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Microzonation of Soil Resistance Based on Shear Wave Velocity Variation: Case Study of Kampung Melayu District, Bengkulu City

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Abstract

This research presents a unique microzonation map based on shear wave variations, specifically V_{s10}, V_{s20}, V_{s30}, V_{s40}, and V_{s50}. Microzonation is dividing a region into smaller zones based on specific characteristics, such as soil resistance to seismic waves. The method used in this research includes secondary data collection of shear wave velocity values and soil layers in the District of Kampung Melayu, then producing shear wave velocity distribution at various depths, soil site class distribution map, and Ground Amplification Factor (GAF) distribution map. The results of this study indicate that the variation in shear wave velocity at different depths provides an overview of the soil type resistance in Kampung Melayu District, Bengkulu City. The resulting microzonation map, a novel approach in this context, indicates an increase in the V_s value with increasing depth. Additionally, the Ground Amplification Factor (GAF) distribution reveals that areas with low soil-specific resistance exhibit higher amplification values, thereby increasing their susceptibility to seismic vibrations. These findings provide valuable and novel information for earthquake risk mitigation and the planning of safer infrastructure in this area, significantly contributing to civil engineering and urban planning.

1. Introduction

Bengkulu Province is situated in the western part of Sumatra Island, which is prone to earthquakes. The capital of the province is Bengkulu City. From a seismological perspective, Bengkulu City is classified as an area of intense earthquake activity in Indonesia (Figure 1). This is due to the confluence of the Eurasian, Indo-Australian, and Pacific plates. Mase (2022) mentioned that the interaction between these plates triggered several significant earthquakes, including the 7.9 earthquake on 4 June 2000 and the 8.6 earthquake on 12 September 2007. According to Mase (2020), the 2007 earthquake caused more damage than previous earthquakes and is considered the controlling earthquake in the Bengkulu City area. These earthquakes trigger geotechnical phenomena such as ground failure, liquefaction, and structural damage (Mase, 2018). Mase (2022) mentioned that the threat of earthquakes remains a problem in Bengkulu City, and the trauma experienced by the local community significantly affects the development of building structures due to concerns over the risk of building collapse. Learning lessons from these earthquakes, research in Bengkulu Province focuses on the Bengkulu City region (Mase, 2018).

Bengkulu City has nine districts with various geological conditions. This research focuses on the Kampung Melayu District, located in the coastal part of Bengkulu City. Kampung Melayu District has an area of approximately 892 hectares, equivalent to 8.82 square kilometres. Kampung Melayu District is located in the eastern region of Bengkulu City. According to the Statistics Agency of Bengkulu Municipality (2024), the topography is dominated by flat areas with altitudes ranging from 3 to 18 meters above sea level in Kampung Melayu, which has a population of 51,953. Kampung Melayu District is a mixed-use area comprising a port, offices, schools, and residential areas. Earthquakes often cause severe damage to buildings, primarily residential buildings (Mase et al., 2023). The subdistricts in this district are Kandang Subdistrict, Kandang Mas Subdistrict, Padang Serai Subdistrict, Muara Dua Subdistrict, Sumber Jaya Subdistrict, and Teluk Sepang Subdistrict.

The dominant formation in Bengkulu City is the alluvium terrace (Qat), which is spread along the coast. This formation consists of sand, silt, clay, and various rock types. In addition, a small portion of reef limestone (QI) is also found in the coastal area. Alluvium (Qa) is generally found in the central part of the city and is composed of boulders, pebbles, sand, silt, mud, and clay. In the west and north of the town, swamp deposits (Qs) consist of sand, silt, mud, clay, and plant remains. Small parts of the andesite (Tpan) and the Bintunan formation (QTb) formations are also found, dominated by conglomerate and polymictic igneous rocks (Farid & Mase, 2020).

The geological conditions of Kampung Melayu District, as depicted in Figure 2, are primarily characterised by alluvium terrace (Qat) sediments in green and reef limestone (QI) in red. These soft and unconsolidated characteristics render the area highly susceptible to seismic wave amplification, emphasising the criticality and urgency of this research. Understanding the potential amplification that seismic waves can cause is of paramount importance, especially in the wake of the 2007 Bengkulu-Mentawai Earthquake, which triggered several liquefaction events along the Bengkulu City coast, particularly in areas dominated by alluvium terrace formations. Liquefaction, a phenomenon in which saturated soil loses its strength and behaves like a liquid, can cause significant damage to buildings and infrastructure (Mase, 2017). According to Mase et al. (2021), sandy soils at 0.4 to 3 m are highly susceptible to liquefaction. Mase et al. (2022) explain that the sandy layer is critical during strong earthquakes because the pore water pressure can reach a limit that triggers liquefaction.

Previous research has focused on the possible impacts of earthquakes by analysing microtremor measurements in the Bengkulu City area (Farid and Mase, 2020; Mase, 2017, 2018, 2020; Refrizon and Mase, 2021). In a recent study, the liquefaction potential in Bengkulu City was analysed with a case study in Kampung Melayu District (Misliniyati et al., 2025). Kamal et al. (2024) also researched the city of Bengkulu, including Kampung Melayu District, by analysing the two-dimensional map modelling of soil parameters. Fikri et al. (2025) recently proposed a three-dimensional model for subsoils in Bengkulu City, incorporating their engineering properties.

In this study, the first is to analyse more deeply the variation of shear wave velocity with depth variations of 10 m (V_{s10}), 20 m (V_{s20}), 30 m (V_{s30}), 40 m (V_{s40}) and 50 m (V_{s50}) with different soil resistance at each depth, where shear wave velocity (V_s) is one of the important parameters in geotechnical analysis and seismicity that describes the ability of soil to transmit shear waves due to earthquakes. The second step is to classify the soil site. The third is to analyse the soil amplification factor (GAF). The fourth part presents the mapping of the analysed results of shear wave velocity variation, site class, and ground amplification factor (GAF) in Kampung Melayu District. The soil resistance to earthquakes depends on the value of shear wave velocity (V_s), the interaction between soil layers, and the amplification factor. Understanding soil resistance at different depths is crucial for assessing seismic hazards and designing earthquake-resistant infrastructure.

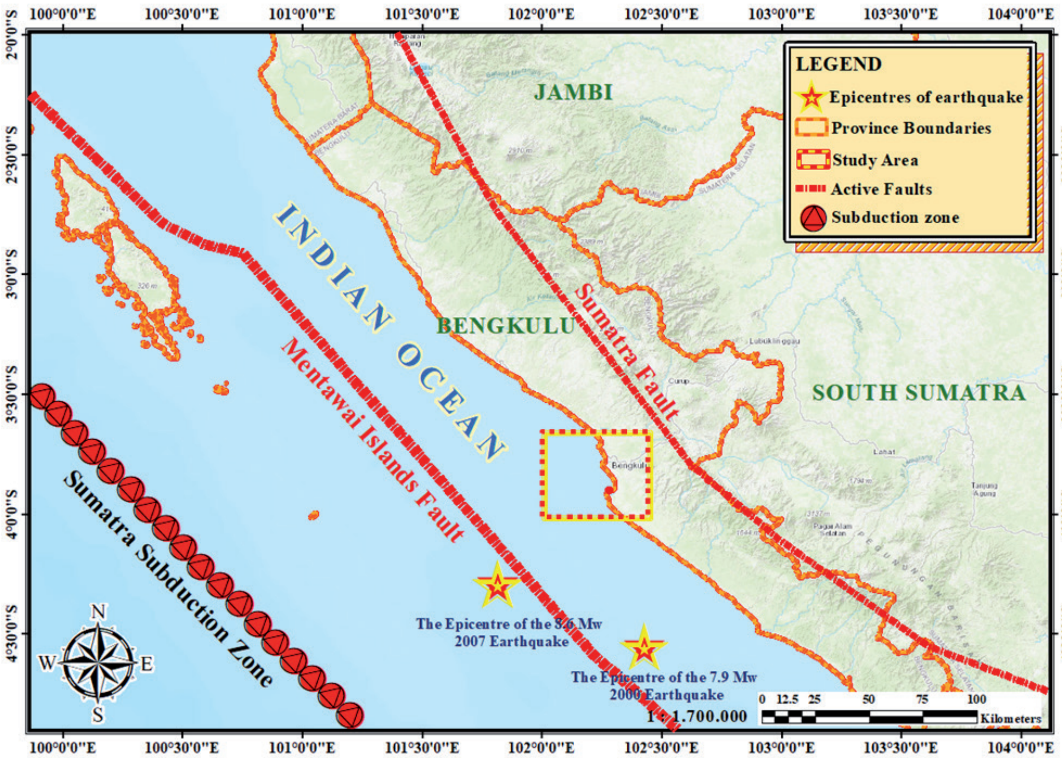


Figure 1. Seismotectonic Settings of Bengkulu Province (modified from Mase 2022).

2. Geologic setting

Figure 2 shows the distribution of 30 points in the Kampung Melayu District, selecting six representative points: KM-10, KM-17, KM-19, KM-20, KM-22, and KM-27. The geological condition is characterised by alluvium terraces (Qat). KM-27 is located in the Teluk Sepang Subdistrict, while KM-22 and KM-20 are in the Sumber Jaya Subdistrict. Meanwhile, KM-19 is in the Kandang Mas Subdistrict, KM-17 is in the Padang Serai Subdistrict, and KM-10 is in the Muara Dua Subdistrict. Point KM-22, which is still part of the alluvium terraces (Qat), is very close to other geological structures, namely the reef limestone (QI).

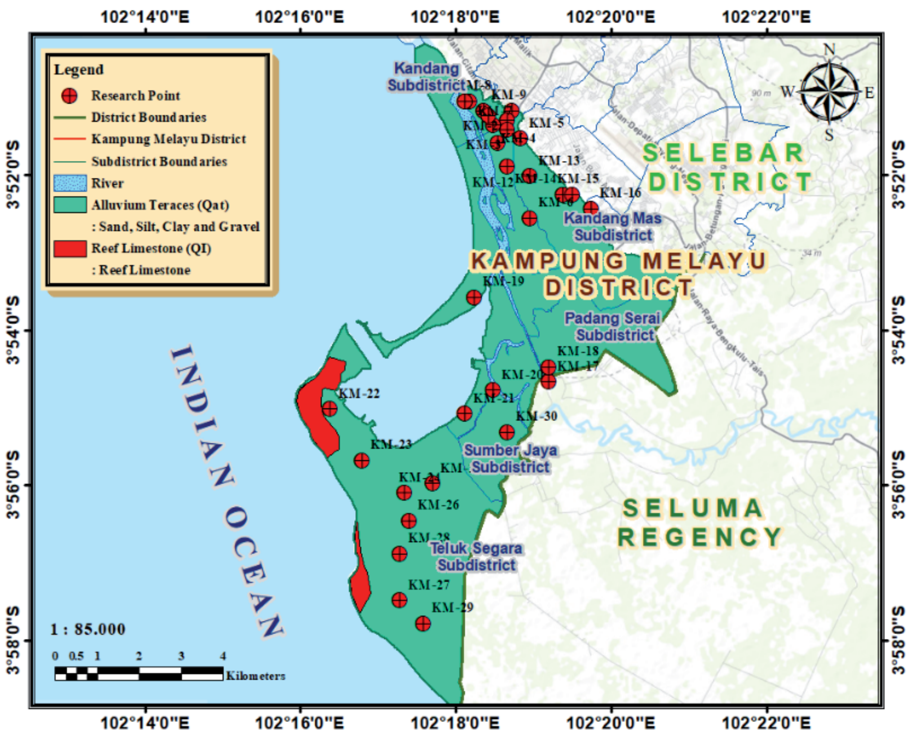


Figure 2. Geological Map and Measurement Points Distribution in Kampung Melayu District.

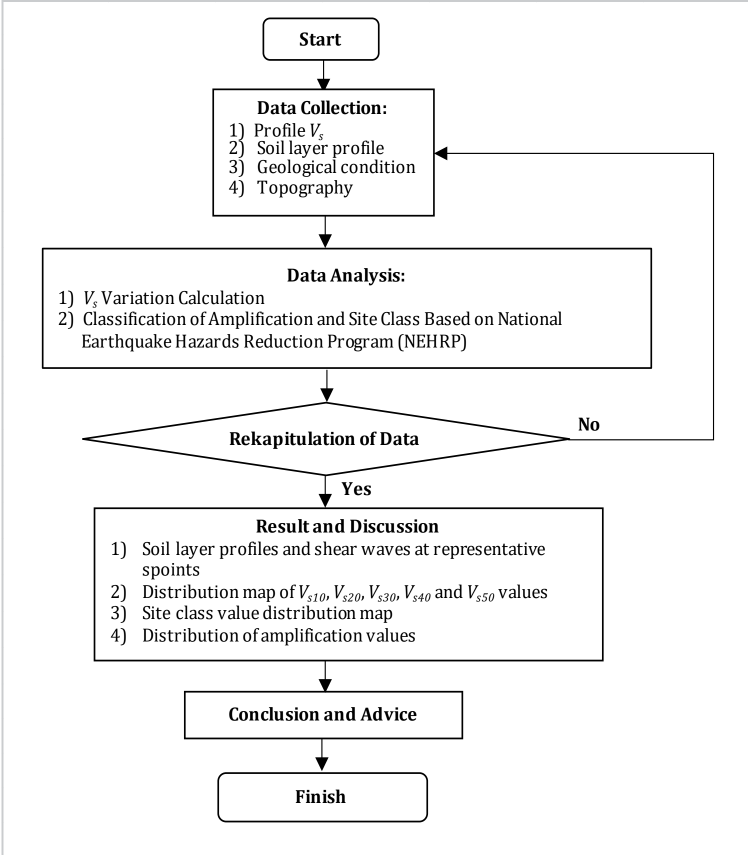


Figure 3. Flowchart of Research.

3. Data and methods

Research Design

The flow of this research, as illustrated in Figure 3, is a comprehensive process. It commences with the collection of V_s profile data in the Kampung Melayu District, which includes information on shear wave velocity (V_s), the soil layer profile, the geological conditions of Bengkulu City, and the topography of the research area. The subsequent data analysis involves calculating variations in soil shear velocity, evaluating the application of seismic waves, and determining the soil site class based on the National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Regulations for new buildings and other structures, as outlined by the Building Seismic Safety Council. This thorough research design instils confidence in the study's methodology and potential to yield valuable insights (BSSC, 2020). The outputs of this research include the shape of the soil profile and shear waves at representative points, distribution maps of V_s values at various depths, maps of site class value distributions, and patterns of wave amplification distribution.

Data Collection and Analysis Technique

Data collection and analysis techniques for V_s, including values determination through geophysical measurements used to calculate the depth of bedrock. Microseismic measurements produce Vs data, such as those using active seismic methods like Multichannel Analysis of Surface Waves (MASW) or passive seismic methods. The Multi-channel Analysis of Surface Waves (MASW) test, a non-destructive geophysical testing method, offers spatial variations in the mean shear wave velocity (Sambath et al., 2025). The V_s values are related to the unit weight of the different types of soil (Mayne, 2007). The data obtained include bedrock depth, base wave velocity (V_s), soil content weight (γ), the thickness of each soil layer (h), and soil type in each layer. These will then be used to analyse soil characteristics and behaviour towards seismic waves.

Mase (2017) describes the stiffness of the soil layer and is a key parameter in determining the site class according to international standards. One of the parameters that should be considered during geotechnical analysis to investigate how the soil responds and amplifies in an area is the shear wave velocity (V_{s30}) from a height of 30 m above the ground surface (Baram et al., 2020; Kamai et al., 2016; Odum et al., 2007; Prajapati et al., 2024; Refrizon & Mase, 2021)

The V_{s30} value can be calculated using Equation 1 based on the National Earthquake Hazards Reduction Program Recommended (BSSC, 2020):

$$V_{s30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \quad (1)$$

In Equation 1, where d_i is the thickness of the soil layer (m), V_{si} is the shear wave in the soil in that layer, and $\sum_{i=1}^{n} d_i$ is the total thickness of the layer (for V_{s30}, it should be 30 m), which is adjusted to each unit depth: 10 m (V_{s10}), 20 m (V_{s20}), 30 m (V_{s30}), 40 m (V_{s40}), and 50 m (V_{s50}). It should be noted that the total thickness is the total considered thickness to be analysed. The parameters of various depths are utilised in soil dynamics analysis and earthquake site classification, adjusting the calculations based on the relevant soil depth. The classification of site classes at values based on V_{s30} is done by the National Earthquake Hazards Reduction Program standard, which defines the soil categories based on the average shear wave velocity (V_{s30}).

Table 1 Classification of Sites into Five Site Classes Based on Shear Velocity Range (V_{s30}) according to the National Earthquake Hazards Reduction Program Recommended (BSSC, 2020).

NEHRP **Classification**	**Description**	**V_{s30} (m/s)**
A	Hard Rock	>1500
B	Rock	760-1500
C	Very Dense Soil And Soft Rock	360-760
D	Stiff Soil	180-360
E	Soil	< 180

Source: Building Seismic Safety Council (BSSC, 2020).

The site class E classification covers soft soil conditions with a range of V_{s30} < 180 m/s, while the site class D classification covers medium soil conditions 180 m/s < V_{s30} < 360 m/s. Site class C is used for complex soil types where 360 m/s < V_{s30} < 760 m/s, followed by site class B, which is characterised by hard rock (760 m/s < V_{s30} < 1500 m/s), and site class A for tough rock layers with Vs30 values exceeding 1500 m/s. Shear waves averaged to a depth of 30 m (V_{s30}) are correlated with site amplification (Aki, 1993; Anbazhagan et al., 2010; Anbazhagan & Sitharam, 2008). In site amplification analyses, the mean shear wave velocity at a depth of 30 m (V_{s30}) is a key parameter (Zhu et al., 2021). The Ground Amplification Factor (GAF) is a standard method for determining site amplification.

Midorikawa et al. (1994) proposed an empirical relationship between V_{s30} and the amplification factor, expressed through the following equation:

$$Log(GAF) = 1.35 - 0.4Log(V_{s30}) \pm 0.18 \quad (2)$$

The Ground Amplification Factor is a parameter that describes the magnitude of ground vibration amplification due to seismic wave propagation from bedrock to the surface, relating ground amplification to the average shear wave velocity at a depth of 30 m (V_{s30}). V_{s30} is used as the primary proxy in determining site response. The GAF, represented in logarithmic form, reveals the non-linear relationship between the shear wave velocity and the amplification factor, indicating that soils with lower V_{s30} values exhibit higher GAF values, making them more susceptible to seismic wave amplification. This is because of the impedance. Seismic impedance determines how much waves are amplified as they pass from one layer to another. The difference in impedance between soft ground and hard rock results in increased amplification.

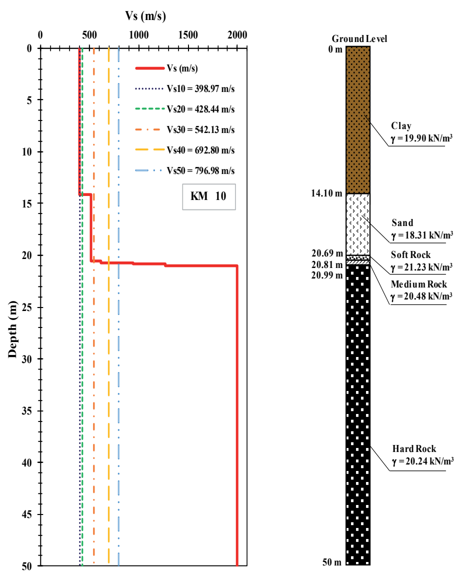
4. Results and Discussion

Soil layer profiles and shear wave at representative points

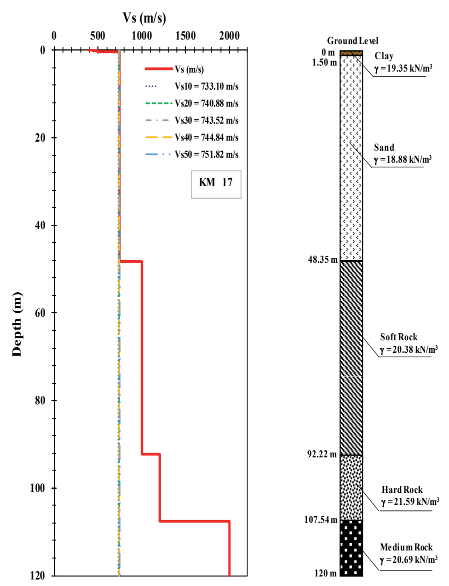
Figure 4 presents the area profile and the study area. It can be observed that there are five types of layers present: clay, sand, soft rock, medium rock, and hard rock. For KM-10 (Figure 4a), the rock starts from a depth of 20.69 m; for KM-17 (Figure 4b) at a depth of 48.35 m; at KM-19 (Figure 4c) at a depth of 66.71 m, for KM-20 (Figure 4d) at a depth of 72.27 m, for KM-22 (Figure 4e) at a depth of 44.87 m and a depth of 37.64 m for KM-27 (Figure 4f). At the first 30 m depth, the shear wave velocity ranges from 339.71 m/s to 978.70 m/s.

The average shear wave velocity (V_s) shows a significant increase with depth. At a depth of 10 m (V_{s10}), the average value reaches 453.25 m/s; at a depth of 20 m (V_{s20}), it increases to 524.33 m/s. For a 30 m depth (V_{s30}), the average velocity was recorded at 611.04 m/s; at a 40 m depth (V_{s40}), it was 687.79 m/s, and at a 50 m depth (V_{s50}), this value reached 754.15 m/s. This pattern of increase reflects the transition from softer soil layers at the surface to denser soil layers or rock at greater depths. The varied V_s and distribution patterns in the study area indicate the importance of selecting the proper foundation according to the region's soil classification and geological characteristics to optimise the structural resistance to vertical and lateral loads and the influence of earthquakes.

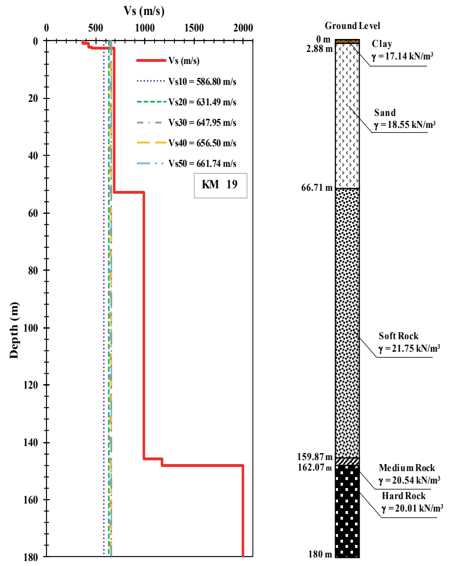
The study area's infrastructure includes ports, offices, schools, residential or housing, and the Pulau Bai Port. In Indonesia, construction design must prioritise earthquake resistance (Mase & Keawsawasvong, 2022). According to Mase et al. (2025) seismic design codes and building performance must be applied, especially in the province of Bengkulu. Foundations are divided into shallow and deep foundations based on depth and how the load is transferred to the ground (International Code Council, 2020). Infrastructure with a shallow foundation is intended for light buildings or low-rise buildings with sufficient bearing capacity at shallow depths (≤ 3 m), corresponding to V_{s10}. In contrast, for water-facing buildings, bridges, and docks, a more complex analysis is required to determine the resistance of the foundation that must penetrate from soft to hard soil, applicable to locations with low V_{s10} and V_{s20} values but shows a significant increase in V_s at depths of V_{s30}, V_{s40}, and V_{s50}.



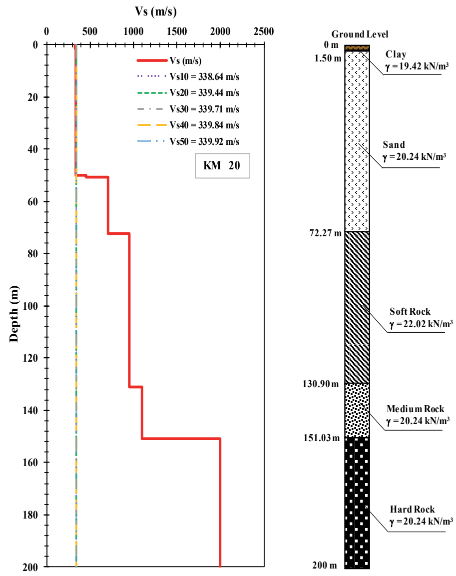
(a) KM-10



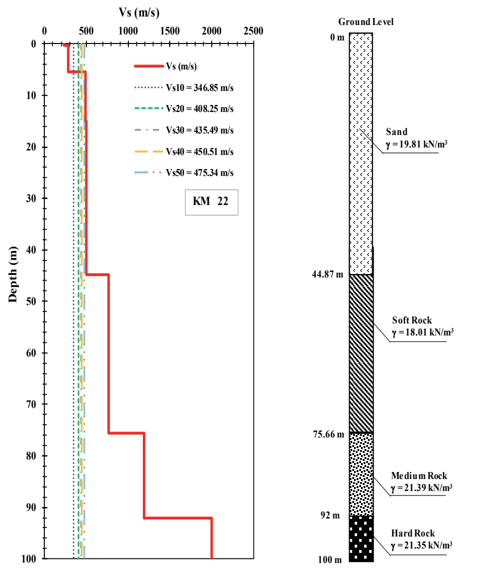
(b) KM-17



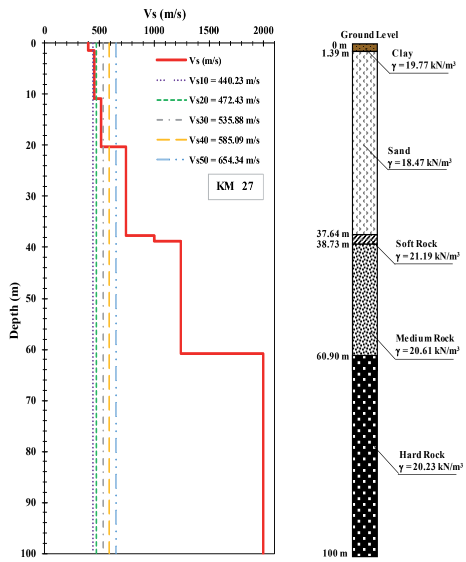
(c) KM-19



(d) KM-20



(e) KM-22



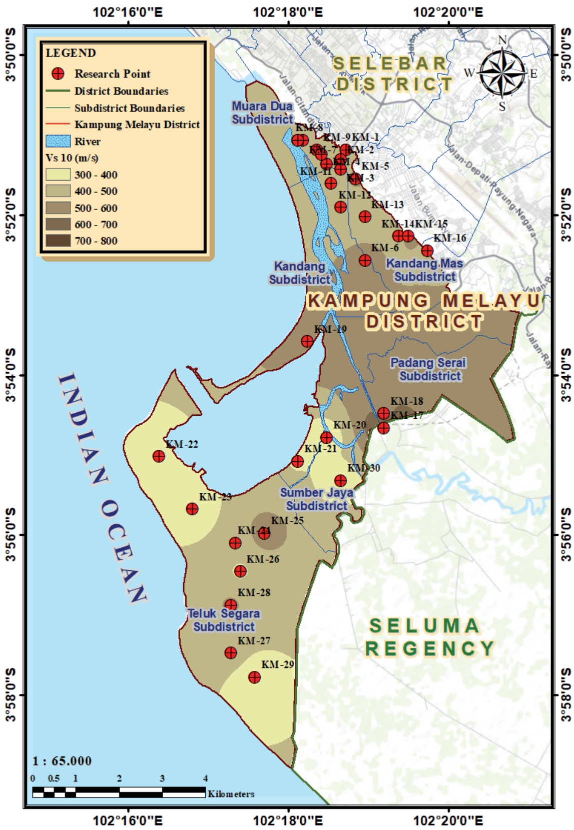
(f) KM-27

Figure 4. V_s profile for representative sites, i.e. (a) KM-10, (b) KM-17, (c) KM-19, (d) KM-20, (e) KM-22, (f) KM-27.

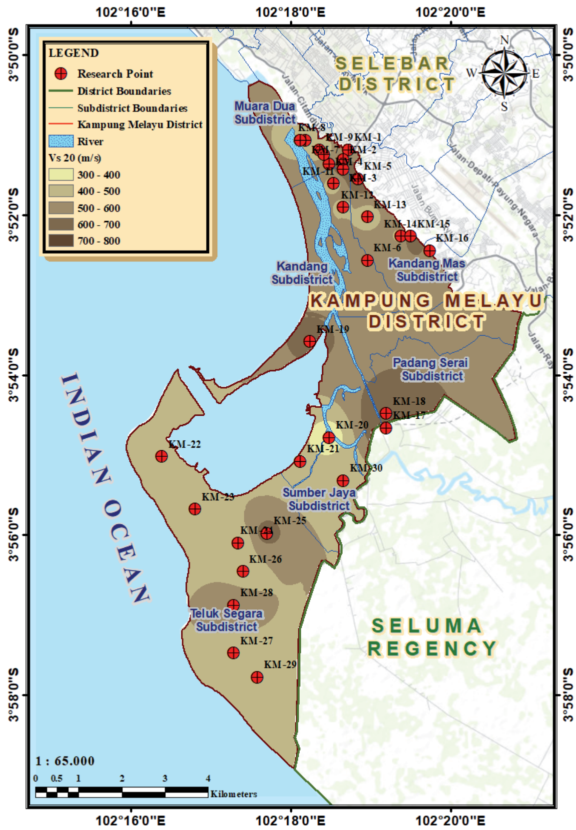
Distribution maps of V_{s10}, V_{s20}, V_{s30}, V_{s40} and V_{s50} values

Based on Figure 5, it is observed that the distribution of values in the shear wave velocity image reveals a variation in values, illustrated by a colour gradient, within the research location area. Low values, indicated by a bright brown colour, correspond to soft soil layers. In contrast, high values with a dark brown colour indicate solid soil or rock. The map covers a range of values from 300 m/s to a maximum of about 1,300 m/s. At a depth of 10 m (V_{s10}), the shear wave velocity remains relatively low due to the predominance of soft soil. This value increases at V_{s20} and rises to V_{s50} as depth increases, reflecting the transition from soft soil layers to denser soils and finally to rock layers. In the clay layer, the highest value is observed in the Kampung Melayu district, ranging from 102 m/s to 400 m/s (Kamal et al., 2024).

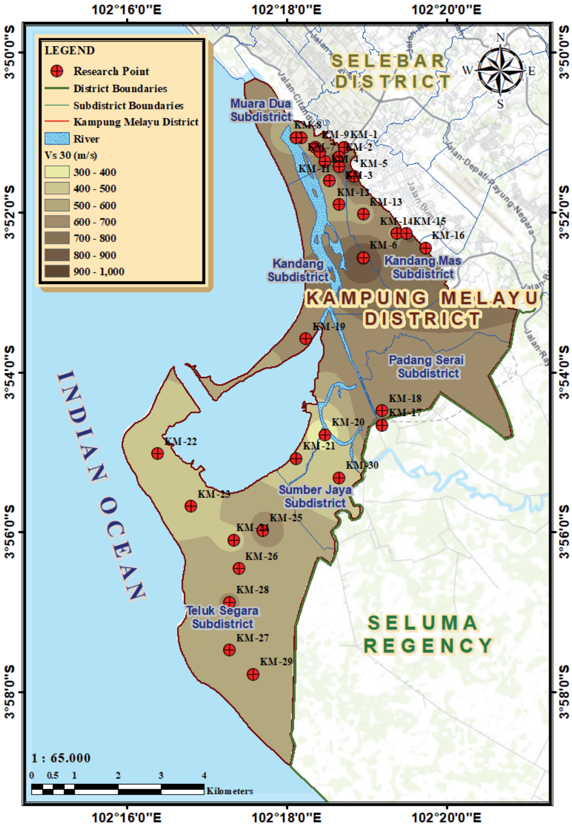
The distribution of shear wave velocity (V_s) at 10m (Figure 5a) and 20 m (Figure 5b) depths is intended to analyse geotechnical information and liquefaction hazard. At a depth of 30 m (Figure 5c), it is a key parameter in analysing the ground amplification factor and site class. In comparison, at 40 m (Figure 5d) and 50 m depth (Figure 5e), it is intended to analyse more complex structural planning, such as the design requirements of high-rise buildings. Proper planning of subsurface investigations is essential to ensure optimal infrastructure design, especially in soils with soft clay characteristics (Gue & Gue, 2022). Many buildings in Indonesia have been damaged due to unstable soils and improper structural design. Therefore, it is essential to consider V_s in building planning to mitigate the damage due to building failure, as assessed through geotechnical analysis and the impact of earthquake shaking.



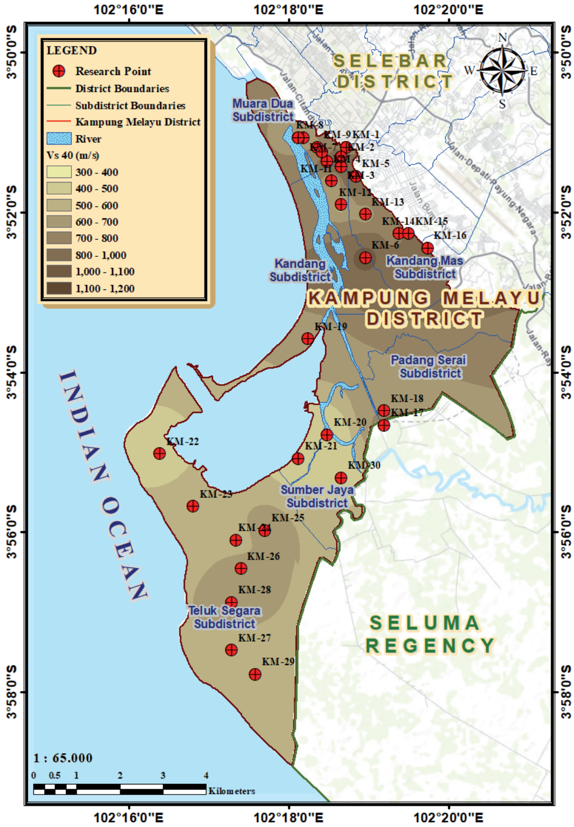
(a) V_{s10}



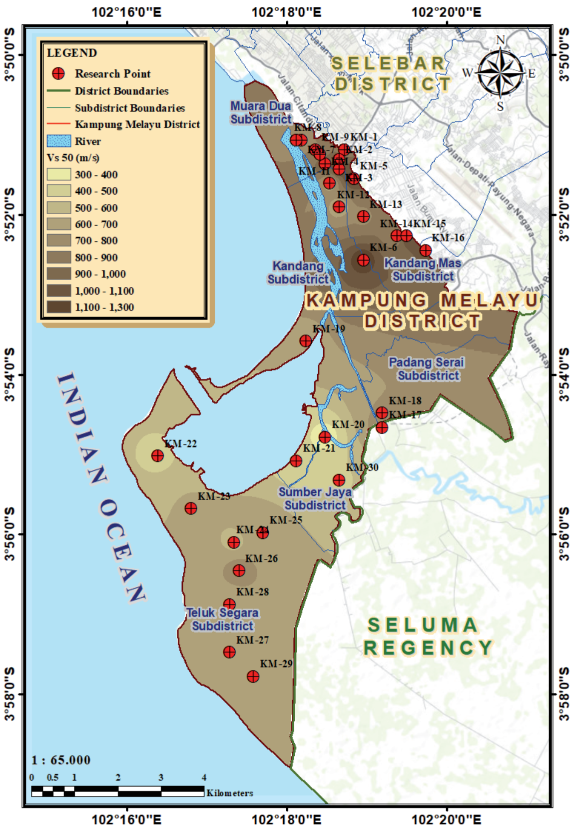
(b) V_{s20}



(c) V_{s30}



(d) V_{s40}



(e) V_{s50}

Figure 5. Maps of V_s Distribution for (a) V_{s10}, (b) V_{s20}, (c) V_{s30}, (d) V_{s40} and (e) V_{s50}.

Site class value distribution map

Equation 1 can be used to calculate the V_{s30} value of each data point in the study area to create a classification map according to the recommendations based on the National Earthquake Hazards Reduction Program (BSSC, 2020). Previous research, Farid & Mase (2020) examined the site class in Bengkulu City. As listed in Table 1, the site classification can be divided into five classes. As shown in Figure 6, there are three classifications of site classes in Kampung Melayu. The first is Site Class C (360 < V_{s30} < 760), the second is B (760-1,500), and the third is at point KM-20, where Site Class D is found, with a value of 339.71 m/s, located in the Alluvium Teraces (Qat) geological type.

Other areas that have similar site classes to the research area in the classification of site class C by NEHRP, such as the western part of Chiang Mai City, Thailand, where the soil is primarily coarse-grain sediments of colluvial and some alluvial soils with a V_{s30} value range of 361 m/s – 573 m/s (Thitimakorn, 2013). Southern Lamphun City, Thailand, with a value of 362 m/s - 471 m/s, which has similar geological conditions to the research site, namely Alluvium (Qa) and Terrace (Qt) (Thitimakorn & Raenak, 2016). Class C is generally found in the central to the eastern part of the Muara Bangkahulu and Dendam Tak Sudah Lake areas, Bengkulu City and the western part with a range of 360-420 m/s, 420-480 m/s, 480-540 m/s, 540-600 m/s, 600-660 m/s; and 660-720 m/s (Mase et al., 2024a, 2024b).

The southern, western, and eastern areas are classified as site class C, which includes the Teluk Segara Subdistrict with Reef Limestone (QI) geology, which is slightly different from other areas, the Sumber Jaya Subdistricts, the Padang Serai Subdistricts and the Sumber Jaya Subdistricts, which has a site class D at KM-21. Site Class D generally consists of sedimentary material, such as sand and soft clay, with a low bearing capacity. Chiang Rai Province, which shares the same site class as the study area, can be categorised as Site Class D (stiff soil) based on V_{S30} values ranging from 180 to 360 m/s (Mase et al., 2018; Mase and Likitlersuang, 2021). Other areas with a similar site class D include the Bandung Region, which has a range of shear wave velocity values at a depth of 30 m (V_{s30}) of around 208-308 m/s (Somantri et al., 2023). The northern area, which includes the Kandang Mas Subdistrict, the Kandang Subdistrict, and the Muara Dua Subdistrict, is dominated by classes B and C in areas with alluvial terrace (Qat) lithology.

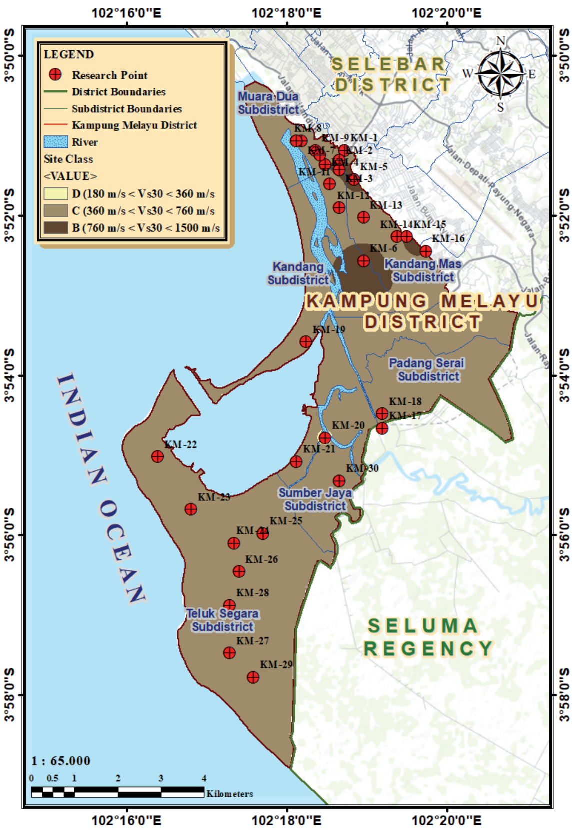


Figure 6. Site Classes Distribution Map.

Distribution of amplification values

Figure 7 shows the Kampung Melayu area ground amplification factor (GAF) microzonation map. The colour gradient on the map illustrates the distribution of ground amplification values, ranging from 1.0 to more than 1.6. Lighter colours indicate lower amplification values, while darker ones indicate higher ones. In addition, amplification has an inverse relationship with shear wave velocity (V_s); the lower the V_s value, especially in soft soil layers, the higher the amplification value. Amplification factors of more than 1.15 are found in some areas of Bengkulu City (Mase et al., 2020). Based on research conducted by Mase (2017), the Lais area exhibited the highest amplification factor in the study area, with a value of 1.480, while Pantai Panjang recorded the lowest amplification factor at 1.115. In this study, the highest amplification value of 1.6 was observed at KM-20, located in Sumber Jaya, which falls under site class D. Conversely, the lowest amplification value of 0.96 was recorded in Kandang Mas, classified as site class B. As such, soft soil layers tend to be more susceptible to seismic waves than denser or rock layers.

Soft soil layers tend to be more susceptible to seismic waves than denser or rock layers due to the difference in seismic impedance between the two soil types. This difference in impedance results in an amplification factor that plays a crucial role in site amplification. To improve the resistance of buildings in areas with high Ground Amplification Factor (GAF), earthquake-resistant structural design, such as deep foundation systems, seismic energy absorbers, and vibration-flexible materials, is necessary. Additionally, site classification data based on V_{s30} and GAF can be utilised to update construction standards, establish seismic zoning in urban planning, and inform planning policies that require building engineering to be tailored to the seismic risk level in each region.

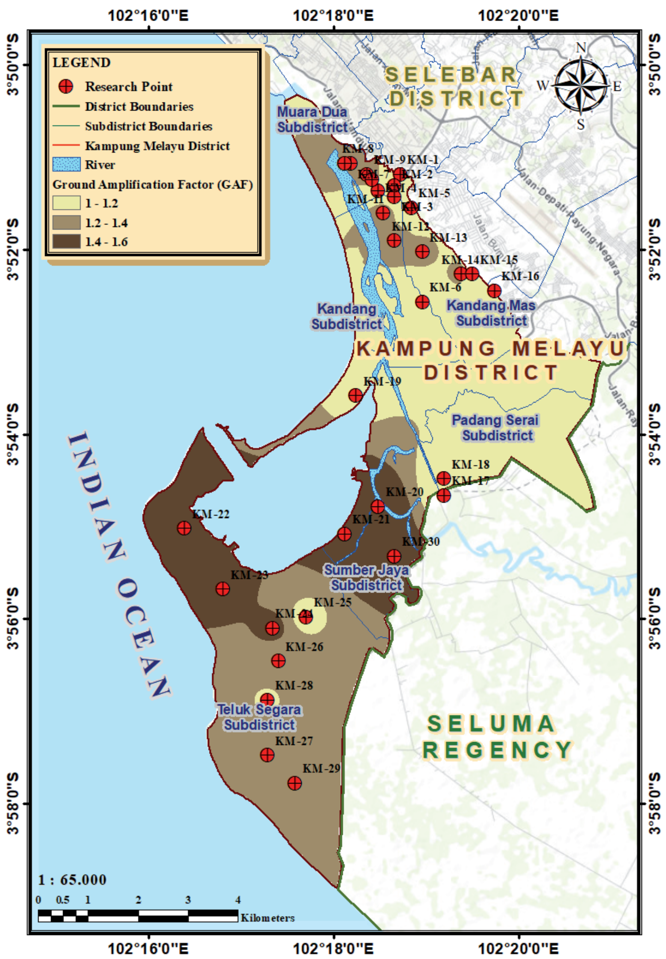


Figure 7. Map of Ground Amplification Factor.

5. Conclusions

Conclusions that can be drawn from this research.

1. This research updates previous studies that have never mapped the variation of V_s values with various depths and Ground Amplification Factors (GAF) in Bengkulu City. The shear wave velocity variation indicates that the V_s value and soil resistance increase with depth. In geotechnical and civil engineering, soil resistance plays a crucial role in determining the bearing capacity of soil for building foundations and slope stability, as well as mitigating the risk of liquefaction and earthquake-induced ground motion.
2. The microzonation map produced in this study can be an important reference for infrastructure planning and earthquake disaster mitigation in Kampung Melayu District, Bengkulu City. By considering the variation in shear wave velocity and the soil amplification factor, this study's results can help determine safer zones for development, improve the resilience of structures to potential future earthquakes, and identify vulnerable zones by analysing the soil more thoroughly.

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