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Microzonation of soil resistance using shear wave velocity (V_s) for earthquake disaster mitigation in Singaran Pati District, Bengkulu City

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Abstract

Singaran Pati District, Bengkulu City, is located in an active subduction zone, making it prone to seismic activity. However, to date, there is no detailed microzonation map available to assess local vulnerability to earthquake shocks. This study aims to produce a microzonation map based on shear wave velocity (V_s) and Ground Amplification Factor (GAF) parameters as indicators of soil resistance. Vs values are calculated sequentially at depths of V_{s10}, V_{s20}, V_{s30}, V_{s40}, and V_{s50} using spectral inversion methods. Soil site classification is based on NEHRP standards. Spatial interpolation uses the Inverse Distance Weighting (IDW) method to map parameter distribution. Results show that Vs velocity increases with depth, with a dominance of Class D sites (moderate soil), followed by Class C (very dense soil and soft rock), and a small portion of Class B (moderate rock). The GAF map identifies points with the highest amplification that are at high risk of damage due to earthquakes. The maximum Ground Amplification Factor (GAF) value is shown in red on the map, with a value of 2.0, while the minimum value is shown in green, representing a value of 1.0. This condition indicates that some areas in Singaran Pati Subdistrict have a significant potential for earthquake impact. Therefore, the use of microzonation maps is crucial as a basis for structural building planning and seismic risk mitigation in the Singaran Pati area.

Introduction

The city of Bengkulu is divided into nine subdistricts, one of which is Singaran Pati Subdistrict, which was selected as the research area as shown in Figure (1). This city is known as an area with high seismic activity because it is located in a subduction zone, which is the area where the Eurasian and Indo-Australian tectonic plates meet. The collision between tectonic plates has a significant impact on western Indonesia, one of which is in Sumatra (Zebua, 2018). Friction between the two plates can trigger the formation of active faults, such as the Sumatra fault and the Mentawai fault. Faults often trigger earthquakes that can cause destructive impacts.

Figure 1. Map of Bengkulu City

According to Qodri et al. (2019) in their research, earthquakes that occur in areas close

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to fault lines are more prone to severe damage, even if their magnitude is relatively small. Over the past two decades, there have been numerous earthquakes recorded in Bengkulu City. The first major earthquake, with a magnitude of 8.03, occurred on 4 June 2000 and is known as the Bengkulu-Enggano earthquake. The second major earthquake, with a magnitude of 8.07, occurred on 12 September 2007 and is known as the Bengkulu-Mentawai earthquake (Mase, 2017).

Previous studies have extensively discussed the characteristics of earthquakes in this region, but in-depth and detailed seismic microzonation studies are still limited, especially in integrating local soil dynamic parameters such as shear wave velocity (V_s). Mase (2017) in his research stated that the earthquake that occurred on 12 September 2007 had the highest level of damage, causing severe damage with an intensity scale of 9. As a result of the earthquake, Bengkulu City was paralysed for some time. In order to reduce the impact of earthquakes, it is necessary to conduct research on the potential for seismic hazards in areas prone to earthquakes (Salsabil et al., 2018).

Previous research conducted by Priani et al. (2024), has compared two approaches in seismic response analysis, namely the equivalent linear method and the non-linear method, using earthquake inputs that have been adjusted to local geological conditions. This study aims to deepen the seismic microzonation study in Singaran Pati District, Bengkulu City, through the compilation of soil resistance maps at depths of 10 to 50 meters and the mapping of site class distribution based on V_{s30} values using the Midorikawa (1994) equation.

Shear wave velocity (V_s), particularly the V_{s30} value (average shear wave velocity to a depth of 30 meters), is an important parameter in seismic vulnerability assessment because it represents the strength and dynamic response of the soil to earthquakes. This parameter is widely used to determine soil site classes and calculate the earthquake wave amplification factor (Ground Amplification Factor or GAF), which is crucial in earthquake-resistant building design and disaster mitigation. Microzonation plays a vital role as the foundation for disaster mitigation efforts and safer spatial planning.

Literatur Review

The literature review is divided based on the analysis topics carried out: shear wave velocity (V_s), land location classification, and soil amplification factor (GAF).

Shear Wave Velocity (V_s)

Shear wave velocity (V_s) is one of the main parameters for determining soil dynamics (Susilanto et al., 2018). The V_s value is needed to analyse and evaluate the influence of location above the bedrock layer (Arifudin, 2021). The characteristics of an area in terms of seismic impact potential are generally determined based on the V_s value at shallow surface layers. Shear wave velocity (V_s) can also be used as one of the factors in determining ground amplification (Wibowo & Huda, 2020).

In this study, the V_s values used ranged from V_{s10} to V_{s50}, which refers to the shear wave velocity at depths of up to 50 meters from the surface. The shear wave velocity parameter at depths of up to 30 meters (V_{s30}) plays an important role in estimating ground motion and analysing the impact of local soil conditions on earthquake vibrations (Susilanto et al., 2019). The V_{s30} value is also used to estimate soil site classes based on the National Earthquake Hazard Reduction Program table (NEHRP, 2003). This programme outlines the relationship between V_s values, soil site class classifications, and descriptions of rock layer structures, including the hardness and characteristics of the rocks (Sugianto & Refrizon, 2021).

Classification of Land Sites

Land classification is the grouping of soil types based on their geotechnical properties, with the aim of identifying potential earthquake risks and designing safe building structures. The shear wave velocity at a depth of 30 meters (V_{s30}) is one of the main parameters used as a reference in determining land site classes. This classification refers to standards set by the National Earthquake Hazard Reduction Programme (NEHRP, 2003).

Table 1 shows that there are five categories of site classes, namely site classes A to E, which cover structures ranging from hard rock to soft soil. The grouping is based on the V_{s30} parameter value. The classification is used to identify areas that are susceptible to damage from earthquakes and areas that are relatively safe. Soil with a V_s value below 180 m/s is classified as soft soil (E). If the V_s value is in the range of 180–360 m/s, the soil is classified as medium soil (D), while a V_s value between 360–760 m/s is classified as very dense soil and soft rock (C). For rocks, a V_s value between 760–1500 m/s is classified as medium rock (B), and a V_s value exceeding 1500 m/s is categorised as hard rock (A).

Table 1. Classification of land sites based on V_{s30} (NEHRP, 2003)

Site Class	Description	V_{s30} (m/s)
A	Hard rock	$V_{s30} > 1500$
B	Medium rock	$760 \leq V_{s30} \leq 1500$
C	Very dense soil and soft rock	$360 \leq V_{s30} \leq 760$
D	Medium soil	$180 \leq V_{s30} \leq 360$
E	Soft soil	$V_{s30} < 180$

Source: National Earthquake Hazard Reduction Program (NEHRP, 2003)

Ground Amplification Factor (GAF)

GAF shows significant differences between soil layers. In other words, seismic waves will experience amplification when propagating through a softer medium compared to the previous medium. The greater the difference in soil characteristics, the higher the GAF value generated (Demulawa & Daruwati, 2021).

GAF is calculated based on the V_{s30} value, which represents the geological conditions of an area, thereby providing an overview of the characteristics of the soil layers at the surface (Janah et al., 2022). GAF and V_{s30} are two important parameters in seismology that are interrelated and can be used to estimate the intensity of earthquakes at the ground surface. GAF indicates the influence of soil conditions on earthquake wave amplification, while V_{s30} indicates soil stiffness (Rahman et al., 2024).

GAF and V_{s30} values have an inverse relationship. Areas with low GAF values are generally located in regions with high V_{s30} values, and vice versa. Areas with low GAF values are mostly located in high-altitude or hilly regions. Conversely, high GAF values have the potential to amplify seismic waves, so that during an earthquake, the effects on the surface can include longer earthquake durations and greater levels of damage (Janah et al., 2022).

Research Methods

The flow chart of this study can be seen in Figure (2). The research began with a literature study as a theortical basis, followed by the collection of geological data, soil profiles, and shear wave values. Geological data included rock structure, formation, and tectonic conditions, while soil profiles showed the composition and thickness of subsurface layers. V_s values were used as the main analysis parameters. Data processing was performed using technical equations to ensure the accuracy of calculations. The results were interpreted and visualised in V_s value distribution maps (V_{s10}, V_{s20}, V_{s30}, V_{s40}, V_{s50}), soil site classification, and ground amplification factor (GAF). Visualisation was performed using ArcGIS with the IDW interpolation method for spatial representation.

Geological Conditions and Research Location

Figure (3) shows that the Singaran Pati subdistrict is formed from two types of geological formations, namely Qa (alluvium) and Qat (terrace alluvium). The Qa formation consists of various components such as boulders, gravel, mud, sand, and clay. Meanwhile, the materials forming Qat consist of silt, sand, gravel, and clay (Farid & Mase, 2020). The seismic vulnerability index (K_g) of Bengkulu City is very high, especially in areas composed of sand, clay, silt, and swamps. This geological configuration, which is part of the Qat formation, nearly covers the entire Singaran Pati District (Sugianto & Refrizon, 2021).

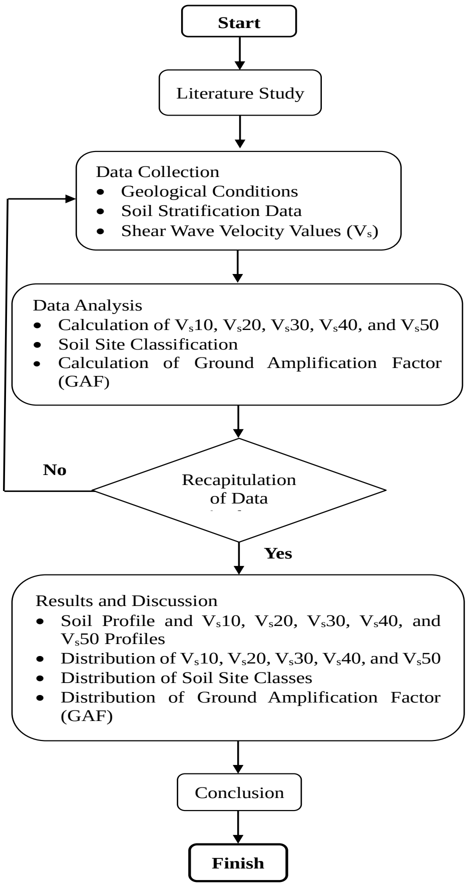


Figure 2. Research flow chart

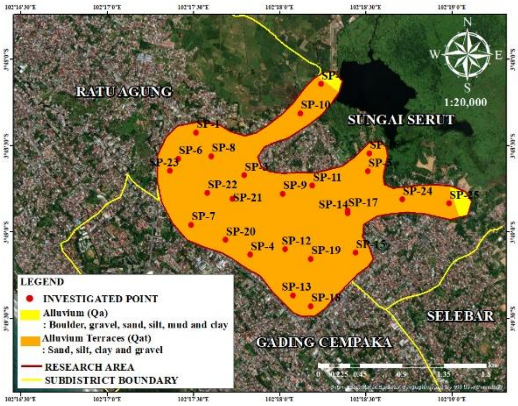


Figure 3. Geological map and research location map

The government has designated Singaran Pati Subdistrict as the administrative center of the subdistrict, which also serves as a center for trade in goods and services, public services, and as the main location for defense and security affairs. In addition, Singaran Pati Subdistrict is also positioned as a health service center that serves the medical needs of the local community (Priani et al., 2024).

There are 25 research points spread across the Singaran Pati District, Bengkulu City, of which 6 points were selected to be representative based on the number of sub-districts in the area. The research sites are denoted by SP, where SP-3 represents Panorama Village, SP-10 represents Dusun Besak Village, SP-12 represents Lingkar Timur Village, SP-14 represents Padang Nangka Village, SP-23 represents Jembatan Kecil Village, and SP-24 represents Timur Indah Village.

Data Collection

Data on soil stratification and shear waves were obtained from secondary data derived from geotechnical investigations. Based on previous studies, these data were obtained through microtremor measurements, which were then analyzed using the inversion method with the Monte Carlo Simulated Annealing algorithm. The soil stratification data obtained includes several parameters, such as the thickness of each soil layer (h), soil bulk density (γ), and average shear wave velocity (V_s). As shown in Figure (3), the study was conducted at several microtremor measurement points, with a total of 25 research points.

Data Analysis

Data analysis is the process of processing and interpreting data to obtain useful information. In the context of soil resilience microzonation, data analysis can include data collection, data processing, and data interpretation.

Shear Wave Velocity (V_s)

Shear wave velocity (V_s) is used to measure the stiffness of soil and rock, as well as to estimate soil response during earthquakes (Sari et al., 2024). In addition, the V_{s30} value plays a role in determining site classes by grouping soil types and geological layers. V_{s30} is also used to calculate the amplification factor, which is then used in the microzonation process to map areas based on the level of potential seismic risk impact. The V_{s30} calculation can be obtained through the following equation:

$$V_{s30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{hi}{vi}\right)} \quad (1)$$

Description:
H_i : thickness of layer i (m)
v_i : shear wave velocity in layer i (m/s)
N : number of layers

Classification of Land Site Classes

Site classification or soil type can be determined using V_{s30} data, which is then compared to the categories listed in the NEHRP table (Table (1)).

Ground Amplification Factor (GAF)

The GAF score is calculated based on the V_{s30} value using Eq. (2) from Midorikawa (1994).

$$Log\left(GAF\right) = 1,35 - 0,47 Log V_{s30} \pm 0,18 \quad (2)$$

Description :
GAF : ground amplification factor
V_{s30} : shear wave velocity at a depth of 30 m (m/s)

Results and Discussion

This study produced soil stratification profiles and shear wave velocity profiles at depths of 10 m, 20 m, 30 m, 40 m, and 50 m, distribution maps of V_{s10}, V_{s20}, V_{s30}, V_{s40}, V_{s50}, distribution maps of soil site classes, and distribution maps of *ground amplification factor* (GAF).

Soil Stratification Profile and Shear Wave Velocity Profile (V_{s10}, V_{s20}, V_{s30}, V_{s40}, V_{s50})

Figure (4) shows the soil layer profile graph and shear wave velocity distribution at representative measurement points. These points represent the number of villages in Singaran Pati Subdistrict, namely SP-3, SP-10, SP-12, SP-14, SP-23, and SP-24. These points provide an overview of the soil characteristics, particularly regarding the variation in shear wave velocity (V_s) measured at each point. The measurement results indicate that V_s varies at each point, depending on the physical properties and conditions of the soil or rock at a specific depth.

The analysis results show that the shear wave velocity varies at each depth. At a depth of 10 meters (V_{s10}), the velocity ranges from 189.68 m/s to 504.62 m/s. At a depth of 20 meters (V_{s20}), the value ranges from 232.81 m/s to 537.65 m/s.

Meanwhile, at a depth of 30 meters (V_{s30}), the velocity ranges from 257.68 m/s to 555.02 m/s. At a depth of 40 meters (V_{s40}), the shear wave velocity is in the range of 303.56 m/s to 677.41 m/s, while at a depth of 50 meters (V_{s50}), the velocity ranges from 350.85 m/s to 784.06 m/s.

Analysis of soil stratification profiles and shear wave velocity (V_s) profiles indicates that V_s values tend to increase with depth. This increase occurs because as the soil or rock becomes deeper, its material structure becomes denser and more compact, allowing shear waves to propagate more quickly.

Research conducted by Makmur et al. (2019) supports this finding, explaining that increased rock density results in a denser and stronger structure, thereby increasing shear wave velocity.

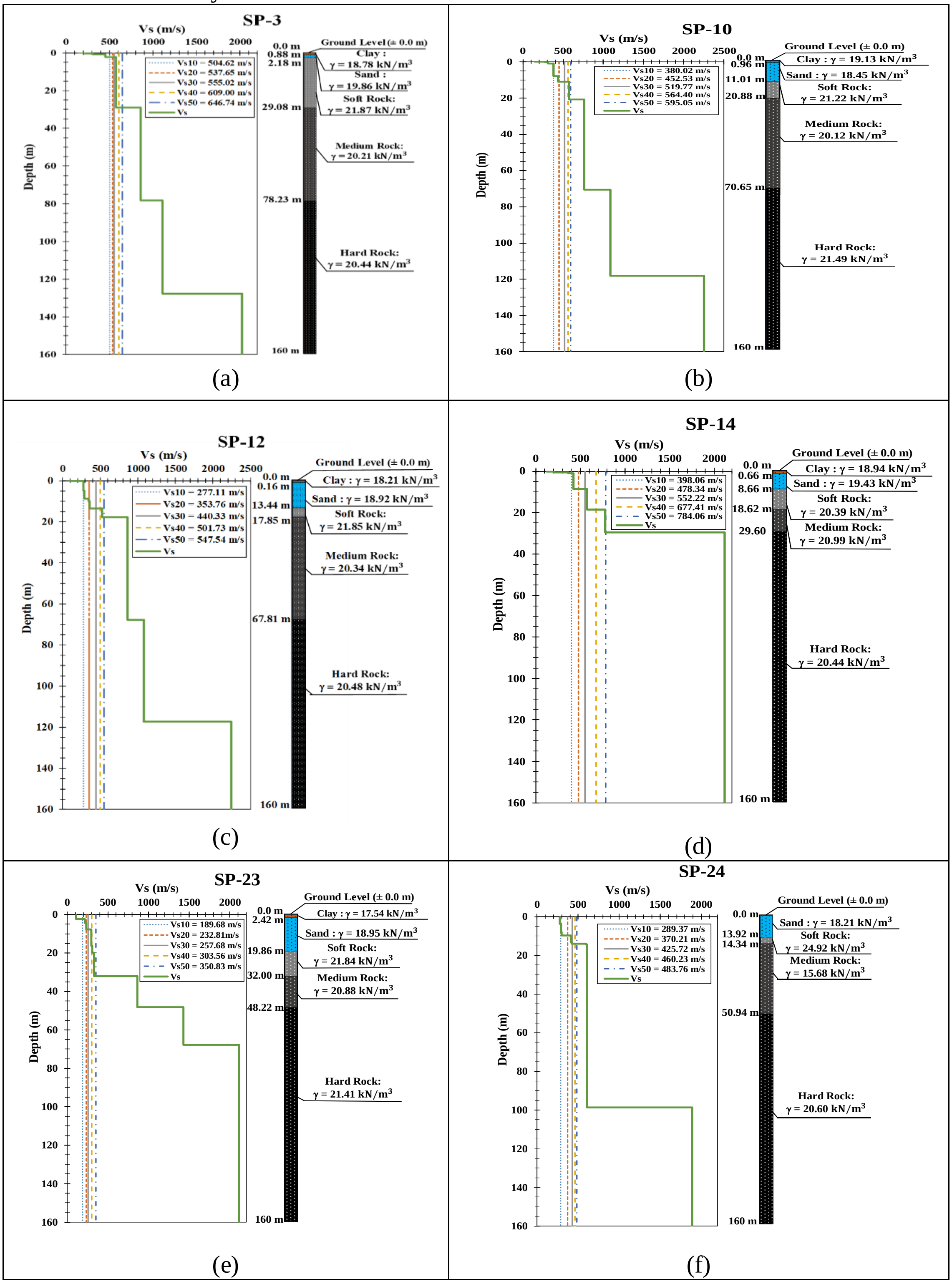


Figure 4. Soil stratification profile and average shear wave velocity profile at depths of 10 m to 50 m at points (a) SP-3, (b) SP-10, (c) SP-12, (d) SP-14, (e) SP-23, and (f) SP-2

Distribution of V_{s10}, V_{s20}, V_{s30}, V_{s40}, and V_{s50}

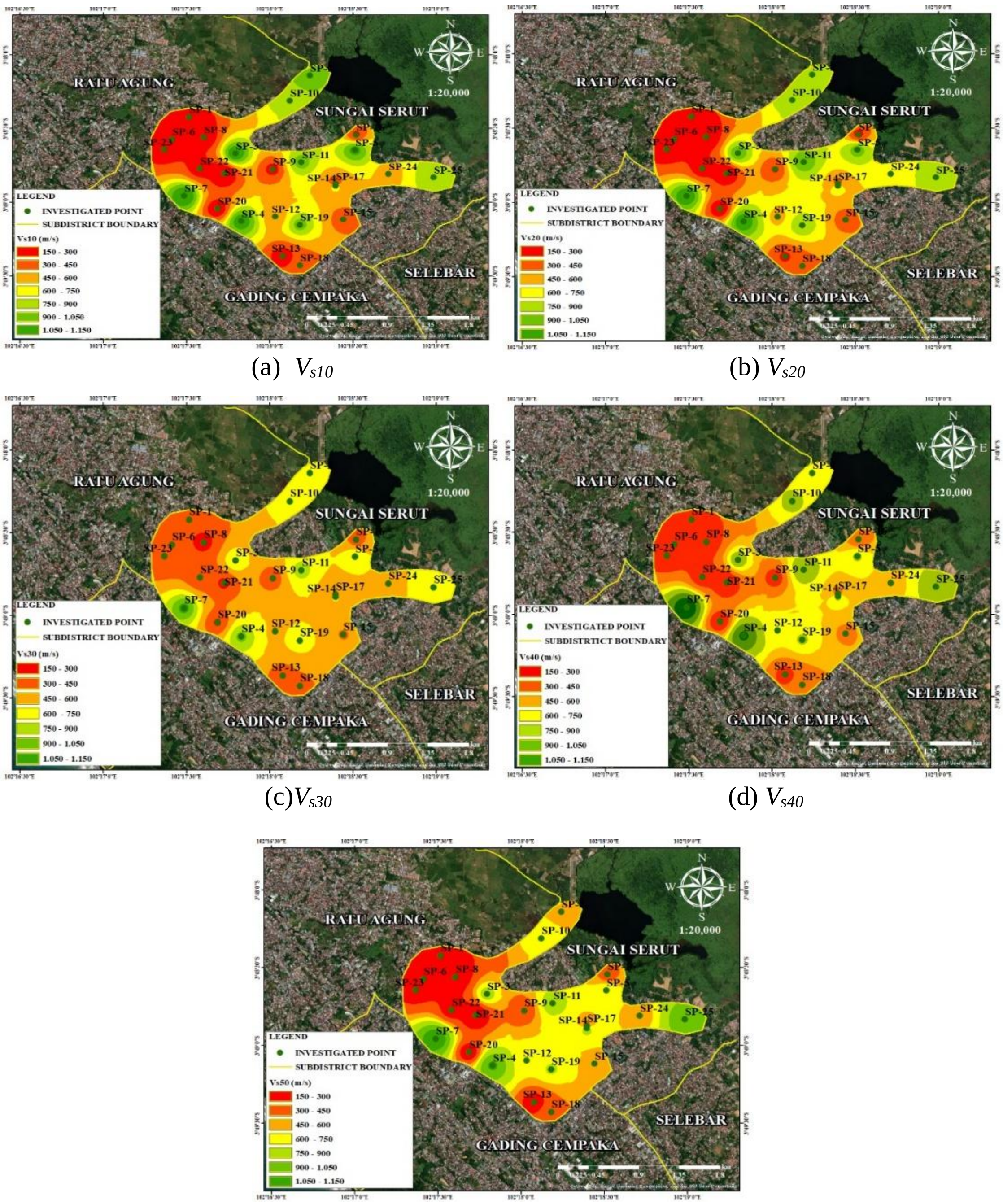
Distribution of V_{s10}, V_{s20}, V_{s30}, V_{s40}, and V_{s50} represent the results of shear wave velocity. The results of shear wave velocity (V_s) measurements with depth variations ranging from 10 m, 20 m, 30 m, 40 m, and 50 m (V_{s10}, V_{s20}, V_{s30}, V_{s40}, and V_{s50}) located in Singaran Pati District, Bengkulu City, can be used to describe the properties of soil and rock, including the level of soil resistance in the study area. Figure (5) shows a map of the distribution of shear wave velocity at the research location. As seen on the map, red to dark orange colours indicate areas with low V_s values, meaning that the soil in those areas tends to be softer. Meanwhile, areas with light orange, yellow to green colours indicate an increase in V_s values compared to the previous area, and light green to dark green colours reflect higher V_s values, indicating that the soil in these areas is denser and harder. In general, an increase in shear wave velocity (V_s) usually indicates that the soil or rock material becomes denser and stronger with increasing depth. This condition also affects the soil's ability to absorb and transmit earthquake waves, where denser layers generally have higher wave speeds.

Based on the analysis results, the shear wave velocity at a depth of 10 meters (V_{s10}) ranges from 134.63 m/s to 520.76 m/s. The shear wave velocity at a depth of 20 meters (V_{s20}) ranges from 179.45 m/s to 619.07 m/s. The shear wave velocity at a depth of 30 meters (V_{s30}) ranges from 208.16 m/s to 792.85 m/s. The shear wave velocity at a depth of 40 meters (V_{s40}) ranges from 243.20 m/s to 938.10 m/s, and the shear wave velocity at a depth of 50 meters (V_{s50}) ranges from 257.19 m/s to 1053.95 m/s.

Distribution of Land Site Classes

The classification of soil site classes can be determined based on the V_{s30} value with reference to Table (1), which is the provision of the *National Earthquake Hazards Reduction Program* (NEHRP, 2003). Based on the analysis results as shown in Figure (6), the study area is divided into three main site classes, namely class B, class C, and class D. Of the 25 research points studied, there is 1 point that falls into site class B, symbolised by the colour green, namely point SP-7 with a V_{s30} value range of 760 m/s to 1,080 m/s, meaning that the soil in that area is medium rock. There are 11 points classified into Class C, symbolised by yellow, namely points SP-2, SP-3, SP-4, SP-5, SP-10, SP-11, SP-12, SP-14, SP-19, SP-24, and SP-25, with a V_{s30} value range between 360 m/s and 760 m/s, meaning that the soil in these areas is classified as hard soil, very compact, or soft rock. The most dominant site class is Class D, with 13 points symbolised by the colour red, namely points SP-1, SP-6, SP-8, SP-9, SP-13, SP-15, SP-16, SP-17, SP-18, SP-20, SP-21, SP-22, and SP-23 with a V_{s30} value range between 180 m/s and 360 m/s, meaning that the soil in this area is classified as medium soil.

According to the NEHRP table, soils classified as Site Classes B and C typically have higher stability due to their composition of denser soil or rock materials. This makes them more resistant to seismic vibrations and reduces the potential impact of earthquakes. Conversely, site class D, which is dominated by soils with lower density, tends to be more susceptible to seismic vibration amplification. This condition increases the likelihood of stronger shaking and greater earthquake impact in the area. These results are in line with research Susilanto et al. (2018), which revealed that areas with high V_{s30} values tend to be more stable during earthquakes. This is due to the denser soil, which is able to dampen vibrations more effectively. Conversely, areas with low V_{s30} values, which generally consist of clay and soft rock, are more susceptible to earthquake wave amplification. These types of soil allow for the amplification and reflection of seismic waves, thereby increasing the intensity of shaking in the area.



(a) V_{s10} (b) V_{s20}

(c) V_{s30} (d) V_{s40}

(e) V_{s50}

Figure 5. Distribution Map

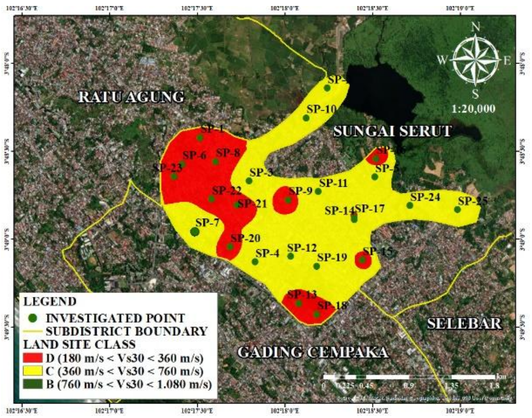


Figure 6. Soil site class map

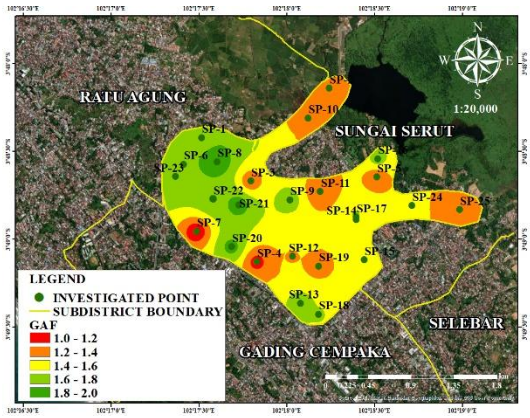


Figure 7. GAF map

Distribution Map Ground Amplification Factor (GAF)

Figure (7) shows a map of GAF distribution with a value range of 1.0 to 2.0. Low GAF values are symbolised by red, orange, and yellow colours with a value range of 1.0 to 1.6. High GAF values are represented by light green and dark green colours, with a range of 1.6 to 2.0. The highest GAF values are found at three points, namely SP-8, SP-20, and SP-21, with GAF values reaching 2.0. The GAF map provides important information for understanding how soil properties in an area can affect the intensity of vibrations, either by amplifying or dampening them due to wave amplification.

According to Bustari & Wibowo (2023), areas with low V_{s30} values tend to have high GAF values. This means that when earthquake waves reach the surface in areas with such soil characteristics, the amplitude of the shaking increases, resulting in greater perceived earthquake energy. Therefore, areas with high GAF values have a greater risk of damage from earthquakes.

Based on the provisions of NEHRP (2003) and Midorikawa's reference (1994), areas with high GAF values and low V_{s30} values have the potential to experience greater peak ground acceleration due to amplification. Structural planning in class D site areas and GAF values > 1.6 must be adjusted to increase the safety factor. In this context, technical recommendations include the use of deep foundations, seismic damping systems, and structural element reinforcement in accordance with the Guidelines for Earthquake Resistance Design of Buildings and Non-Buildings (SNI 1726:2019).

When compared to similar research results in the Central Bengkulu and North Bengkulu City areas (Sugianto & Refrizon, 2021; Bustari & Wibowo, 2023), the V_{s30} value in Singaran Pati District is classified as moderate to high. Most of the study sites fall into Class D and C, similar to other areas with alluvial formations and soft rocks. However, the GAF values in Singaran Pati show significant variation, with some sites reaching a GAF value of 2.0, slightly higher than the maximum GAF value of 1.8 reported in the eastern Bantul region by Bustari & Wibowo (2023). This indicates that the local soil characteristics in Singaran Pati may provide greater amplification of seismic waves, even though the geological formations are similar.

Conclusion

This study produced soil stratification profiles and shear wave velocity profiles at depths of 10 m, 20 m, 30 m, 40 m, and 50 m, a map of shear wave velocity (V_s) values, a map of soil site classes, and a map of ground amplification factor (GAF) in Singaran Pati District, Bengkulu City. Based on the maps produced, it can be concluded that the area has varying levels of soil resistance, with a dominance of site class D (medium soil), C (hard soil, very dense, and soft rock), and a small portion of site class B (medium rock). Areas with site class D tend to have a higher potential for seismic impact due to high vibration amplification, while site classes C and B have better resistance to seismic shocks. Points with high GAF values indicate a greater risk of structural damage in the event of an earthquake. Therefore, special attention is required in the planning and design of buildings in this area.

Mitigation strategies that can be implemented include the use such as the use of deep foundations, structural reinforcement with earthquake-resistant materials, and following design guidelines in accordance with SNI 1726:2019. Local governments need to use this microzonation data as a reference in technical regulations for development and mitigation priorities. Further research is expected to cover a wider area and a denser number of observation points. It is also recommended that further research develop a V_{s30} and GAF-based PGA predictive model to estimate structural response to various earthquake scenarios, and link microzonation results with spatial analysis of building damage risk.

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