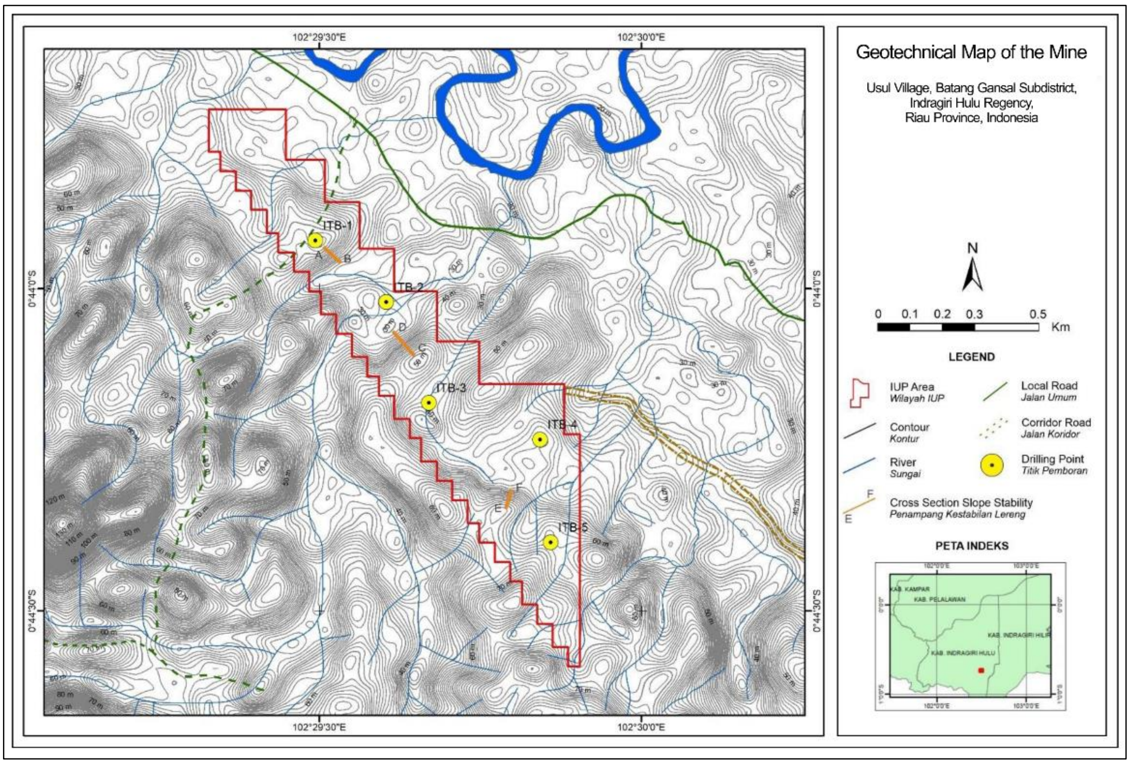

Fig. 5: Map of Slope Stability Simulation in the Andesite Quarry Area

The simulation on this slope was carried out under conditions without seismic factors and loads, only utilizing groundwater factors. From the simulation on slope A-B, a Safety Factor value of 2.614 was obtained, categorized as a very safe slope. Refer to the simulation image on slope A-B below (Fig. 6).

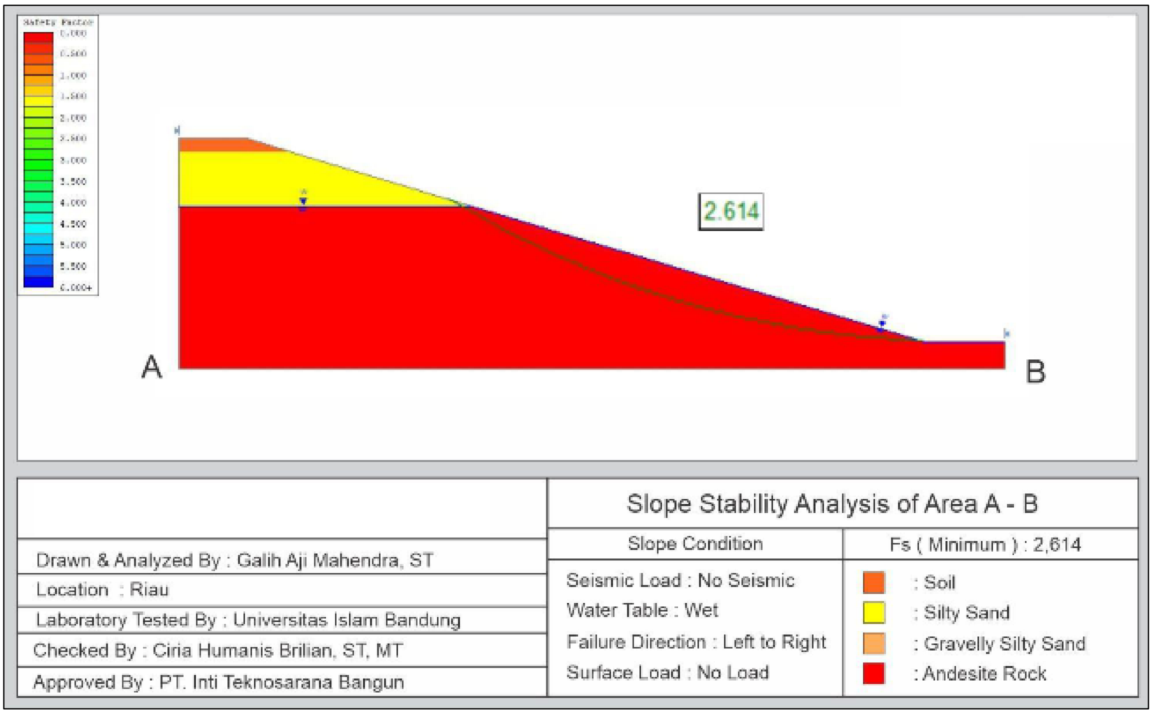

Fig 6. Simulation of Slope Stability in Block III Section A-B

Subsequently, in Block II, the simulation was conducted on section C-D using drilling data ITB-3 along with its laboratory results. The simulation on this slope was performed under conditions without seismic factors and loads, only utilizing groundwater factors. From the simulation on slope C-D, a Safety Factor value of 1.839 was obtained, categorized as a very safe slope (Fig. 7).

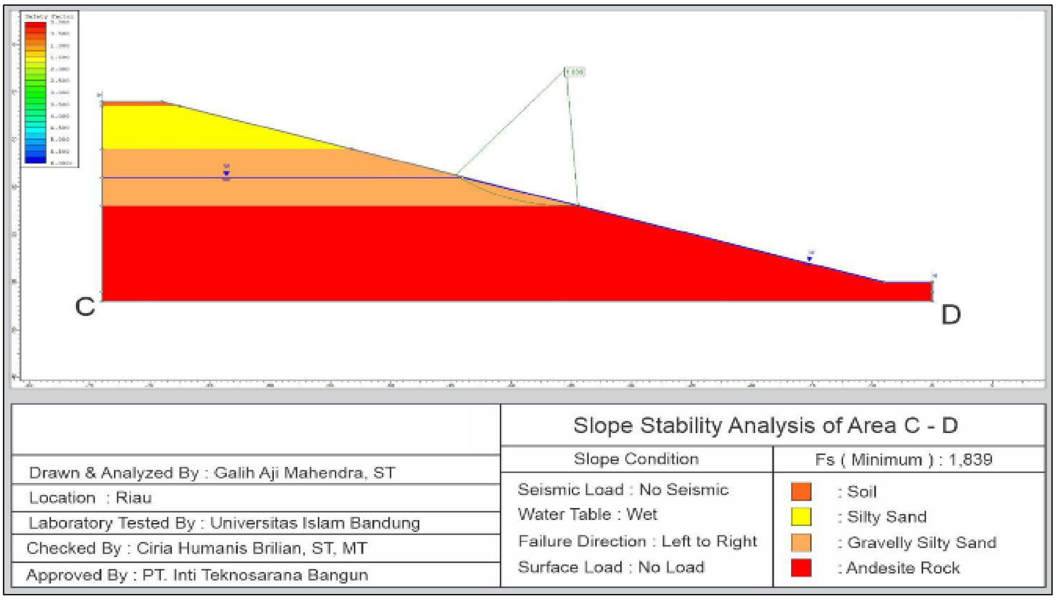

Fig 7. Simulation of Slope Stability in Block II Section C-D.

Lastly, the final simulation was carried out in Block I, namely on section E-F using drilling data ITB-5 along with its laboratory results. The simulation on this slope was conducted under conditions without seismic factors and loads, only utilizing groundwater factors. From the simulation on slope E-F, a Safety Factor value of 1.601 was obtained, categorized as a very safe slope. Refer to the simulation images below for slopes C-D and E-F (Fig. 8).

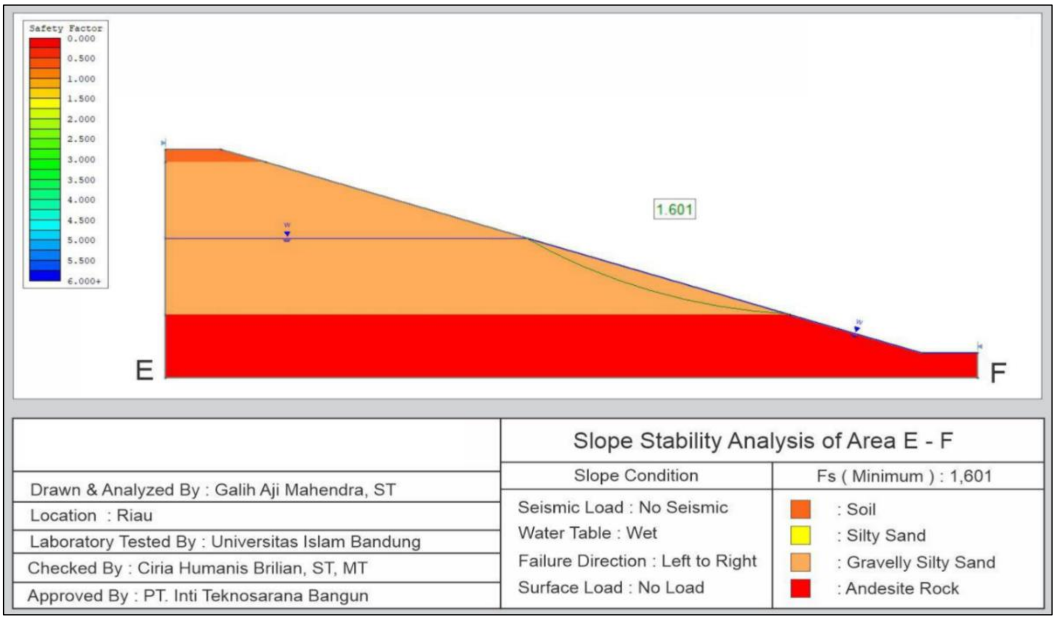

Fig 8. Simulation of Slope Stability in Block I Section E-F

Based on the results of the slope stability simulation in the quarry area, a very safe Safety Factor (FS) value was obtained. Thus, the research area supports the implementation of mining methods such as open cut mining or excavation from the surface to the bottom with specific slope angles.

5. Conclusion

The conclusion of this geotechnical research on Andesite quarry slopes, based on the data and calculated values, underscores the feasibility and safety of mining operations in the researched area. Through meticulous analysis and simulation, it has been determined that the quarry slopes exhibit high levels of stability, thus providing a secure foundation for mining activities. The calculated Factor of Safety (FS) values, derived from rigorous geotechnical calculations and slope stability assessments, consistently indicate favourable conditions for mining operations.

The simulations conducted on various sections of the quarry slopes, including Blocks I, II, and III, have yielded reassuring results, with FS values well above the recommended thresholds for safe mining practices. In Block I, where mining benches were constructed to a depth of 15 meters, the calculated FS of 1.238 demonstrates a robust level of stability, ensuring safe mining operations. Similarly, Blocks II and III exhibit FS values of 0.967 and 1.269, respectively, further confirming the stability and safety of the quarry slopes.

Moreover, the implementation of the open-cut method, supported by meticulous slope design and blasting techniques, enhances the safety and efficiency of mining operations in the Andesite quarry. The careful consideration of slope angles, excavation depths, and bench designs ensures optimal stability while minimizing the risk of landslides or other hazardous incidents during mining activities.

In conclusion, the comprehensive geotechnical analysis presented in this research provides compelling evidence for the suitability of the Andesite quarry slopes for mining operations. With calculated FS values exceeding safety thresholds and robust slope designs in place, the researched area offers a conducive environment for sustainable and secure mining practices, thereby facilitating the extraction of Andesite resources while prioritizing worker safety and environmental integrity.

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