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Mapping of Natural Frequency, Amplification, Seismic Vulnerability, and Vs30 Velocity in Selebar District, Bengkulu City

Samuel Siagian[1], Refrizon[2,*], Arif Ismul Hadi[2]

[1]Physics Study Program, Physics Department, Faculty of Mathematics and Natural Sciences, Bengkulu University, Indonesia, 38371.
[2]Geophysics Study Program, Physics Department, Faculty of Mathematics and Natural Sciences, Bengkulu University, Indonesia, 38371.

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Abstract

Research using the microtremor method has been conducted in Selebar District, Bengkulu City, to estimate the ground response to earthquake vibrations. The purpose of this research is to support building mitigation in earthquake-prone areas. Microzonation mapping is conducted by analyzing the dominant frequency (f_0), amplification factor (A_0), seismic vulnerability (K_g), and shear wave velocity (Vs30). The Horizontal to Vertical Spectral Ratio (HVSR) method is used in microtremor analysis. The results show the dominant frequencies consist of 40.8% hard gravelly sandstone, 26.5% alluvial rock with a thickness of 5 meters, 18.4% alluvial rock with bluff formation and 14.3% delta sediments. The amplification values include 40.8% in the low category, 56.1% in the medium category and 3.1% in the high category. The seismic vulnerability index indicates that 63.3% is below 3 level, 26.5% is between 3-6 level and 10.2% is between 6-9 level. The shear wave velocity (Vs30) values show that 8.2% is above 1500 m/s, 10.2% is between 750 m/s and 1500 m/s, 55.1% is between 350 m/s and 750 m/s, 25.5% is between 175 m/s and 350 m/s, and 1.1% is below 175 m/s. In conclusion, Selebar District has hard rock layers and low seismic vulnerability, rendering it generally safe from earthquakes.

✉ Correspondence address:
Geophysics Study Program, Physics Department, Faculty of Mathematics and Natural Sciences, Bengkulu University, Indonesia, 38371
E-mail: refrizon@unib.ac.id

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INTRODUCTION

The increasingly massive infrastructure development has transformed the landscape of Bengkulu City. However, before undertaking construction, it is necessary to conduct research on the area as a consideration for development, because Bengkulu City is an earthquake-prone area that could potentially damage buildings. Previous research in Selebar District, Bengkulu City, which used the microtremor method to analyze areas prone to building damage from earthquakes, was conducted with 60 measurement points. Although the research provided an initial overview of earthquake vulnerability in the area, the relatively distant spacing between measurement points made the research results less detailed. To obtain more detailed results regarding areas vulnerable to earthquakes and potential building damage, further research was conducted with a more specific number of measurement points, namely by measuring at 38 additional points, with closer distances between points. This serves to expand the data used in the analysis of the research results, providing more detailed information about earthquake vulnerability in Selebar District, Bengkulu City, thereby aiding in the development of more effective earthquake disaster mitigation strategies.

Bengkulu City, located in an earthquake-prone area, is due to its position close to the subduction zone between the Indo-Australian and Eurasian plates, as well as major faults in Sumatra such as the Musi segment and the Manna segment. This geographical condition makes is described as a region that is highly vulnerable to earthquake shocks, therefore Bengkulu City must exercise caution in development planning and be well-prepared to face potential earthquakes. This is due to its proximity to both the subduction earthquake source and the Sumatra fault. Implementing comprehensive earthquake damage mitigation strategies is essential to minimize potential risks (Firdausa, 2020). Bengkulu city has experienced a devastating earthquake, with the epicenter located at 4.44° S 101.37° E, which occurred on September 12, 2007. The earthquake occurred at a depth of 34 km, with a magnitude of 8.5 M, causing severe damage to office buildings, schools, markets, and hospitals. In this incident, more than 1,400 houses were lightly damaged and 2,000 houses were severely damaged. The disaster caused economic losses to the communities living in the area (Lestari et al., 2018).

Preventive measures to minimize the adverse effects of earthquakes can be carried out through natural disaster mitigation. One of the mitigation methods involves mapping and analyzing soil vulnerability to earthquake risks, which helps illustrate the physical characteristics of the rocks in the area. Mapping illustrates how geology and earthquake distribution, average shear wave velocity to a depth of 30 meters (Vs30), peak ground acceleration (PGA), earthquake magnitude as well as Modified Mercalli Intensity (MMI), dominant frequency, and amplification factors related to elastic strain as well as Ground Shear Strain (GSS) and sediment layer thickness can be used to analyze the potential building damage from an earthquake disaster (Hadi et al., 2021). Natural frequency (f_0) is the seismic wave number that often appears during ground recording using a seismometer. From the natural frequency value, it can be analyzed in relation to the geological characteristics in the research area (Hafid et al, 2017). Areas with hard rocks and thin sediments tend to have high natural frequencies, while areas with soft rocks and thick sediments tend to have low natural frequencies

Areas with low natural frequencies are considered vulnerable to earthquake disasters because the less rigid soil structure can increase the impact of seismic vibrations and the potential for damage to buildings and infrastructure. With the presence of the dominant frequency value, it can help analyze the potential level of building damage if located in the studied area, in an effort to mitigate earthquake-related risk(Harsuko, et al., 2020). Building failures due to earthquakes are often caused by a lack of attention to the natural vibration period limits of the soil, in the structural design planning of building (estika et al., 2022). Determining the value of the vibration period limit involves the natural frequency of the building and the ground beneath it. Additionally, it is important to consider the building's damping level against shocks as an additional factor. The comparison between the natural frequency of the building and the natural frequency of the ground becomes key in projecting the potential damage to the building due to an earthquake. By taking into account the interaction between the vibration characteristics of the building and the ground beneath it, construction planners can anticipate how well the building can withstand earthquake shocks. This emphasizes the importance of considering these factors in the structural design planning of buildings to enhance earthquake resistance (Desmita, et al., 2022).

Microtremor research utilizes ground vibrations at the research location that arise from waves or vibrations due to natural conditions or human activities (Arintalofa et al., 2020). The results of microtremor measurements indicate a consistency between the soil amplification factor values obtained using natural wave and earthquake observation data, and further observations will be conducted using the Horizontal to Vertical Spectral Ratio (HVSR) method (Saraswati, 2007). The analysis results of the Horizontal to Vertical Spectral Ratio (HVSR) will show peaks in the spectrum at the dominant frequency (f_0) and amplification factor (A_0), which describe the dynamic characteristics of the soil. The dominant frequency, which is the frequency that often appears and is considered the main representation of the frequency of rock layers in a certain area, plays an important role in understanding soil properties. By measuring the dominant frequency values at the ground surface, the geological structure and subsurface characteristics of the soil can be determined. Information regarding the dominant frequency of an area can serve as a strong foundation in the planning and design of earthquake-resistant buildings. By conducting research in the area, development planners can enhance the resilience of buildings and infrastructure against potential earthquake risks, thereby strengthening more effective and proactive disaster mitigation efforts (Putra et al., 2023).

One of the parameters often used to estimate ground motion acceleration at the surface is through the use of amplification factors. (Saputra, 2023). The amplification factor provides information about the change or increase in ground motion acceleration from the bedrock to the surface. The increase in ground motion acceleration occurs due to the difference in shear wave velocity (Vs) between the bedrock and the soil layer (sediment). The greater the value of the amplification factor, the greater the acceleration of ground movement at the surface. Therefore, direct observation of the geological influence of the area during an earthquake and microtremor research can also be used as an alternative approach to predict the amplification factor (Partono et al.,2021).

By conducting research using the microtremor method, the vulnerability value of the surface soil layer to deformation during an earthquake will be obtained. The Seismic Vulnerability Index value is directly related to geomorphological conditions, which influences how vulnerable an area is to earthquakes. The Seismic Vulnerability Index value considers the level of vulnerability of an area to earthquakes and geomorphological factors such as

Soil type, topography, and geological structure that can affect the impact of earthquakes in that location (Iswanto et al., 2019). Seismic waves propagate through weathered layers towards the bedrock, meaning these waves travel depending on the elasticity properties of the rock, where significant changes in frequency and amplitude of the waves occur. This results in increased acceleration, which, if comparable to or exceeding the natural frequency of a building, can cause serious damage due to the high acceleration (Nova et al.,2019). To estimate the natural frequency of the ground, experts rely on the peak amplitude value of the HVSR (Horizontal to Vertical Spectral Ratio) spectrum, which is obtained by processing amplification values from microtremor measurement data. These two parameters have a direct influence on the Soil Vulnerability Index, which is a key indicator in evaluating the vulnerability level of an area to earthquakes. Therefore, the values of frequency, amplitude, and the Soil Vulnerability Index are very important in efforts to mitigate earthquake disaster risks and in planning earthquake- resistant buildings (Hidayat et al., 2020).

METHOD

In this study, microtremor data from 98 measurement points in the Selebar District, Bengkulu City (refer Figure 1) were used to assess seismic activity. The collection of microtremor data was carried out using a Portable Short Period Seismometer, specifically the PASI Mod Gemini 2 Sn-1405 Seismometer. Microtremor data were obtained in the time domain consisting of three components, namely vertical (Up-Down) and horizontal (East-West dan North-South). The data processing was carried out using Geopsy software, applying the HVSR (Horizontal to Vertical Spectral Ratio) method, which previously involved a windowing stage with a length between 10 to 50 seconds to eliminate signals originating from transient effects during the measurement process. This step ensures that the obtained data can be interpreted more accurately and produces more precise information. The dual horizontal component signals (North-South and East-West) in the frequency domain are combined. signals originating from transient effects during the measurement process. This step ensures that the obtained data can be interpreted more accurately and produces more precise information. The dual horizontal component signals (North-South and East-West) in the frequency domain are combined. After combining these two horizontal components, the ratio between the horizontaland vertical components is calculated to analyze the seismic response (H/V) (Harsuko et al., 2020).

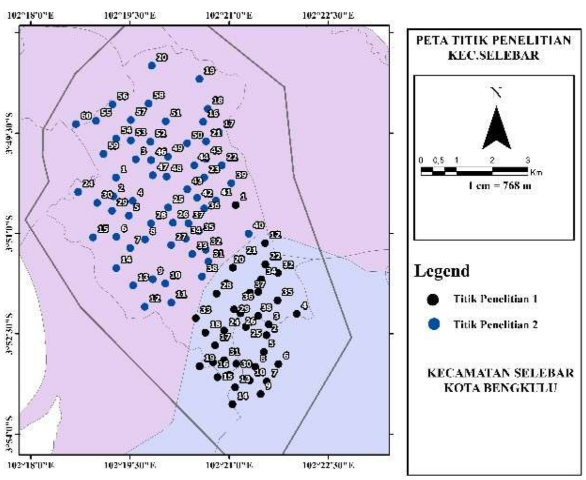

Figure 1. Map of the microtremor research area and its measurement points (Selebar District, Bengkulu City).

After performing data windowing in the geopsy software, the value s of the soil's dominant frequency parameter (f_0) and the soil amplification factor (A_0) for each measurement will be obtained through the H/V curve display in geopsy. With these parameter values obtained, it is important to obtain values for other parameters to refine the results of microtremor research. To obtain the seismic vulnerability value (K_g), calculations are performed by squaring the peak value of the microtremor spectrum divided by the resonance frequency using the following formula (Putra et al., 2023):

$$Kg = \frac{A0^2}{f0}$$

In microtremor research, it is important to analyze the value of the shear wave velocity (Vs), as this parameter is essential for comparison and for improving the accuracy of data processing from other parameters. By performing an inversion of the processed data from geopsy, which yields the values of the dominant frequency and the amplification factor, shear wave velocity (Vs) data can be obtained through data inversion. The inverted shear wave velocity (Vs) values can be used to estimate the Vs30 value at each measurement point. The process of calculating Vs30 is an important step in seismic analysis, where this value represents the shear wave velocity at a depth of up to 30 meters below the ground surface. The calculation of Vs30 at each measurement point is carried out using equations that have been established based on the Vs values obtained from the previous inversion process. Vs30 plays a crucial role in earthquake analysis and mapping of the research area and is an important parameter in evaluating the potential seismic vulnerability of a region (Syamsuddin et al., 2021).

By performing inversion on each data, the next step is to observe the natural frequency data (f_0), amplification (A_0), seismic vulnerability index (K_g), and Vs30 (Shear wave velocity up to a depth of 30 meters). To observe the data, amplification level classification tables and soil type classification for each parameter can be used as a reference or as a structured conceptual framework that can explain how soil types and their responses to earthquake shocks work. Mapping the values of each parameter obtained allows for predicting the damage that may occur in the event of an earthquake. From several parameters, mitigation can be carried out before construction in the research area (Putra et al., 2023).

RESULTS AND DISCUSSION

The dominant frequency value from the HVSR (Horizontal to Vertical Spectral Ratio) curve can provide important information in building planning, in efforts to mitigate disaster due to earthquakes because the dominant frequency value reflects the subsurface conditions of the measured area and can be used to anticipate the risk of resonance during an earthquake. Resonance can amplify the amplitude of earthquake vibrations, which can ultimately cause damage to the buildings situated above them. From the research results using the microtremor method, the results shown in Figure 2 with varying colors indicate low, medium, and high values in the measurement point area in Selebar District, Bengkulu City. The colors on the map in Figure 2 range from the lowest to the highest values, which are green, yellow, orange, and red, as shown in Figure 2 below.

In the measurements, the results of the dominant frequency values at all points with different types and characteristics of soil were obtained. The observation of the dominant frequency data used the soil classification found in Table 1 as follows; The results show the dominant frequencies consist of 40.81632653% hard gravelly sandstone, 26.53061224% alluvial rock with a thickness of 5 meters, 18.36734694% alluvial rock with bluff formation and 14.28571429% delta sediments.

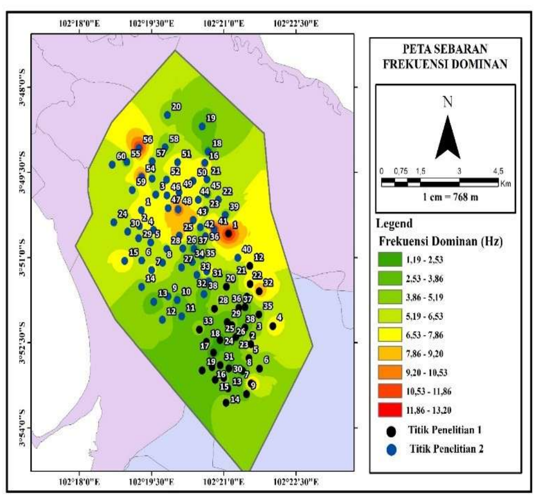

Figure 2. Map of Natural Frequency Value Distribution (f_0).

Table 1. Soil classification based on the dominant frequency of microtremor by Kanai (Arifin, dkk, 2013).

Dominant frequency (Hz)	**Kanai Classification**	**Description**
6,67-20	Tertiary or older rocks. Consists of sandy, gravel, etc. rocks.	The thickness of the surface sediment is very thin, dominated by hard rocks.
4-6,67	Alluvial rocks, with a thickness of 5m. Consisting of sandy – gravel, sandy hard clay, loam, etc. he surface sediment is very thin, dominated by hard rocks.	The thickness of the surface sediment falls into the medium category of 5 – 10 meters.
2,5-4	Alluvial rocks, with a thickness of >= 5m. Consists of sandy – gravel, sandy hard clay, loam, etc.	The thickness of the surface sediment falls into the category of approximately 10 – 30 meters
<2,5	Alluvial rocks formed from delta sedimentation, topsoil, mud, etc. With a depth of 30 m or more.	The thickness of the surface sediment is very thick

Based on the amplification value (A0) obtained from the data processing of the research area in Selebar District, Bengkulu City, in general, has a low amplification factor value, which indicates that the research area falls into a region with a lower level of building damage during an earthquake, and the obtained A0 value can describe the dynamic characteristics of the soil. According to Suharna (2009), as cited in (Widyawarman & Fauzi, 2020). The amplification factor values are classified as shown in the following table:

Table 2. Classification of amplification levels (Suharna, 2009).

Amplificati on level	Level of vulnerability	Meaning of application
<3	1	Low
3-6	2	Intermediate
6-9	3	Height
>9	4	Very high

In the Selebar District, Bengkulu City, the amplification factor (A0) shows that 40.81632653% falls within the low category, 56.12244898% falls within the medium category, and 3.06122449% falls within the high category (as shown in the figure3). Therefore, areas with low to medium amplification factor values are considered safe for construction. The results of the observation of the amplification factor value support or align with the observation results of the dominant frequency value, concluding that Selebar District, Bengkulu City, generally has areas with low potential for earthquake damage, making it safe for habitation.

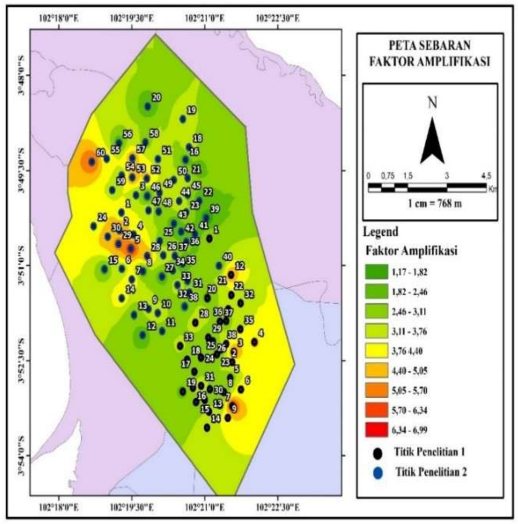

Figure 3. Map of Amplification Factor Value Distribution (A0).

From the results of the research conducted, the seismic vulnerability index (Kg) value was obtained, and its mapping has been created, as shown in Figure 4. The seismic vulnerability index is influenced by the maximum amplitude and natural frequency. If the maximum amplitude is large and the natural frequency is small, the earthquake vulnerability index will be high. Conversely, if the maximum amplitude is small and the natural frequency is large, the earthquake vulnerability index will be low. With the obtained seismic vulnerability index (Kg) values measured from 98 points at the research location, it can be used to estimate or predict the potential effects of an earthquake in the Selebar District. The data processing results indicate the seismic vulnerability index (Kg) at measurement points in Selebar District, Bengkulu City, where the area is generally not prone to building damage due to earthquakes. The vulnerability index shows that 63.26530612% is below 3, 26.53061224% is between 3-6, and 10.20 is beween 6-9 (high). For areas within the 6-9 range, special treatment for building foundations is required if construction takes place.

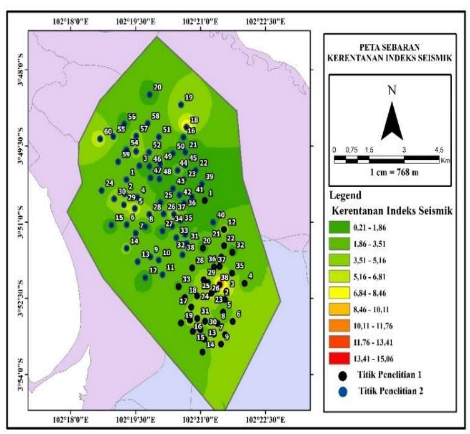

Figure 4. Map of Seismic Vulnerability Distribution (Kg).

Amplification is the main cause of building damage during earthquakes. The stiffness of the soil significantly affects its response to seismic events. This response is influenced by the impact of earthquake vibrations on the soil, which can be measured by shear wave velocity (Vs). Shear wave velocity (Vs) is considered the most reliable indicator for assessing soil properties and its behavior under earthquake vibrations. The average shear wave velocity up to a depth of 30 meters (referred to as Vs30) becomes an important criterion in evaluating the level of soil stiffness aimed at mitigation during construction.

In this study, the value of shear wave velocity (Vs) was obtained as an important parameter for comparison with other parameters, which can illustrate the vulnerability of the soil at the microtremor research location. The UBC97 (Uniform Building Code 1997) classification divides the soil into five different classes. These classes include hard rock, medium rock, hard soil and soft rock, medium soil, and soft soil.

Table 3. Site classification based on Vs30 data.

Class Site	**Vs30 (m/s)**
SA (hard rock)	>1500
SB (rock)	750 - 1500
SC (hard soil, very dense, and soft rock)	350 – 750
SD (medium soil)	175 -350
SE (soft soil)	175

In the research results, the values of shear wave velocity up to a depth of 30 meters (Vs30) and observations on the distribution map as shown in Figure 5, out of 98 measurement points, The shear wave velocity (Vs30) values up to a depth of 30 meters in Selebar District, Bengkulu City, show that 8.163265306122449% is above 1500 m/s, 10.204081632653061% is between 750 m/s and 1500 m/s, 55.10204081632653% is between 350 m/s and 750 m/s, 25.510204081632654% is between 175 m/s and 350 m/s, and 1.0204081632653061% is below 175m/s. In conclusion, Selebar District has hard rock layers and low seismic vulnerability, making it generally safe from earthquakes

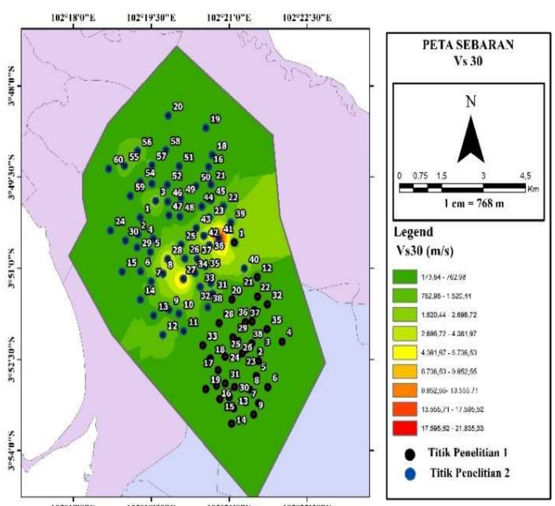

Figure 5. Shear Wave Velocity Map to a Depth of 30 Meters (Vs30).

CONCLUSION

From the research conducted, it can be concluded that:

1. In Selebar District, Bengkulu City, based on the f0 values, most of the area has a sediment thickness categorized as relatively thin, making it generally safe for residential development. The results show

that the dominant frequencies consist of 40.8% hard gravelly sandstone, 26.5% alluvial rock with a thickness of 5 meters, 18.4% alluvial rock with bluff formation, and 14.3% delta sediments.

2. The amplification factor (A0) in Selebar District, Bengkulu City, shows that 40.8% falls within the low category, 56.1% falls within the medium category, and 3.1% falls within the high category.Therefore, areas with low to medium amplification factor values are considered safe for construction.
3. The data processing results indicate the seismic vulnerability index (Kg) at measurement points in Selebar District,Bengkulu City, where the area is generally not prone to building damage due to earthquakes. The vulnerability index shows that 63.3% is below 3 level, 26.5% is between 3-6 level, and 10.2% is between 6-9 level (high). For areas within the 6-9 range, special treatment for building foundations is required if construction takes place.
4. The shear wave velocity (Vs30) values up to a depth of 30 meters in Selebar District, Bengkulu City, show that 8.2% is above 1500 m/s, 10.2% is between 750 m/s and 1500 m/s, 55.1% is between 350 m/s and 750 m/s, 25.5% is between 175 m/s and 350 m/s, and 1.0 % is below 175 m/s. In conclusion, Selebar District has hard rock layers and low seismic vulnerability, making it generally safe from earthquakes

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