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MORALITY BEFORE KNOWLEDGE

Integration of geotechnical parameters and infrastructure preparedness policy in disaster mitigation in earthquake-prone areas

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ABSTRACT

Background: This study investigates the geotechnical characteristics and seismic response of soils, which lies near the active Seulimum Fault. The research aims to analyze soil behavior under seismic influences through laboratory testing and theoretical calculations. Laboratory tests included determining water content, specific gravity, grain size distribution, and Atterberg limits to classify soil types and evaluate their physical properties. The study also analyzed earthquake acceleration and uplift forces to assess the dynamic response of the soil. **Methods:** Soil samples were collected from a depth of 10 meters and analyzed for moisture content, specific gravity, particle size distribution, and Atterberg limits to determine their geotechnical properties. Earthquake-induced ground acceleration and uplift forces were then calculated to assess soil behavior under seismic loading. All tests followed standard ASTM procedures to ensure reliable and comparable results. **Findings:** Results showed that the soil has an average specific gravity of 2.619 and a plasticity index of 38.42%, indicating a highly plastic clay (CH) with low shear strength and high swelling potential. The maximum ground acceleration reached 0.00236 g, while uplift force increased from 0.82 kg to 7.47 kg over 96 hours, suggesting rising pore-water pressure that can reduce effective stress and stability. **Conclusion:** The findings emphasize the importance of integrating geotechnical results into spatial planning and disaster mitigation policies. This study provides novel insights into linking soil mechanics and seismic risk assessment for infrastructure resilience in earthquake-prone zones. **Novelty/Originality of this article:** This study provides novel insights by integrating laboratory-based geotechnical analysis with seismic response modeling to evaluate soil behavior near an active fault, offering practical guidance for infrastructure resilience and disaster mitigation in earthquake-prone areas.

KEYWORDS: disaster mitigation; earthquake acceleration; geotechnical; specific gravity; water content.

1. Introduction

Indonesia is located within the Pacific Ring of Fire, a seismic belt that encircles the Pacific Ocean and serves as a meeting point for active plates. This makes Indonesia highly susceptible to seismic and volcanic activity (Sabilla et al., 2024; Simanjuntak & Ririmasse, 2021). Consequently, earthquakes and volcanic eruptions frequently occur, with significant impacts on infrastructure, the environment, and the socio-economic well-being of the community (Malawani et al., 2021; Wijayanti et al., 2025). In the context of sustainable development, these geological conditions require a disaster mitigation system that is not

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merely reactive but also proactive, incorporating planning and policies based on scientific data, including geotechnical data (Chaudhary & Piracha, 2021; Chen, 2023). Integrating technical aspects and infrastructure preparedness policies is crucial for reducing potential disaster risks, particularly in earthquake-prone areas such as Aceh Province (Sufri & Lassa, 2024; Sasaki et al., 2025). Aceh is one of the provinces with a long history of earthquakes and tsunamis, especially since the major event in 2004 that shook the entire world. In addition, seismic activity in this region continues to occur to this day, including in inland areas such as Bener Meriah Regency, Central Aceh, and surrounding areas (Iskandar et al., 2022; Jihad et al., 2023). Variable geotechnical soil conditions are an important factor that affects the vulnerability of infrastructure to earthquake vibrations (Sabilla, 2023). One area of interest for study is the Barbate–Paya Kameng Quarry, which is geographically located in an area with high seismic activity potential and has a strategic function as a source of construction materials and an area of local economic development. However, despite its economic potential, this area also faces complex geotechnical and mitigation policy challenges.

Soil and rock characteristics play a major role in determining a region's vulnerability to earthquakes (Ghafoor et al., 2025; Salata & Uzelli, 2022). Parameters such as moisture content, specific gravity, Atterberg limits, sieve analysis, and maximum soil acceleration (amax) can provide an overview of soil stability and the potential for deformation during an earthquake (Arciniegas, 2023). Soil conditions with high water content or high plasticity tend to increase the risk of liquefaction and a decrease in soil bearing capacity (Bidaki & Ghalandarzadeh, 2025). Therefore, laboratory testing of geotechnical parameters is the first step in understanding the actual soil conditions in the study area. The results of these tests are not only important for technical infrastructure planning but also as a basis for disaster mitigation policy-making at the regional level. Meanwhile, from a policy perspective, infrastructure preparedness for earthquakes has not been fully integrated into regional development planning systems, especially in industrial or mining areas such as Quarry Barbate–Paya Kameng.

Many spatial planning and infrastructure development policies do not adequately consider detailed geotechnical conditions and potential local seismic hazards (Soehaimi et al., 2025). As a result, when earthquakes occur, much of the infrastructure is severely damaged or collapses because it was not designed in accordance with local soil characteristics (Sufri & Lassa, 2024). In fact, policies informed by geotechnical studies can determine safe construction zones, the appropriate types of foundations, and the need for proper drainage or slope stabilization systems (Kinde et al., 2024). Therefore, the integration of geotechnical research findings with infrastructure preparedness frameworks is an urgent necessity for earthquake-prone regions in Indonesia, including Aceh. Ideally, earthquake disaster mitigation should not only focus on emergency response but also emphasize prevention and structural preparedness from the planning stage (Nefianto, 2023). This approach aligns with the “build back better” paradigm, which underscores the importance of constructing disaster-resilient infrastructure. In this context, geotechnical data provide the scientific foundation for defining safe design parameters, while infrastructure preparedness policies ensure that these technical insights are effectively translated into regulations, design standards, and construction supervision practices (Çetin & Kirchherr, 2025; Der Sarkissian & Diab, 2022). In the Barbate–Paya Kameng Quarry area, such integration can serve as a model for data-driven mitigation that promotes economic sustainability while ensuring community safety and environmental protection.

Although numerous studies have explored the geotechnical and seismic aspects of quarry areas, most have remained limited to technical stability assessments or numerical modeling without addressing their implications for infrastructure preparedness or disaster mitigation policy. For instance, (Firoozi et al., 2024) developed an integrated geotechnical model for predicting earthquake-induced landslides in the East African Fracture Zone, whereas (Bezie et al., 2024) focused on rock slope stability in limestone quarries using kinematic and finite element analyses. However, these studies did not incorporate policy-oriented disaster preparedness frameworks or evaluate site-specific soil characteristics within a local governance context. Consequently, a gap remains in research that connects quantitative geotechnical parameters with spatial and policy frameworks for disaster mitigation. This study aims to bridge that gap by integrating laboratory-based soil testing results and seismic acceleration analysis with infrastructure preparedness policy for earthquake-prone quarry zones in Aceh Province.

The integration of geotechnical parameters and infrastructure preparedness policies is not merely a technocratic concept but a practical necessity in the field. In practice, many development projects remain overly focused on cost efficiency without adequate consideration of structural resilience against natural hazards. This approach often results in long-term losses far exceeding the initial investment required for geotechnical-based planning. The present research at the Barbate–Paya Kameng Quarry is intended to provide a clear demonstration of the importance of using technical soil data in the early planning process and how these findings can be effectively translated into measurable and actionable mitigation policies. Taking all these aspects into consideration, this study focuses on integrating the results of geotechnical parameter analysis with infrastructure preparedness frameworks to enhance disaster mitigation efforts in earthquake-prone areas. The Barbate–Paya Kameng Quarry was selected as the case study because it represents the complex geological characteristics of Central Aceh and holds strategic significance in the context of regional development. The novelty of this research lies in its interdisciplinary integration of quantitative geotechnical data with spatial and policy frameworks for disaster mitigation. Unlike previous studies that primarily emphasized slope stability analysis or numerical modeling without policy implications, this research explicitly bridges the gap between laboratory-based soil mechanics and practical infrastructure preparedness planning. Through this approach, geotechnical findings are not only used to interpret subsoil behavior but are also contextualized as empirical input for strengthening local disaster management strategies and spatial planning decisions. This study is therefore expected to contribute to the advancement of evidence-based mitigation policies and serve as a scientific reference for both local governments and the private sector in planning earthquake-resilient infrastructure in Aceh Province.

2. Methods

This research was conducted in the Barbate–Paya Kameng Palm Garden Quarry area, Blang Bintang District, Aceh Besar Regency. This location was chosen because it is close to the Seulimum Fault, one of the active faults in Aceh Province that has the potential to cause significant seismic activity. Soil samples were collected from the research site at a depth of 10 meters below the ground surface using disturbed soil samples, which were considered representative of the geological and physical conditions of the study area. Tests were conducted on water content, specific gravity, particle distribution, and Atterberg limits to determine the geotechnical characteristics of the soil. All tests referred to ASTM D2216–98, ASTM D854– 00, and ASTM D4318–00.

2.1 Moisture content test

Soil moisture content represents the volume of water present in the soil voids or pores compared to the dry weight of the soil. This value can be determined through calculations using the following equation (Sulaiman et al., 2025). Based on Eq. 1, Where W represents the water content (%), W1 denotes the weight of the empty dish, W2 indicates the weight of the dish plus wet soil, and W3 refers to the weight of the dish plus dry soil.

$$W = \frac{W2-W3}{W3-W1} x100\% \quad \text{(Eq. 1)}$$

Table 1. Soil type classification based on water content in saturated soil conditions

Soil type	Moisture content in saturated condition (%)
Loose sand with uniform grains	30
Compact sand with uniform grains	16
Loose sand with angular grains	25
Dense sand with angular grains	15
Stiff clay	21
Soft clay	30-50
Soil	25
Soft organic clay	90-120
Glacial till	10

(Asmara & Triarso, 2025)

2.2 *Soil specific gravity test*

Soil specific gravity (Gs) is the ratio between the density of the solid particles that make up the soil and the density of water at the same temperature. This parameter is measured using a pycnometer with the following equation (Li et al., 2020). According to Equation (2), W_1 represents the weight of the pycnometer (g), W_2 denotes the weight of the pycnometer with dry soil (g), W_3 indicates the weight of the pycnometer containing soil and water (g), W_4 refers to the weight of the pycnometer filled with water (g), t_2 represents the temperature after 24 hours, and *Hp* denotes the specific gravity of the pycnometer.

$$G_s = \frac{W2-W1}{Hp+(W2-W1)-t2} \quad \text{(Eq. 2)}$$

Table 2. Classification of soil types based on soil specific gravity values

Soil Type	Specific Gravity (Gs)
Gravel	2.65 – 2.68
Sand	2.65 – 2.68
Inorganic silt	2.62 – 2.68
Organic clay	2.58 – 2.65
Inorganic clay	2.68 – 2.75
Humus	1.37
Peat	1.25

(Asmara & Triarso, 2025)

2.3 *Sieve analysis test*

Dry sieve analysis is a method for determining the particle size distribution of dry materials through a process of sieving and weighing, which is commonly used for granular materials such as sand, gravel, and aggregates. The procedure involves stacking sieves from the largest to the smallest hole size, placing the dry sample on the top sieve, shaking it until the particles separate, and finally weighing the mass of material retained on each sieve to calculate its weight percentage . The percentage of particle fractions retained on each sieve is then calculated using the following equation (Ayal, 2023). According to Equation 3, Where P represents the cumulative retained percentage (%), M denotes the mass of the test object, and R refers to the mass of the retained particles. The following table shows the soil classification based on particle size.

$$P = \frac{M-R}{M} \quad \text{(Eq. 3)}$$

Table 3. Soil classification based on soil particle size

Soil Type	Particle Size (mm)
Clay	<0.0020
Silt	0.0020 – 0.0074
Sand	>0.0074 – 4.7500
Gravel	>4.7500

(Asmara & Triarso, 2025)

2.4 Atterberg limits test

Atterberg limits are used to describe changes in the properties and behavior of finegrained soils due to variations in their water content. This test covers three main parameters , namely the Liquid Limit (LL), which indicates the water content at which the soil changes from a plastic to a liquid state; the Plastic Limit (PL), which determines the moisture content when the soil begins to lose its plastic properties and becomes semi-solid; and the Plasticity Index (PI), which represents the range of moisture content at which the soil still has plastic properties, and its value is obtained through calculation using the following Equation 4 (Dewi et al., 2022). The higher the PI value, the greater the clay mineral content and the higher the plasticity. Based on the classification by Table 4.

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL}\ (\%) \tag{Eq. 4}$$

Table 4. Classification of soil properties, types, and cohesion based on soil PI values

PI	Properties	Soil Type	Cohesion
0	Non-plasticity	Sand	Non-cohesion
<7	Low plasticity	Silt	Partially cohesive
7 – 17	Moderate plasticity	Silt loam	Cohesive
>17	High plasticity	Clay	Cohesive

(Asmara & Triarso, 2025)

2.5 Calculation of earthquake acceleration

The Donovan, Newmark, and Kawashumi empirical equations were selected to represent a range of seismological assumptions and soil conditions. Donovan's formulation emphasizes magnitude–distance relationships derived from historical earthquake records, Newmark's approach is widely applied for engineering-based slope and foundation assessments, and Kawashumi's method accounts for near-source attenuation effects relevant to shallow crustal faults such as the Seulimum Fault. Using multiple formulas allows cross-validation of acceleration estimates and highlights uncertainty inherent in empirical seismic models. The limitation of these approaches lies in their simplified assumptions, which may underestimate local site amplification; therefore, results are interpreted conservatively within a disaster mitigation framework. This determination was made by examining earthquake data and calculating the ground acceleration at the research site relative to the earthquake source. This study was conducted using the earthquake magnitude and the hypocenter distance from the earthquake source to the test site. Earthquake acceleration and earthquake magnitude have an empirical relationship as follows (Munirwansyah et al., 2023). Based on earthquake acceleration data in Papua New Guinea, Japan, and the United States, Donovan (1974) states the relationship as follows (Khalisa et al., 2024).

$$a = \frac{1080e^{0,5\,M}}{(d+25)^{1,52}} \tag{Eq. 5}$$

$$a = \frac{1320e^{0,58\,M}}{(d+25)^{1,52}} \tag{Eq. 6}$$

According to the formula developed by Estevan, which is based on the formulation proposed by A. J. Hendron Jr (Newmark, 1968), the calculation for hard soil conditions, as applied in (Sabilla, 2023), is expressed as follows Equation 7. For equation 8 stated by Kawashumi, it is also an equation to find earthquake acceleration, where M represents the magnitude of the earthquake on the Richter scale, a indicates the acceleration of the earthquake on the ground surface measured in m/s^2, d refers to the distance of the hypocenter from the earthquake source expressed in kilometers, and e is Napier's logarithmic constant.

$$a = \frac{1230e^{0,8\,M}}{(d+25)^2} \quad \text{(Eq. 7)}$$

$$\text{Log a} = \text{M} - 5{,}45 - 0{,}00084(\text{d} - 100) + \log\left(\frac{100}{\text{d}}\right) \text{x} \left(\frac{1}{0{,}43429}\right) \quad \text{(Eq. 8)}$$

The distance of the hypocenter (d) from the epicenter is obtained using the Pythagorean formula by entering the depth of the earthquake (D) and the horizontal distance (R) from the epicenter, as shown in Figure 1. The horizontal distance (R) is obtained by entering the coordinates of the epicenter and the coordinates of O (object). The horizontal distance is calculated using the following equation (Sabilla, 2023). Where φE represents the longitude coordinate of the epicenter (°), φS denotes the longitude coordinate of the object (°), LE refers to the latitude coordinate of the epicenter (°), and LS indicates the latitude coordinate of the object (°).

$$R = \sqrt{(\phi\text{E} - \phi\text{S})^2 + (LE - LS)^2} \quad \text{(Eq. 9)}$$

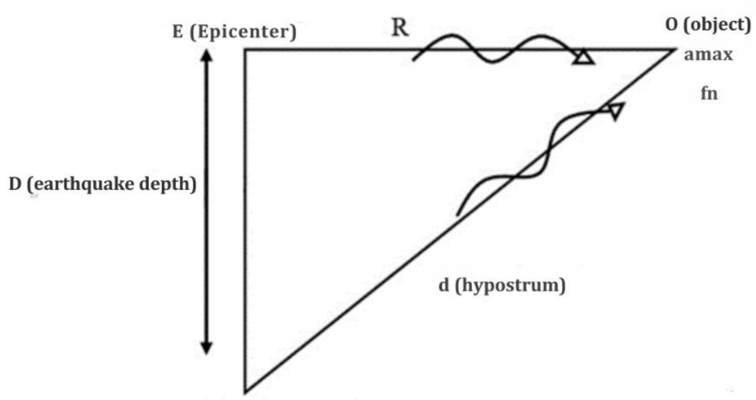

Fig. 1. Illustration of horizontal distance from earthquake epicenter (Sabilla, 2023)

2.6 Calculation of uplift value

The rise and fall of the groundwater level can affect structures built on the ground. Therefore, an assessment is needed to determine whether the ground is experiencing significant uplift and subsidence that the structures above it cannot withstand, or vice versa. This also occurs because the soil is problematic clay with a high swelling value and a very high PI value. To obtain the uplift value, the following formula is used (Sabilla, 2023):

$$Uplift\ Force\ (Kg) = Dial\ reading\ x\ calibration\ number \quad \text{(Eq. 10)}$$

$$\text{Lift Force Unit (kg/cm}^2\text{)} = \frac{Dial\ reading\ x\ calibration\ number}{Mold\ Area} \quad \text{(Eq. 11)}$$

3. Results and Discussion

3.1 Tectonic conditions and research location

The research area is located in the Barbate–Paya Kameng Date Palm Quarry, Blang Bintang District, Aceh Besar Regency, which tectonically belongs to the active Seulimum Fault Zone, one of the segments of the Sumatran Fault Zone. This fault system extends parallel to the island of Sumatra and plays a major role in seismic activity in western Indonesia (Fig. 2). Based on the tectonic structure map of Sumatra–Indian Ocean (Figure 2), it can be seen that Sumatra Island is influenced by two main systems, namely the Sumatran Subduction Zone in the west and the Sumatran Fault Zone on land. These two systems form a complex interaction that is the source of moderate to strong earthquakes, especially in the Aceh, West Sumatra, and Lampung regions. The Sumatra Fault is divided into several active segments, one of which is the Seulimum segment, which crosses the Aceh Besar region towards the southwest. This segment is known to have high seismic activity, with several significant earthquakes occurring in the last two decades.

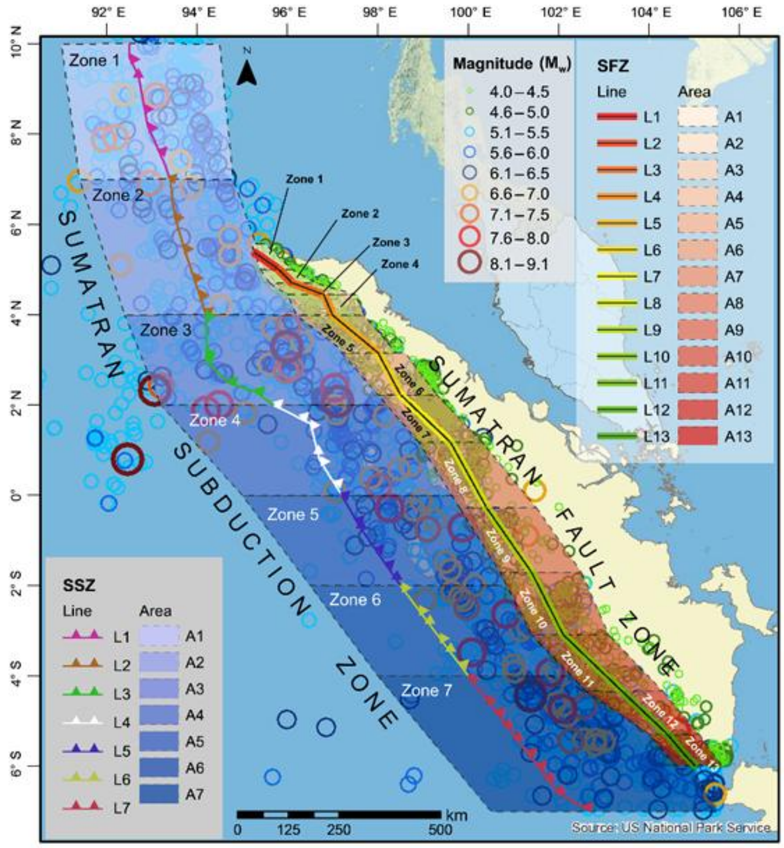

Fig. 2. Tectonic structure of the Sumatra-Indian Ocean region
(Loi et al., 2018)

The research location in the Research location Barbate area is within a radius of several kilometers from the Seulimum segment, so geotectonically this region is included in a zone with a moderate to high level of vulnerability to seismic shocks. The earthquake source used for soil acceleration analysis was taken from the Seulimum Fault segment, with magnitudes varying between 3.0 SR and 6.5 SR and a hypocenter depth of 15 km. This magnitude range was chosen to represent the variation in earthquake energy recorded in the Aceh region, including the 2016 Pidie Jaya earthquake with a magnitude of 6.5, which was used as the main reference. The construction location was taken at the coordinates of the Barbate–Paya Kameng Quarry area, with measurements of the perpendicular distance to the Seulimum fault as the basis for determining the epicentral distance (R) and hypocenter distance (d).

This step was used to obtain soil acceleration values that represent the actual geotechnical conditions in the field.

3.2 Soil physical parameter analysis

3.2.1 Sieve analysis results (grain gradation)

Sieve analysis was conducted to determine the distribution of soil particle sizes at the research location in the Barbate–Paya Kameng Quarry area, Blang Bintang District, Aceh Besar Regency. This test aims to determine the physical characteristics of the soil, which play an important role in the dynamic response of the soil to earthquakes, especially in relation to vibration amplification and the soil's ability to resist water seepage. The results of the soil sieve analysis test from the research location are presented in Table 5.

Table 5. Results of sieve analysis testing

Diameter (mm)	% above	% below
4.76	0	100
2.00	0	97.220
0.84	1.05	91.282
0.42	1.85	87.948
0.25	2.867	82.191
0.177	3.467	72.019
0.149	3.85	68.029
0.105	4.933	60.765
0.074	5.917	53.08

Test results based on Table 5 data show that the percentage of particles passing through a 0.074 mm sieve reached 53.08%, indicating a fairly high content of silt or clay. Meanwhile, no particles were retained in coarse sieves such as 4.76 mm, indicating a minimal gravel component. This gradation distribution shows that the soil has medium to fine sieve characteristics, which can affect the seepage properties, density, and bearing capacity of the soil against infrastructure loads. This condition is important in analyzing infrastructure preparedness for earthquakes, because fine-grained soils tend to have the potential for liquefaction and a decrease in shear strength during seismic vibrations.

3.2.2 Soil specific gravity value

Specific gravity testing is essential for identifying soil's physical characteristics, particularly its mineral composition and particle density. In this study, three soil samples from the Barbate–Paya Kameng Quarry were tested using the pycnometer method to determine the specific gravity (Gs). The results of the specific gravity testing from the research location are presented in Table 6.

Table 6. Results of Soil Specific Gravity Test Analysis

Test No	1	2	3
No piknometer	7	1	21
Empty pycnometer weight (W1)	53.83	58.80	55.53
Weight of pycnometer + dry soil (W2)	79.53	83.40	81.28
Weight of pycnometer + dry soil + water (W3)	169.07	173.63	170.60
Temperature of soil + water mixture (T1)	29	29	29
Weight of pycnometer + water (W4)	152.84	158.20	154.44
Dry soil weight (W2-W1)	79.53	83.40	81.28
Soil particle volume (W4+(W2-W1)-W3)	9.56	9.26	9.68
Gs (at T1 ^{o}C) = (W2/W1)/(W4)+(W2-W1)-(W3)	2,688	2,657	2.660
Correction, K	0.99597	0.99597	0.99597
Gs (at 20 ^{o}C) = Gs (at T1 ^{o}C) x K =	2.613	2,625	2.618
Gs (at 20 ^{o}C) average = /cc	2.619		

From the analysis of soil specific gravity at table 6, the average Gs value obtained was 2.619, with a range of values between samples of 2.613 to 2.625. This value indicates that the soil has a high silicate mineral content with a predominance of fine sand and silt fractions. The relatively stable specific gravity between samples indicates the homogeneity of the soil material at the study site, suggesting that the soil has a fairly good density. This characteristic is important in evaluating the bearing capacity and stability of the soil against infrastructure loads in earthquake-prone areas.

3.2.3 Plasticity index (PI)

Atterberg limit testing was conducted to determine the plasticity properties of fine soil, which plays an important role in assessing soil behavior in response to changes in water content. This parameter includes the liquid limit (LL), plastic limit (PL), and plasticity index (PI), which together indicate the level of cohesion and potential for soil expansion and shrinkage when saturated or dry. The results of the plastisity index from the research location are presented in Table 7.

Table 7. Atterberg limit test results

Liquid Limit (LL)	70.75 %
Plastic Limit (PL)	32.33 %
Plasticity Index (PI)	38.42 %

Test results show that Table 7, the liquid limit (LL) is 70.75%, the plastic limit (PL) is 32.33%, and the plasticity index (PI) is 38.42%. These values indicate that the soil falls into the category of high plasticity clay (CH) according to the USCS classification. Soils with high plasticity have strong cohesion but are susceptible to volume changes and deformation when there are changes in moisture content. These conditions indicate that the soil at the study site is expansive and sensitive to earthquake vibrations, thus requiring special attention in the planning of foundations and drainage systems for infrastructure.

3.3 Dynamic response analysis

Earthquake acceleration analysis is an important component in geotechnical studies to assess soil response to seismic activity. The maximum soil acceleration parameter (amax) describes the intensity of shaking that can affect soil stability and the resistance of surface infrastructure. In this study, earthquake acceleration calculations were performed using several empirical approaches, namely the Donovan, Newmark, and Kawashumi methods, each of which has a different formulation basis for predicting acceleration magnitude based on earthquake magnitude and distance from the source. The results of the dynamis response from the research location are presented in Table 8.

The results of the earthquake acceleration analysis presented in Table 8 indicate that the maximum ground acceleration (amax) at the Barbate–Paya Kameng Quarry research site is relatively low, with a value of 0.00236 g obtained using the Kawashumi method. Although this acceleration is far below the threshold specified in the Indonesian National Standard for Earthquake Resistance (SNI 1726:2019), this does not necessarily imply that the area is free from seismic hazards. In fact, field observations and geotechnical test results reveal that the physical condition of the soil and topography in this area significantly increase its susceptibility to local amplification and secondary seismic effects. The quarry site is located on an open slope with minimal vegetation cover and is positioned adjacent to a major roadway, which makes it particularly vulnerable to deformation and surface instability. The absence of vegetation reduces root cohesion and water retention capacity, thereby facilitating erosion, increased pore water pressure, and slope movement during ground shaking or heavy rainfall.

Table 8. Earthquake acceleration values

Depth (km)	Magnitude	d (Km)	a max (g)			
			Donovan	Donovan (a*2,5)	Newmark	Kawashumi
15	6.5	10,646	0.00026	0.00064	0.00018	0.00236
15	6.4	10,646	0.00024	0.00060	0.00017	0.00188
15	6.3	10,646	0.00023	0.00057	0.00015	0.00149
15	6.2	10,646	0.00021	0.00054	0.00014	0.00118
15	6.1	10,646	0.00020	0.00051	0.00013	0.00094
15	6.0	10,646	0.00019	0.00048	0.00012	0.00075
15	5.8	10,646	0.00017	0.00043	0.00010	0.00047
15	5.6	10,646	0.00015	0.00038	0.00009	0.00030
15	5.4	10,646	0.00013	0.00034	0.00007	0.00019
15	5.2	10,646	0.00012	0.00030	0.00006	0.00012
15	5.0	10,646	0.00011	0.00027	0.00005	0.00007
15	4.8	10,646	0.00010	0.00024	0.00005	0.00005
15	4.6	10,646	0.00008	0.00021	0.00004	0.00003
15	4.4	10,646	0.00008	0.00019	0.00003	0.00002
15	4.0	10,646	0.00006	0.00015	0.00002	0.00001
15	3.8	10,646	0.00005	0.00013	0.00002	0.00000
15	3.6	10,646	0.00005	0.00012	0.00002	0.00000
15	3.4	10,646	0.00004	0.00011	0.00001	0.00000
15	3.2	10,646	0.00004	0.00009	0.00001	0.00000
15	3.0	10,646	0.00003	0.00008	0.00001	0.00000

The geotechnical properties of the soil, characterized by high plasticity and a predominance of fine-grained material, exacerbate this vulnerability. The Atterberg limit test results showed a plasticity index (PI) of 38.42%, indicating a high-plasticity clay (CH) that is highly sensitive to changes in moisture content. Such soils tend to experience significant volumetric changes and plastic deformation under dynamic loading, which can lead to a reduction in shear strength and bearing capacity during an earthquake. As seismic vibrations propagate through this fine-grained, saturated layer, the energy is often amplified near the surface, increasing the likelihood of localized failure. Consequently, light structures, road embankments, and shallow foundations around the site may suffer from cracking, differential settlement, or even partial collapse when subjected to repeated seismic loads. Moreover, the combination of seismic shaking and rainfall infiltration can trigger shallow landslides or slope creep, particularly on the exposed quarry face, where weathering and water seepage continuously weaken the soil mass.

Given these conditions, it is essential to adopt an integrated engineering and mitigation approach in this region. Foundation designs should consider local acceleration values and incorporate soil improvement methods such as compaction, replacement, or stabilization with cementitious materials to enhance shear strength. In addition, the implementation of deep or pile foundations can effectively transfer structural loads to more stable layers beneath the plastic clay zone. Proper surface and subsurface drainage systems are also critical to control water infiltration and prevent excessive pore pressure buildup. Furthermore, reforestation or the establishment of vegetation cover on quarry slopes will help increase stability through root reinforcement and natural water absorption. These combined measures not only align with the safety standards mandated by SNI 1726:2019 but also support sustainable land management practices that reduce disaster risk. Thus, even though the calculated acceleration value is low, the interaction between soil characteristics, topography, and hydrological factors makes the Barbate–Paya Kameng Quarry area an environment with a potentially high local seismic hazard requiring continuous monitoring and adaptive engineering interventions.

3.4 Analysis of uplift forces and their impact on soil stability

The analysis of uplift forces due to earthquakes is directly related to the increase in pore water pressure, which reduces the effective stress of the soil. When the pore water pressure rises significantly, uplift pressure acts upward on the foundation base, potentially causing loss of contact. The results of the uplift analisys from the research location are presented in Table 9.

Table 9. Summary of Uplift Force Values

Time (Hours)	Test Object (kg)
1	0.82
2	1.63
4	2.45
8	2.69
12	2.90
24	3.02
36	3.89
48	5.00
72	6.69
96	7.47

Based on the test results in Table 9, the uplift force values show an increasing trend over time. At hour 1, the uplift force formed was only 0.82 kg, then increased nearly ninefold to 7.47 kg at hour 96. This increase indicates that the pore water pressure in the soil accumulated gradually, causing the upward force on the test object to become greater. This phenomenon indicates that the soil responds dynamically to changes in water pressure, which can affect the stability of the structure above it. The longer the duration of loading and vibration, the higher the pore water pressure generated, thereby increasing the uplift force and potentially reducing the effective stress of the soil under the foundation.

3.5 Integration of geotechnical results with infrastructure preparedness policy

3.5.1 Evaluation of policy and regulatory documents

This study integrates geotechnical test results with spatial planning and disaster mitigation policy documents applicable in the Aceh Besar Regency. Based on a review of the 2012– 2032 Aceh Besar Regency Spatial Plan/*Rencana Tata Ruang Wilayah* (RTRW), the Barbate–Paya Kameng Quarry area is not explicitly mentioned as a zone with earthquake disaster mitigation priority. However, geotechnical test results indicate significant geotechnical vulnerability to seismic vibrations and soil deformation. The Aceh Besar Regency RTRW focuses more on coastal and urban areas as high-risk areas for earthquakes and tsunamis, while mining areas and open hills such as Barbate–Paya Kameng have not received adequate policy attention.

Atterberg limit testing results show a liquid limit (LL) of 70.75%, a plastic limit (PL) of 32.33%, and a plasticity index (PI) of 38.42%, indicating a high plastic clay (CH) soil type. Soil with these characteristics has a high water retention capacity, expands easily when saturated, and loses its shear strength when subjected to earthquake vibrations. Based on SNI 1726:2019, these conditions fall under the category of soil that requires special analysis before being used as a foundation or location for vital infrastructure. However, there are no specific provisions in the RTRW or technical documents of the Regional Disaster Management Agency/*Badan Penanggulangan Bencana Daerah* (BPBD) that mention the importance of soil microzonation mapping based on geotechnical characteristics.

Soil specific gravity (Gs) analysis also shows that the soil at this location has a high silicate mineral content and a predominantly fine grain composition. This value is in the range of medium-density mineral soils, which can provide a greater dynamic response when earthquake waves occur, especially in water-saturated layers. This confirms that the soil conditions at the Barbate–Paya Kameng Quarry have low seismic energy attenuation potential, which needs to be taken into account in the context of risk-based spatial planning. In the RTRW policy document, this area has not been designated as an area with high potential for ground movement or seismic amplification, resulting in a gap between the geotechnical findings and the applicable spatial planning policy.

Furthermore, the results of soil acceleration analysis using the Donovan, Newmark, and Kawashumi methods show that the maximum acceleration (amax) ranges from 0.00003 g to 0.00236 g, depending on the simulated magnitude. The highest value of 0.00236 g indicates the potential for local amplification due to highly saturated plastic clay layers. Although this value is relatively low compared to the national acceleration standard specified in SNI 1726:2019, these results indicate local seismic dynamics that need to be considered in the design of micro-infrastructure in the area. The fact that this area is a bare slope on the edge of a main road adds to the risk of instability, especially when there is a combination of earthquakes and high rainfall, which can increase pore water pressure (uplift).

Meanwhile, the uplift force test results show a significant increase in pore water pressure over time. The uplift force value increased from 0.82 kg in the first hour to 7.47 kg in the 96th hour, with the uplift force unit reaching 0.020 kg/cm^2 or around 1.96 kPa. This increase illustrates a process of increased pore water pressure that has the potential to reduce the effective stress of the soil by more than 30%. This condition is crucial in the context of disaster mitigation because it can cause a loss of contact between the foundation and the subgrade, resulting in structural deformation or even partial collapse of light infrastructure. In the BNPB and RTRW policies, there are no technical guidelines linking changes in pore water pressure due to earthquakes with infrastructure resilience in the field, resulting in a technical policy gap between geotechnical results and applicable mitigation regulations. When compared to the disaster-prone zoning map contained in the Aceh Besar Regency RTRW, the research area is included in the moderate activity zone with a moderate construction control priority. In fact, based on technical results, the soil in the area shows physical characteristics that support earthquake wave amplification and slope instability.

This discrepancy between empirical data and policy zoning has the potential to create hidden risks, especially for road infrastructure, public facilities, and settlements around the quarry area. Therefore, the integration of geotechnical research results with spatial planning and disaster mitigation documents is an urgent need so that development policies can be more based on real risks in the field. Another gap is evident in the institutional and technical aspects of mitigation. The Disaster Management Plan (RPB) and Earthquake Contingency Plan documents belonging to the Aceh Besar District Disaster Management Agency (BPBD) are still macro in nature and do not include micro identification based on soil characteristics and local geological conditions. For example, there are no technical guidelines regarding geotechnical criteria for construction in hilly areas or former quarries. However, based on the results of this study, the geotechnical conditions in these areas show a high dynamic response to changes in water pressure and vibration loads. This indicates the need for a new approach to disaster mitigation policy at the local level that integrates the results of geotechnical laboratory tests into regional spatial planning and infrastructure design.

3.5.2 Integrative recommendations for mitigation

Based on the results of the technical analysis and policy evaluation above, this study proposes a multi-level integration between geotechnical results, preparedness policies, and infrastructure planning. This integration is expected to strengthen the region's resilience to earthquakes, especially in areas that are not yet administratively included in the mitigation priority zone but show significant geotechnical vulnerability. The first recommended step is to compile a microzonation map of local ground acceleration based on geotechnical test parameters. These microzonation maps are important for mapping variations in soil response to earthquakes on a more detailed scale, especially in areas with mining or slope engineering activities such as in Barbate–Paya Kameng. Local governments, through the Public Works and Public Housing Agency/*Dinas Pekerjaan Umum dan Penataan* (Dinas

PUPR) and the Regional Disaster Management Agency (BPBD), can use the results of these maps to determine safe zones, vulnerable zones, and technical criteria for development. The results of the study show that increased pore water pressure and uplift forces play a significant role in reducing soil stability during earthquakes. Therefore, preparedness policies need to adopt geotechnical observation results as early indicators of potential soil instability. An early warning system based on geotechnical data can be developed through monitoring of pore water pressure (piezometers) and soil vibration sensors connected to the regional disaster information system.

From a disaster risk perspective, the identified high-plasticity clay and increasing uplift forces pose direct threats to road embankments, quarry slopes, and light infrastructure near the study area. Even moderate shaking may trigger cracking, differential settlement, or shallow landslides, especially during periods of high rainfall. These conditions can disrupt transportation networks, endanger workers and nearby communities, and reduce emergency accessibility following earthquakes.

This data can then be incorporated into the risk-based RTRW revision process, as mandated by Minister of Agrarian Affairs and Spatial Planning/National Land Agency Regulation No. 1 of 2018 concerning Guidelines for the Preparation of Disaster-Based Spatial Plans. Geotechnical results are not only technical data, but also adaptive policy instruments that support science-based decision making. Soil conditions with high plasticity and significant uplift forces require foundation designs that are appropriate for local parameters. Based on the research results, soil with a PI = 38.42% and an uplift value of 0.020 kg/cm^2 has the potential to experience a decrease in effective stress of up to 30% during high earthquake acceleration. Therefore, shallow foundations for light buildings should be replaced with pile foundations or bored piles that are capable of transferring loads to more stable soil layers. For quarry slopes, the application of retaining walls, subsurface drainage systems, and vegetation cover are strategic measures to control water infiltration and prevent an increase in pore water pressure. In addition to technical aspects, integrating geotechnical results into preparedness policies also requires strengthening regional institutions.

The Aceh Besar Regency Government needs to form a Geotechnical Earthquake Mitigation Technical Team involving academics, geotechnical practitioners, and disaster management agencies. This team will interpret geotechnical research data and convert it into operational policies, such as restrictions on construction on bare slopes, determining safe distances from quarry edges, and monitoring drainage in hilly areas. Through this mechanism, mitigation policies will be more synchronized with physical conditions in the field. The results of this study confirm that the Barbate–Paya Kameng Quarry area should be treated as an area with moderate to high risk of earthquake shock, not only based on macro-seismicity maps, but also because of the physical properties of the soil, which is plastic, saturated, and sensitive to pore water pressure. Therefore, the RTRW and RPB policies of Aceh Besar need to be updated to include local microzonation maps and technical guidelines for development based on geotechnical results. This integration will not only strengthen infrastructure resilience but also improve community preparedness and the effectiveness of risk-based spatial planning in earthquake-prone areas.

4. Conclusions

This study concludes that the Barbate–Paya Kameng Quarry area has a high level of geotechnical and seismic vulnerability due to its location on an active segment of the Seulimum Fault, part of the Sumatran Fault System in the Pacific Ring of Fire. Laboratory test results indicate that the soil at the study site has an average specific gravity of 2.619 and a plasticity index (PI) of 38.42%. It is categorized as high plastic clay (CH) with high shrinkage and swelling potential and is highly sensitive to changes in water content. The maximum ground acceleration (amax) of 0.00236 g and the increase in uplift force from 0.82 kg to 7.47 kg indicate an increase in pore air pressure, potentially reducing effective stress and soil stability. These findings highlight the importance of site-specific geotechnical analysis in earthquake-resistant infrastructure planning.

From a policy perspective, the study reveals a gap between empirical geotechnical data and spatial planning documents (RTRW) and disaster mitigation strategies in Aceh Besar Regency. The study area, technically classified as moderate to high vulnerability, has not been listed as a priority zone for earthquake mitigation. This discrepancy poses hidden risks to infrastructure and public safety, making the integration of geotechnical results into spatial planning and infrastructure preparedness policies essential. This study confirms that geotechnical parameters such as specific gravity, plasticity index, ground acceleration, and uplift have direct implications for infrastructure preparedness in earthquake-prone areas. Integration of technical results with science-based mitigation policies needs to be implemented through microzonation mapping, the development of foundation design guidelines, and the establishment of Geotechnical Mitigation Technical Teams at the regional level. This case study serves as an important example for the implementation of sustainable and disaster-resilient infrastructure development in earthquake-prone areas in Indonesia.

The findings confirm that geotechnical parameters such as plasticity index, pore-water pressure, and local ground acceleration are critical determinants of infrastructure vulnerability in earthquake-prone areas. Beyond technical implications, this study emphasizes the need for integrating geotechnical data into regional spatial planning, microzonation mapping, and disaster mitigation regulations. Policymakers and local governments are encouraged to adopt science-based foundation design guidelines, slope management strategies, and monitoring systems to enhance community safety and long-term resilience.

This study has several limitations, one of which is that the geotechnical analysis conducted is still focused on laboratory test data and does not include numerical modeling or three-dimensional (3D) dynamic analysis that can provide a more comprehensive picture of the soil response to seismic loads. The results of the uplift and acceleration tests were also conducted under controlled laboratory conditions, so they do not fully represent variations in field conditions, especially in areas with lithological heterogeneity and high air content. For further research, it is recommended that further studies be conducted using a numerical modeling approach and GIS-based microzonation mapping to obtain a spatial picture of the potential for earthquake wave amplification and pore pressure distribution. In addition, the development of a real-time pore air pressure and ground vibration monitoring system at mining sites can be an important step in supporting geotechnical data-based mitigation. Collaboration between geotechnical practitioners and policymakers is also expected to strengthen the implementation of this research results in the form of technical guidelines and integrated disaster mitigation policies.

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