

Analysis of Earthquake Risk Estimation for Sustainable Development Using Microtremor Data Based on V_s30 Distribution: Comparative Study of DFA and Geopsy in Central Bengkulu, Indonesia

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Article Info	ABSTRACT
<p>Article History:</p> <p>Received February 24, 2025 Revised July 03, 2025 Accepted August 02, 2025 Published online September, 05, 2025</p> <hr/> <p>Keywords:</p> <p><i>microtremor</i> <i>HVSR</i> <i>Seismic Vulnerability</i> <i>Disaster Mitigation</i></p> <hr/> <p>Corresponding Author:</p> <p>Refrizon Refrizon, Email: refrizon@unib.ac.id</p>	<p>This research was conducted in Pondok Kelapa Subdistrict, Central Bengkulu Regency, to analyze subsurface characteristics using microtremor data and the Horizontal-to-Vertical Spectral Ratio (HVSR) method. The research compared DFA (Diffuse Field Assumption) and Geopsy approach. In this study, 40 points were measured with a distance between points ranging from 200 to 300 meters. The data were processed using Terraware-HV and Geopsy software with a Monte Carlo approach to model the 3D subsurface structure. Results show that the dominant frequencies range from 0.64 to 8.19 Hz, with high amplification zones between 1.92 and 7.72 concentrated in areas of loose soil, indicating their high seismic susceptibility. V_s30 values range from 55 to 465 m/s, reflecting the dominance of soft to medium materials, such as clay, gravel, sand, and soft rock at specific depths. 3D modeling revealed a heterogeneous distribution of subsurface materials, with high amplification zones requiring special mitigation. This study provides important insights for seismic risk zoning, disaster mitigation, and earthquake-resistant structure design, and supports sustainable development planning in earthquake-prone areas. The results are expected to serve as a reference in spatial management based on earthquake risk mitigation.</p>

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1. INTRODUCTION

Pondok Kelapa sub-district, one of the sub-districts in Central Bengkulu Regency, Bengkulu Province, has rock formations dominated by alluvial and lake deposits, as identified by Gafoer et al. (1992). These rock formations have physical characteristics such as seismic wave velocity and mass density that are relatively low due to a lack of cohesiveness, making these rock formations very vulnerable to earthquake disasters (Hadi et al., 2021). This condition can potentially increase vulnerability to the destructive impact of earthquakes, especially in areas with uncompacted soil.

Based on data from the National Disaster Management Authority (BNPB), the Central Bengkulu region has experienced two significant earthquakes, one of which occurred in 2000 with a magnitude of 7.3 on the Richter Scale (SR). It caused severe damage to many homes along the Bengkulu coastline (Marwan & Firmansyah, 2013). Only seven years later, in 2007, Bengkulu was again rocked by an even greater magnitude of 7.9 earthquake. In addition to taking lives, the earthquake

disaster in Central Bengkulu has also resulted in material and immaterial losses in the form of prolonged psychological trauma (Dwi, 2020; Siburian et al., 2023, 2024).

There has been some research on the distribution of V_s30 values in the Bengkulu area, one of which is a study conducted by Mase et al. (2021), who used microtremor data and inversion techniques to obtain secondary wave velocity (V_s) values. According to the NEHRP (National Earthquake Hazard Reduction Program) classification, this study found that the site classification that dominates the Bengkulu city area refers to silty clay (SC) with many clay components that show better stability trends. Other site classifications refer to sandy dirt (SD), referring to sandy soils that are more easily affected by water and tend to be unstable. Another study by Nabhan et al. (2023) conducted on the Bengkulu Tengah-Kepahiang alternative road section showed that V_s30 values in the area were generally high, with soil classifications from Hard, Very Solid, to Soft Rock (SC to SB). Farid et al. (2024) also used the HVSr method to assess the shoreline change rate due to abrasion in Central Bengkulu Regency, resulting in V_s30 values ranging from 227 to 1235 m/s. Furthermore, Fitriana et al. (2019) used microtremor data to investigate the attenuation coefficient related to sediment vulnerability during seismic events in Central Bengkulu, specifically in the Beringin Raya and Kandang Limun areas.

Microtremors have many applications, including seismic microzonation and understanding site characteristics and amplification. Horizontal-to-vertical spectral Ratio (HVSr) is a method for obtaining subsurface information based on microtremor measurements that can be used to determine site amplification and dominant frequency. It is a method introduced by Nakamura (1989), while the amplification factor occurs when seismic waves are trapped in the ground. The amplification factor is determined by comparing the horizontal amplitude component at the surface with the vertical amplitude component, which can be written according to the equation (Edison, 2022).

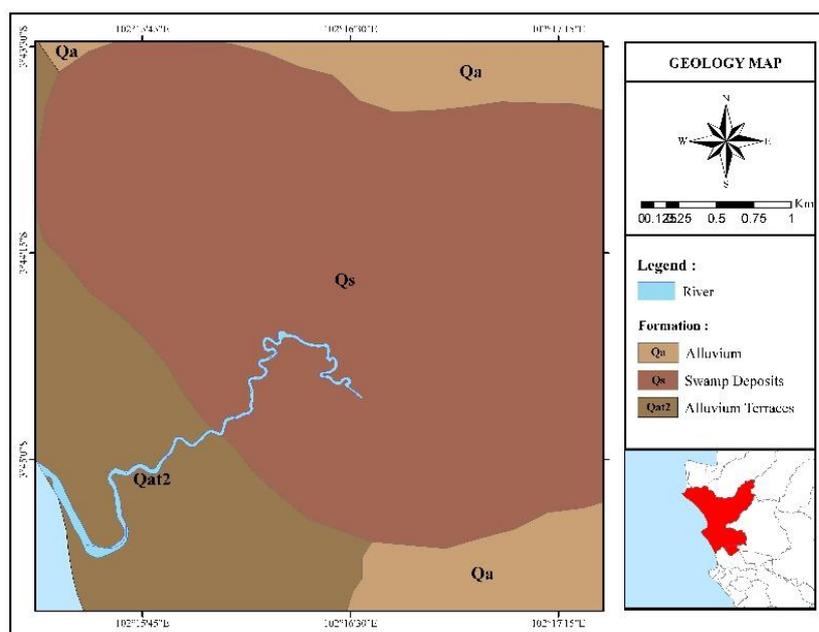


Figure 1. Geological map of Pondok Kelapa District, modified from Gafoer et al. (1992).

The method used in the research conducted is HVSr. The fundamental concept of the HVSr approach is the parallel between the transport of waves from bedrock to the surface and the horizontal-to-vertical spectral ratio. According to Nakamura, the soil's natural period and amplification factor are comparable to the dominant period and peak value of the spectral ratio (H/V) (Partono et al., 2013). The HVSr method is carried out by estimating the ratio of the vertical component's Fourier spectrum to the horizontal component. The first peak HVSr ratio is the local natural frequency, and the local geological amplification value is the HVSr ratio at the natural frequency (Sitorus & Purwanto, 2016). The HVSr (Horizontal to Vertical Fourier Amplitude Spectral Ratio) technique of microtremor data analysis has been widely used for local effects studies and microzonation. Besides being simple and able to be done

anytime and anywhere, this technique is also able to estimate the resonance frequency directly without having to know the shear wave velocity structure and subsurface geological conditions first. Nakamura et al. (2000) mentioned that the HVSR method for microtremor analysis can be used to obtain the natural frequency of sediments, as also stated by Mufida et al. (2013).

Processing of microtremor data to obtain the value of V_s using Terraware-HV Software, where the performance of the Software is achieved by selecting the window type, Smoothing, to see the peak of the curve, and a model to produce the appropriate V_s value. The V_s value obtained in microtremor data processing with Terraware-HV Software to determine the thickness of the subsurface sedimentary layer, which aims to illustrate that the area under study can be used for Sustainable Development to minimize the risk of buildings that are vulnerable to earthquakes (Arintalofa et al., 2020).

Previous study results have not fully described the condition of the subsurface layer in the Central Bengkulu region as a whole, especially in the Pondok Kelapa sub-district. This results from the disparate distribution of the measuring stations over the study area. Therefore, to ascertain the value of V_{s30} , the distribution of shear wave velocity in deeper layers, and the seismic vulnerability index in the Pondok Kelapa sub-district, more thorough research on the subsurface layer in this area is required.

2. METHOD

2.1 Geology Regional

Pondok Kelapa sub-district is located in Central Bengkulu Regency, Bengkulu Province, Indonesia. The area is in a geological area with various rock formations, as shown by the Gafoer geological map (Gafoer et al., 1992). The rock formations are dominated by the Aluvium Formation (Qa), Aluvium Terrace (Qat2), and Swamp Deposits (Qs), each with different characteristics based on sediment grain size. Rock formation areas tend to have lower seismic wave velocity values, making them potentially more vulnerable to earthquake amplification and building damage (Utami, 2024). Geological maps provide an important overview of the variations in rock formations and geological structures in a region, which influence the behavior of rocks towards seismic activity and the risk of natural disasters, especially earthquakes, as shown in Figure 1.

Based on research conducted by Sugianto et al. (2017), the hardness of the rocks in each formation is an important factor in determining how much the rocks can resist earthquake-induced ground motion. Rock formations with low hardness, such as Qa and Qtb, are more susceptible to ground motion, so areas dominated by these rocks should be treated as areas with higher seismic risk. In contrast, rock formations with higher hardness, such as Qs and Qat, tend to be more stable and better able to withstand earthquake impacts.

2.2 Acquisition Data

This research was conducted in October 2024 in Central Bengkulu Regency and Bengkulu City. This research uses the Microtremor method, with the equipment used being a Portable Short Period Seismometer model Gemini 2 Sn-1405, GPS, Compass, and Laptop. The operational standard of the tool is based on the SESAME European research project, with a duration of 30 minutes between measurement points. In this study, there are 40 scattered points, which will be carried out with an interval between measurement points of about 200-300 meters (Figure 2).

Earthquake risk can be analyzed using the Deterministic Seismic Hazard Analysis (DSHA) method. The ground motion evaluation for a region is based on the region's earthquake scenario. This earthquake scenario contains an earthquake event with a certain magnitude that will occur at a certain location (Talumepa et al., 2019). In finding the value of ground acceleration at a place, the value of the soil's dominant period at that location must be used, based on the relationship:

$$T = \frac{1}{f} \quad (1)$$

with the period (s) and the frequency (Hz), finding the value of the dominant frequency first will reveal the value of the dominant period of the soil in a location. The Horizontal to Vertical Spectral Ratio

(HVSr) technique can be used to find the value of the dominant frequency of the soil. The characteristics of earthquake waves during an earthquake are affected by local soil conditions (R Anindya et al., 2017).

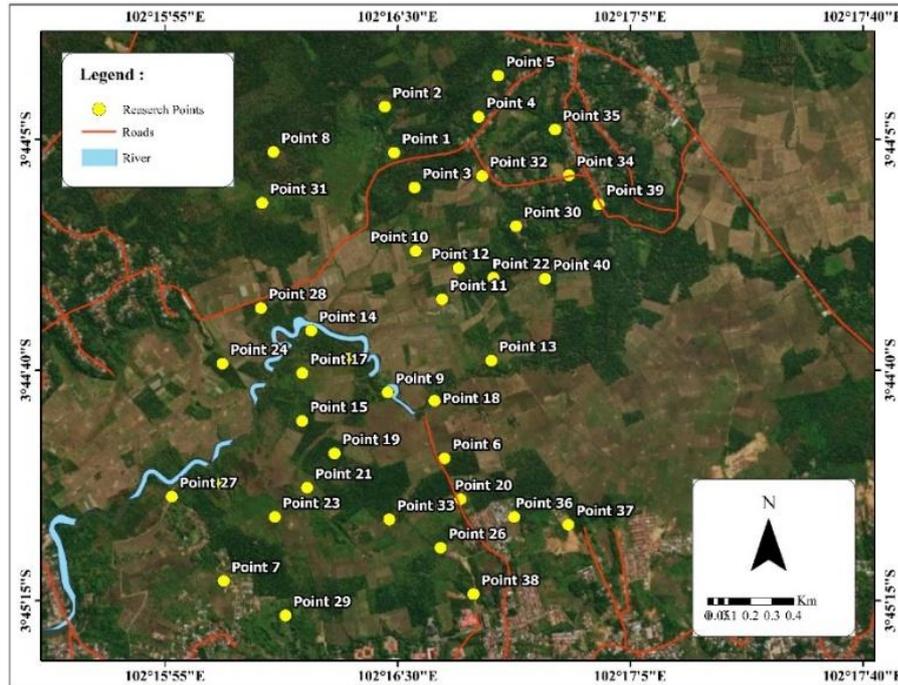


Figure 2. Location map of Pondok Kelapa and Muara Bangkahulu Sub-districts showing the observation points.

The amplification factors of horizontal and vertical motions at the sedimentary soil surface are often compared to characterize the Site Effect (TSITE) at the sedimentary layer's surface (SESAME, 2004).

$$T_{site} = \frac{T_h}{T_v} \tag{2}$$

$$T_H = \frac{SHS}{SHB} \tag{3}$$

where SHS represents the spectrum of horizontal motion components at the surface, and SHB represents the spectrum of horizontal motion components at the bottom of the soil layer. The magnitude of the vertical amplification factor, T_v , is given by:

$$T_v = \frac{SVS}{SVB} \tag{4}$$

the vertical motion component spectrum at the ground surface is denoted by SVS, and the vertical motion component spectrum at the subsurface base is denoted by SVB (Handayani et al., 2023).

Table 1. Classification based on value Vs30 (UBC, 1997)

Soil Class	General Description	Vs30 (m/s)
A	Hard Rock (<i>Granit, Gneiss</i>)	> 1500
B	Medium Rock (<i>Sandstone, Schist</i>)	760 – 1500
C	Hard Soil and Soft Rock (<i>Moraine</i>)	360 – 760
D	Medium Soil (<i>Sand</i>)	180 – 360
E	Soft Soil (<i>Gravel</i>)	< 180

Rayleigh waves account for most of the vibration data compared to some other wave types. The spectral ratio of the horizontal and vertical components of the rock mass is nearly one because Rayleigh waves have the same effect on microtremor registration for both vertical and horizontal components in the frequency range of 0.2 to 20.0 Hz:

$$\frac{SHB}{SVB} \approx 1. \tag{5}$$

by substituting the horizontal amplification equation with the vertical amplification equation, the vertical amplification becomes the horizontal and vertical amplification on the sedimentary soil surface:

$$T_{SITE} = \frac{SHS}{SHB} \tag{6}$$

the following formula serves as the foundation for determining the ratio of the microtremor spectral component to its vertical component (HVSr): (Arifin et al., 2014)

$$HVSr = T_{SITE} = \frac{\sqrt{f(SNorth-South)+(SWest-East)^2}}{SVertical} \tag{7}$$

One key element in ground motion analysis and earthquake risk assessment is V_s30 (Lantu et al., 2018). Further investigation into the impact of local soil properties on earthquake shaking is required to understand the potential for amplification (Sunardi, 2019). Table 1 shows the classification of soils based on V_s30 values as formulated by UBC (1997).

Subsurface properties are described through the spatial distribution of repetitive seismic waves via the microtremor method, characterized by ground vibrations ranging from 0.1 to 1 μ m. The Horizontal-to-Vertical Spectral Ratio (HVSr) method is used to process the HVSr data, resulting in HVSr curves (Harlianto et al., 2024). To display the underlying structure, crucial parameters such as resonance frequency and amplification factor are examined (Mutaram et al., 2022).

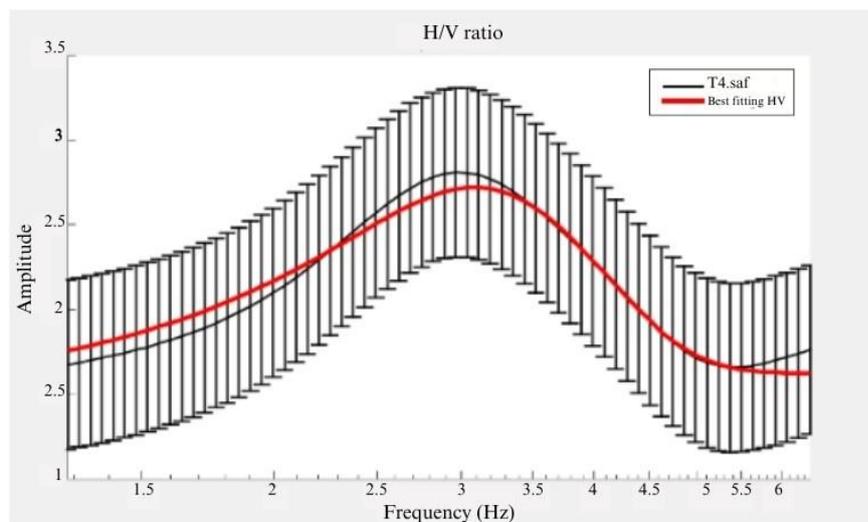


Figure 3. Inversion model curve based on the Monte Carlo principle.

Data processing uses Geopsy and DFA (Diffuse Field Assumption) software. Geopsy is a practical tool used in the field to analyze seismic data, while DFA is a theoretical approach that underlies the understanding of wave behavior in heterogeneous media.

Processed microtremor frequency and amplification value curves are inputted into the Hv-Inv software as an output of the processed data. García-Jerez et al. developed the HV-Inv application, which is MATLAB-based and uses Monte Carlo (MC) principles to analyze and model subsurface structures (Yovi et al., 2022). Then, it is analyzed using a Monte Carlo simulation to obtain the most suitable curve. The curve is said to be suitable if the misfit value obtained is small and the H/V graph overlaps. In the data processing with Hv-Inv, the thickness, shear wave velocity, compressive wave velocity, and density parameters were obtained as shown in Figure 3.

DFA (Diffuse Field Assumption) assumes that the equal energy-sharing principle determines the relative power of each seismic state that makes up the lighting. The H/V values generated by the DFA are inherent characteristics of the system that need to be compared with properly processed data

(Piña-Flores et al., 2017). Data processing, such as a windowing process to separate microtremor data and transient data. Then, Frequency Sampling is set to see the peak of the curve. And directly inverted on the Inversion page to produce a curve model and velocity model, as shown in Figure 4.

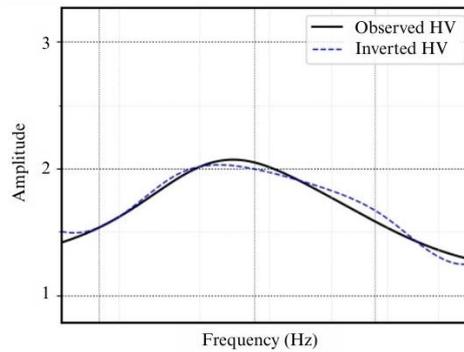


Figure 4. DFA (Diffuse Field Assumption) model curve.

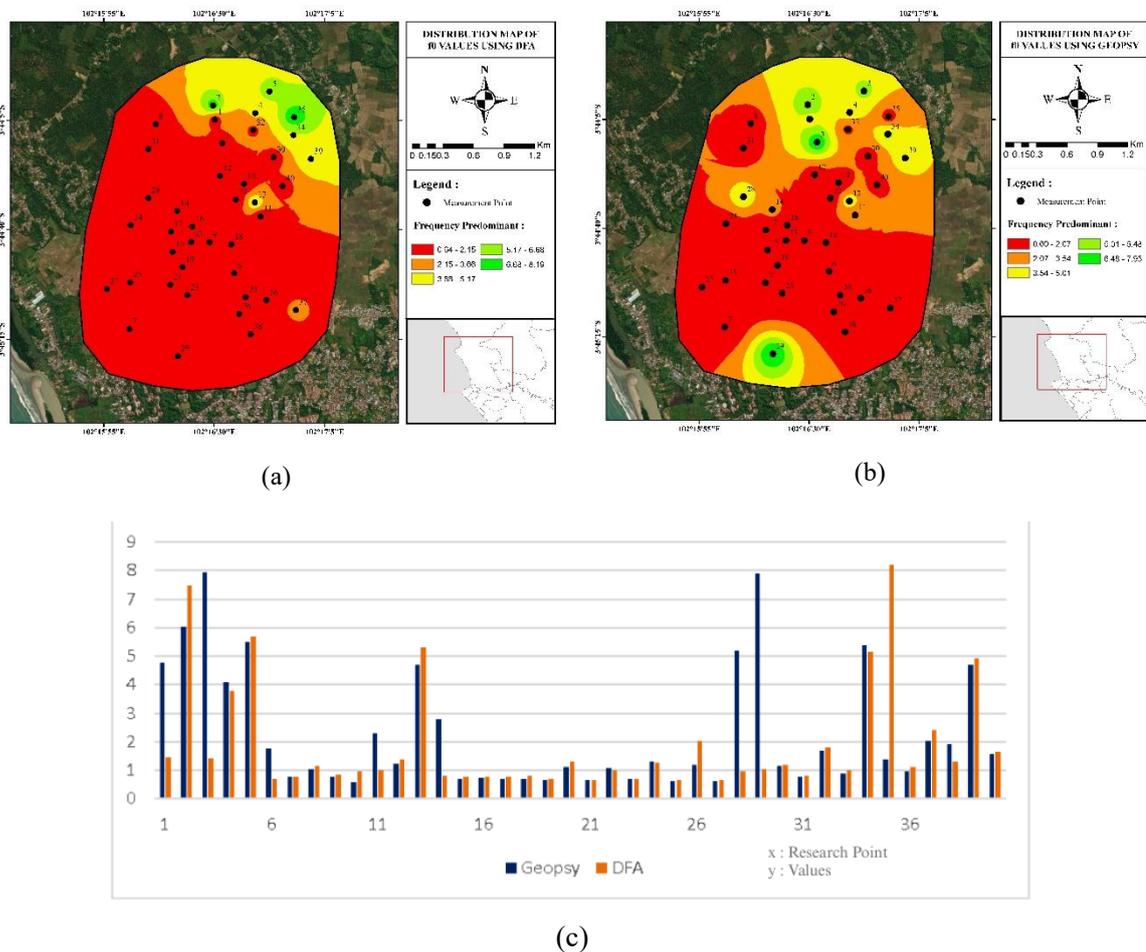


Figure 5. (a) Field measurement points using DFA overlaid on the dominant frequency distribution map of the study area; (b) field measurement points using Geopsy overlaid on the dominant frequency distribution map of the study area; (c) comparison graph of f_0 values obtained from DFA and Geopsy.

3. RESULTS AND DISCUSSION

The value of the natural frequency describes the thickness of the weathered layer below the surface and the speed of the waves through the medium (Syamsuddin et al., 2021). The dominant

frequency is the frequency value that often appears, making it recognizable as the frequency value of the rock layer in the area, which can indicate the type and characteristics of the rock (Shakya, 2015).

The study area's dominant frequency (f_0) runs from 0.64 Hz to 8.19 Hz, which can be seen in the dominant frequency (f_0) distribution map using DFA software in Figure 5a. This map illustrates the variation of soil characteristics with an even distribution of measurement points. The red color indicates the low dominant frequency (0.64-2.15 Hz), covering most of the area, while the orange color (2.15-3.66 Hz) marks the transition area to denser soils. Yellow colors (3.66-5.17 Hz) indicate denser soils, and green to dark green colors (5.17-8.19 Hz) indicate stable soils such as hard or rock layers. While the dominant frequency distribution map using Geopsy software in Figure 5b is still dominated by red color with low dominant frequency (0.60-2.07 Hz) in the southern part of the area, there is a green zone with high dominant frequency (6.48-7.95 Hz). The percentages for the difference in f_0 values compared using DFA and Geopsy are quite varied.

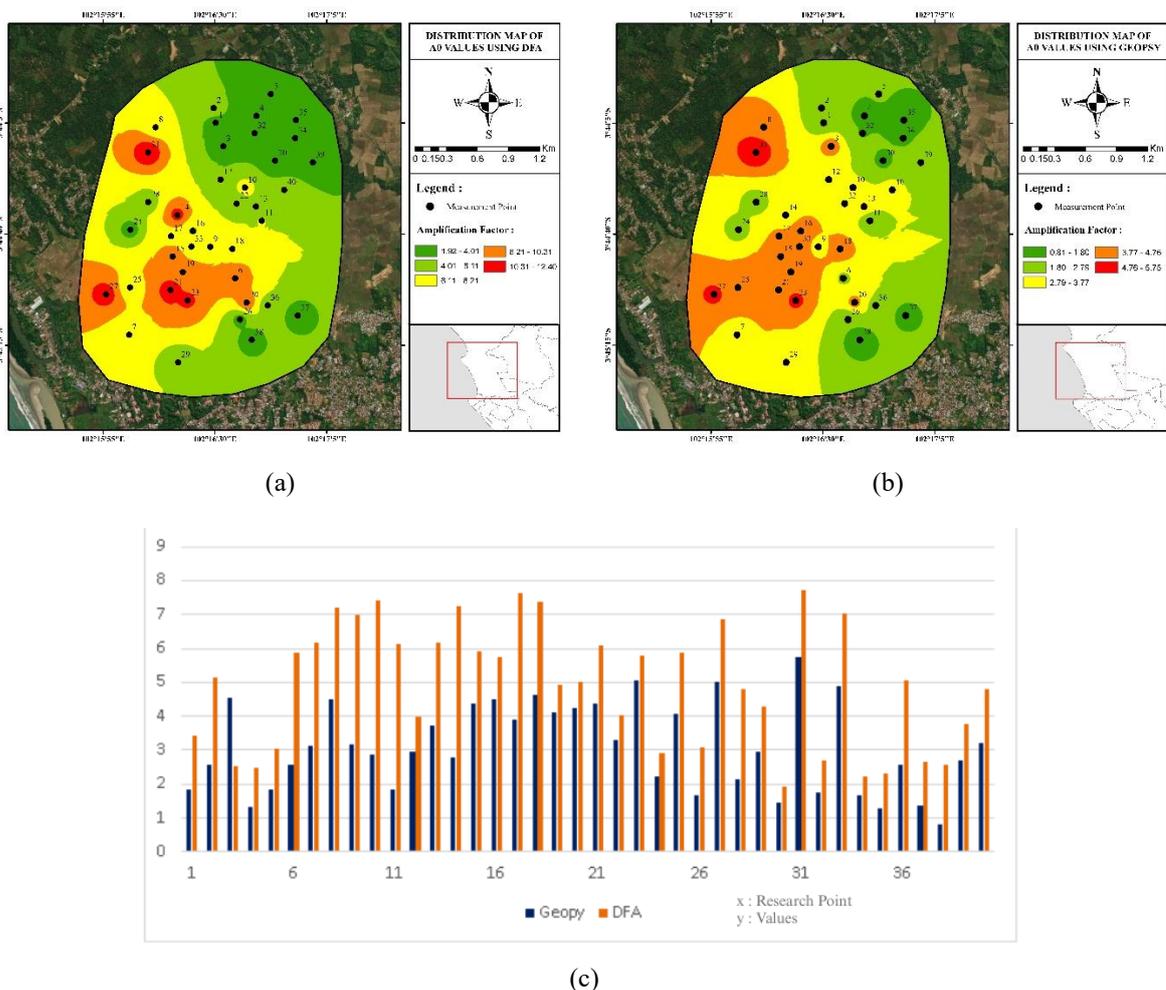


Figure 6. (a) Field measurement points using DFA overlaid on the amplification factor distribution map of the study area; (b) field measurement points using Geopsy overlaid on the amplification factor distribution map of the study area; (c) comparison graph of A_0 values obtained from DFA and Geopsy.

Amplification is the magnification of seismic waves that occurs due to the presence of significant differences between layers. In other words, seismic waves will experience magnification if they propagate from a medium to another medium that is softer than the initial medium through which they travel (Shakya, 2015).

The distribution map of the amplification factor (A_0) in the study area shows the variation of soil amplification to seismic waves. Green areas (1.92-4.24) indicate stable soils, while yellow colors

(4.24-5.45) reflect moderate amplification. Orange color (5.45-6.56) marks the transition zone, and red (6.56-7.72) indicates high amplification and vulnerability. High amplification is concentrated in the northeast and southeast, as seen in the amplification factor distribution map with DFA software, Figure 6a. While the map of the amplification factor in Geopsy software in Figure 6b shows the color of the zone with a dominant low to high difference, as in the middle zone, there is a difference where the value on Geopsy does not show high amplification, which is different from the map using DFA software. Percentages for comparison of the difference in A_0 values using DFA and Geopsy are quite varied.

The vulnerability index formulation used in this study is based on the GNDT II level approach.

This seismic vulnerability methodology is based on post-earthquake damage observations and survey data covering a large number of elements, focusing on the most important aspects and features that determine building damage (Ferreira et al., 2017).

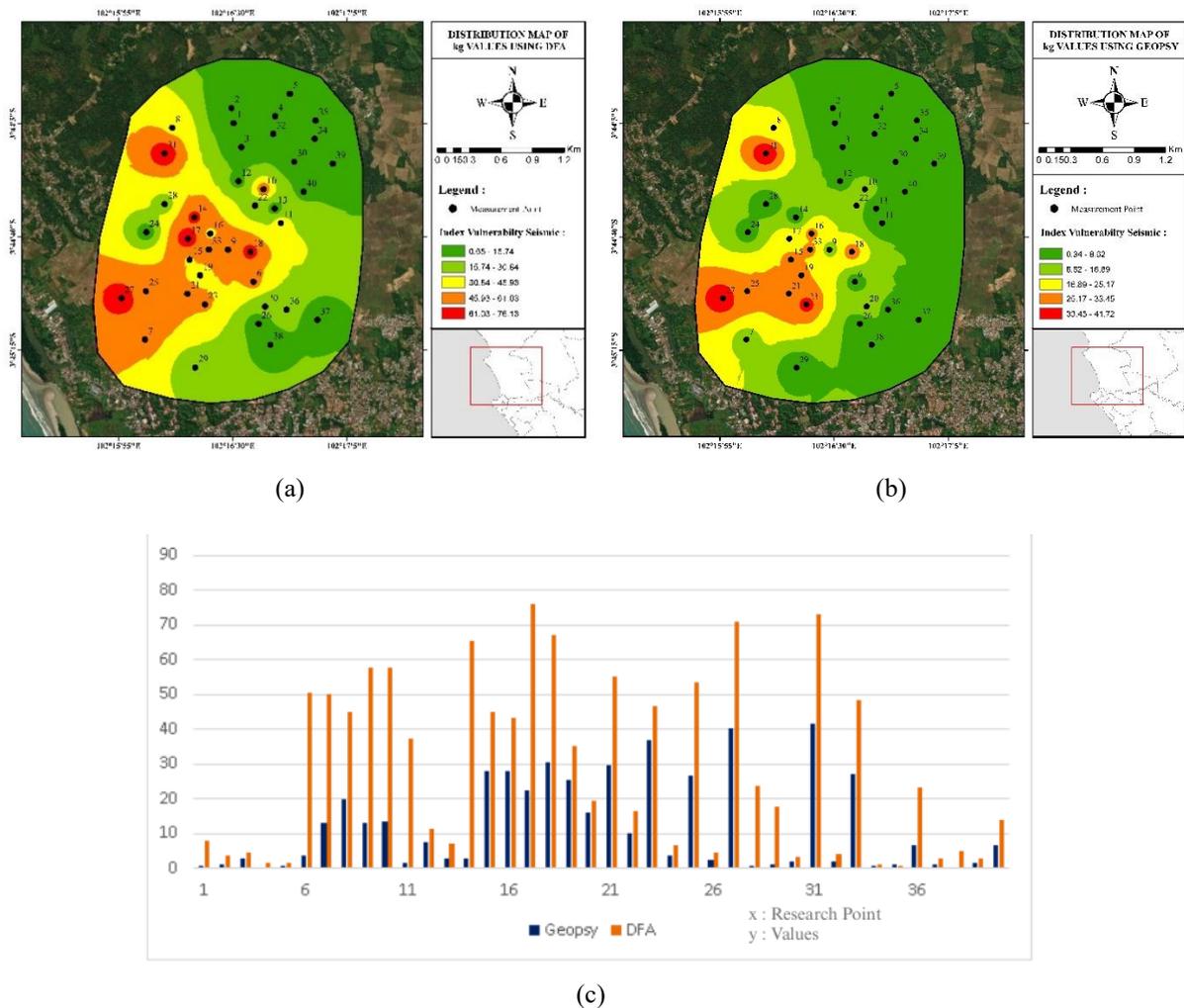


Figure 7. (a) Field measurement points using DFA overlaid on the seismic vulnerability index distribution map of the study area; (b) field measurement points using Geopsy overlaid on the seismic vulnerability index distribution map of the study area; (c) comparison graph of kg values obtained from DFA and Geopsy.

Figure 7a shows the zone with the lowest value (0.65-15.74) in green, reflecting low seismic vulnerability. The yellowish green zone (15.74-30.84) is a transition area, while the yellow color (30.84-45.93) indicates higher vulnerability. Orange (45.93-61.03) and red (61.03-76.13) zones mark the areas of highest vulnerability. At the same time, the seismic vulnerability index distribution map in Figure 7b is dominated by dark green to light green zones (0.34-16.89) with a few orange zones to red zones (25.17-41.72) where the difference with the map using DFA is significant, as high vulnerability is seen

in the center of Figure 7b. Percentages for comparison of the difference in kg values using DFA and Geopsy are quite high.

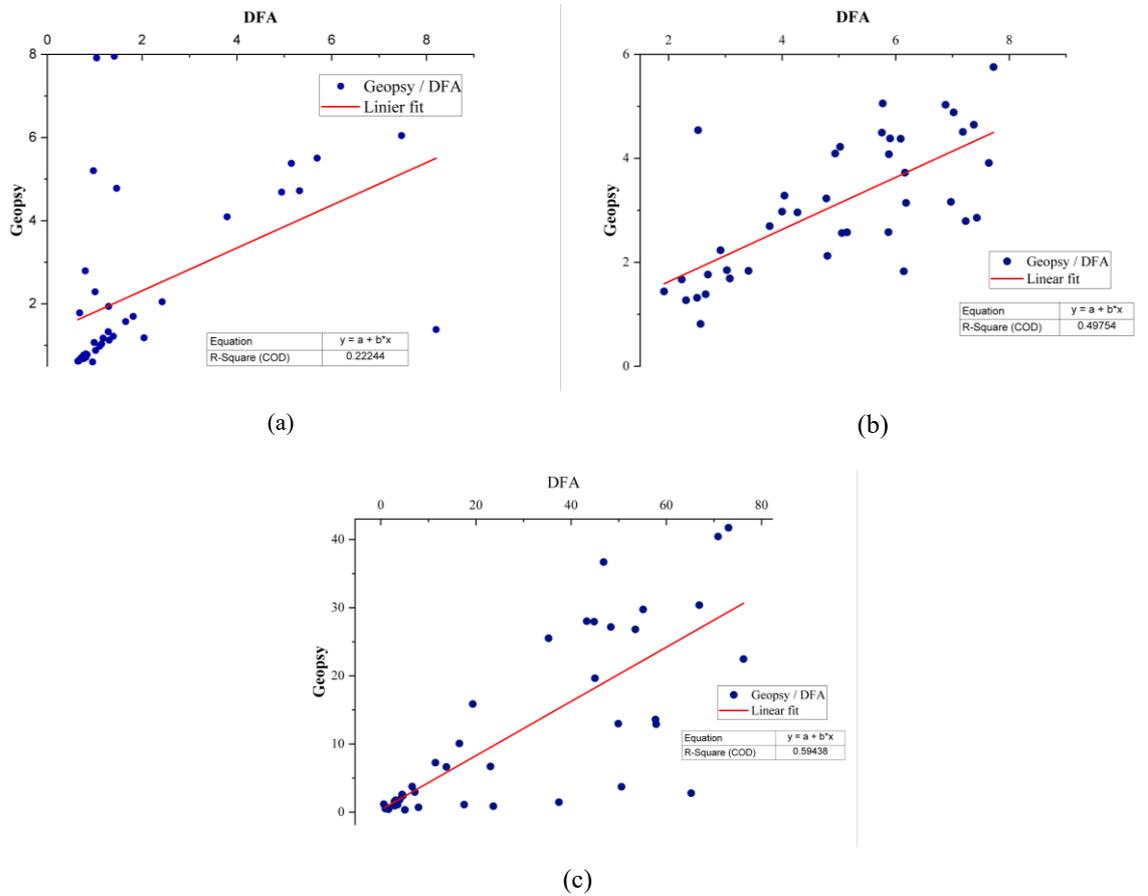


Figure 8. (a) Differences in f_0 values related to the coefficient of determination (R²); (b) differences in A_0 values related to the coefficient of determination (R²); (c) differences in kg values related to the coefficient of determination (R²).

The value of V_s is obtained from the correlation results of processing with DFA and Hv-Inv software. Results of 1D microtremor data processing show examples of dominant lithological variations, such as soil, clay, gravel, and sand at several research points. Figure 9a is point 17, where the rock layer is stable. Figure 8b is point 18, where the soil layer is thicker than the other layers. Figure 9c is point 20, where the clay layer is thin while the gravel layer is thick. Figure 9d is point 33, where the soil layer is quite thick. The surface is generally soil and clay or a mixture of gravel and sand with low to medium stability, while the intermediate layer is dominated by sand with medium to high bearing capacity. Soft rock is found at certain depths, providing good stability for deep foundations.

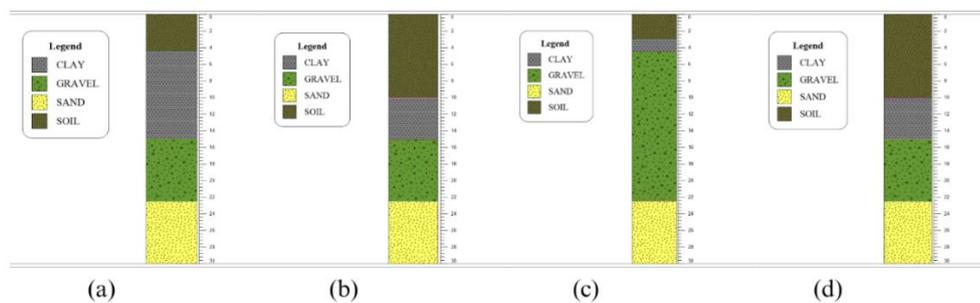


Figure 9. Lithology at observation points: (a) Point 17; (b) Point 18; (c) Point 20; (d) Point 33.

Based on research conducted by Putri et al. (2025) in the Rawa Makmur area and the border between Bengkulu City and Central Bengkulu Regency, it is known that the average V_{s30} in the area varies between 121 and 574 m/s. Based on the classification of the National Earthquake Hazards Reduction Program (NEHRP), this range of values falls into the medium soil (class C-D) to hard soil (class B) category, indicating that most of Aisyah's research area has geological characteristics that are relatively stable to earthquake shaking.

Table 2. Lithology of the research point (Rahmawati et al., 2024).

No	Research Point	Soil Class	V_{s30} (m/s)	Material Type
1	Point 1	E	< 180	Soil
		E	< 180	Clay
		D	180-360	Sand
		E	< 180	Gravel
2	Point 2	E	< 180	Gravel
		E	< 180	Clay
		D	180-360	Sand
		C	360-760	Soft Rock
3	Point 3	E	< 180	Gravel
		D	180-360	Sand
		E	< 180	Clay
		C	360-760	Soft Rock
4	Point 4	D	180-360	Sand
		E	< 180	Gravel
		C	360-760	Soft Rock
5	Point 5	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
6	Point 6	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
		B	760-1500	Sandstone
7	Point 7	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
8	Point 8	E	< 180	Gravel
		E	< 180	Soil
		D	180-360	Sand
		C	360-760	Soft Rock
9	Point 9	E	< 180	Gravel
		E	< 180	Clay
		D	180-360	Sand
10	Point 10	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
11	Point 11	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
12	Point 12	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
13	Point 13	E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
14	Point 14	E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock

15	Point 15	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
16	Point 16	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
17	Point 17	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
18	Point 18	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
19	Point 19	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
20	Point 20	E	< 180	Soil
		E	< 180	Clay
		D	180-360	Sand
21	Point 21	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
22	Point 22	E	< 180	Soil
		E	< 180	Clay
		D	180-360	Sand
		E	< 180	Gravel
23	Point 23	E	< 180	Soil
		E	< 180	Clay
		D	180-360	Sand
		E	< 180	Gravel
		C	360-760	Soft Rock
24	Point 24	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
		B	760-1500	Sandstone
25	Point 25	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
26	Point 26	E	< 180	Gravel
		E	< 180	Clay
		D	180-360	Sand
		C	360-760	Soft Rock
27	Point 27	D	180-360	Sand
		E	< 180	Clay
		E	< 180	Gravel
		C	360-760	Soft Rock
28	Point 28	E	< 180	Soil
		D	180-360	Sand
		E	< 180	Clay
		E	< 180	Gravel
		C	360-760	Soft Rock
29	Point 29	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
30	Point 30	E	< 180	Gravel
		E	< 180	Clay

		D	180-360	Sand
31	Point 31	E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
32	Point 32	E	< 180	Gravel
		D	180-360	Sand
		B	760-1500	Sandstone
		C	360-760	Soft Rock
33	Point 33	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
34	Point 34	E	< 180	Soil
		E	< 180	Gravel
		D	180-360	Sand
		C	360-760	Soft Rock
35	Point 35	E	< 180	Gravel
		E	< 180	Clay
		D	180-360	Sand
36	Point 36	E	< 180	Soil
		E	< 180	Clay
		E	< 180	Gravel
		D	180-360	Sand
37	Point 37	D	180-360	Sand
		C	360-760	Soft Rock
		E	< 180	Clay
38	Point 38	E	< 180	Soil
		D	180-360	Sand
		E	< 180	Gravel
		C	360-760	Soft Rock
39	Point 39	E	< 180	Soil
		E	< 180	Gravel
		E	< 180	Clay
		D	180-360	Sand
40	Point 40	E	< 180	Gravel
		D	180-360	Sand
		E	< 180	Clay
		C	360-760	Soft Rock

In contrast, the results of our research, which focuses on areas in Central Bengkulu Regency, show different soil characteristics. Based on the results of microtremor data analysis, V_{s30} values were obtained in the range of 50 to 360 m/s. This range indicates that the soils in our study area are classified as soft to medium soils (class E to D according to NEHRP classification). This suggests that most areas in Central Bengkulu tend to have softer soil characteristics, potentially amplifying the effects of earthquake shaking compared to the border areas of Bengkulu City studied by Putri et al. (2025).

This comparison is important in earthquake disaster mitigation efforts, as areas with low V_{s30} (soft soils) have the potential for greater wave amplification and therefore a higher risk of damage to building structures. The results of this study can serve as a basis for local government in developing seismic vulnerability zoning as well as more disaster-resilient development strategies, particularly in the Central Bengkulu region (Putri et al., 2025).

Shear wave velocity is an important parameter in interpreting the subsurface conditions of an area. The V_s is also a direct indicator of soil stiffness and strength, where the greater the shear wave velocity, the greater the hardness of the soil or rock (Rahmawati et al., 2024). 3D microtremor modeling in Pondok Kelapa reveals the spatial distribution of V_s in the range of 55-465 m/s. Low V_s zones (55-157 m/s), colored red, indicate soft materials such as clay or loose sand, while high V_s zones (260-465 m/s), colored orange to yellow, reflect dense sand to bedrock. Vertically, the shallow layers (0-10 m) are dominated by soft materials that have the potential for seismic amplification, while depths >10 m show a transition to denser materials. Laterally, low V_s are scattered across the surface, while high V_s are concentrated in specific areas, reflecting geological heterogeneity. The isosurface model identifies

“island” shaped anomalies representing hard material zones. Geological interpretation shows the shallow layer consists of low-consolidation alluvial material, while the deep layer is dominated by compact sand to more seismically stable bedrock. These findings are crucial for seismic analysis, risk zoning, and construction planning.

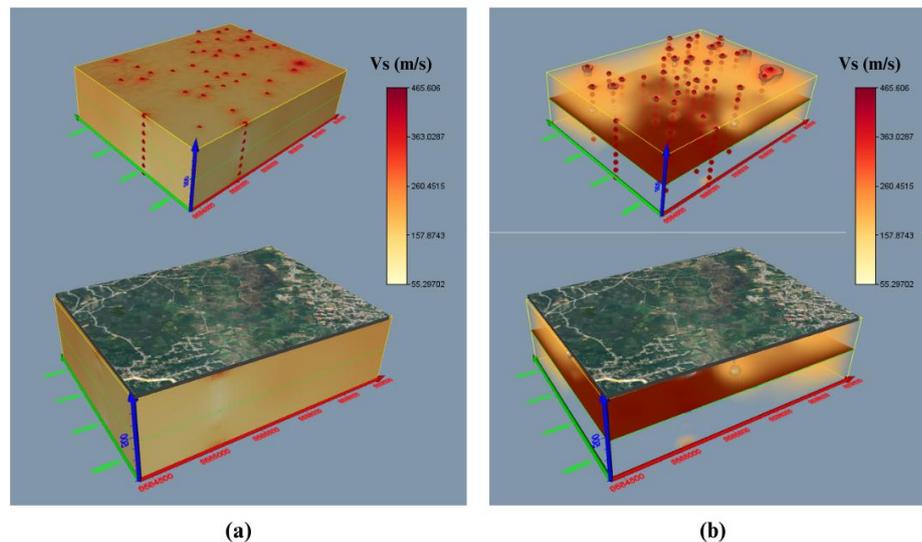


Figure 10. (a) 3D model of V_s variations from the surface to depth based on microtremor measurement points; (b) 3D model of soil characteristic zones identified by isolating areas with similar V_s values from microtremor data.

The modeling results have various applications, such as seismic risk zoning, where areas with low V_s values need special attention due to the potential for high amplification of earthquake waves, thus risking greater damage. Understanding the V_s distribution is also important for construction planning, especially in determining foundation design in high-risk zones or selecting construction sites in stable zones with high V_s values. In addition, the 3D modeling provides insight into the subsurface structure, including the presence of hard materials that are important for geotechnical evaluation.

4. CONCLUSION

The research results indicate that areas dominated by low frequencies (0.54–5.17 Hz in DFA and 0.60–5.01 Hz in Geopsy) are more susceptible to seismic amplification, highlighting the need for careful consideration in earthquake disaster mitigation. In contrast, areas characterized by higher dominant frequencies (1.92–8.21 Hz in DFA and 0.81–3.77 Hz in Geopsy) are relatively more stable and therefore more suitable for large-scale infrastructure development. Zones with low dominant frequencies require special structural design to reduce resonance risks during seismic events, while areas with high amplification (red and orange zones) should be prioritized in disaster mitigation efforts, including earthquake-resistant construction and prudent spatial planning. Conversely, zones with low amplification (green zones) are better suited for major infrastructure projects due to lower seismic risks. Furthermore, the seismic vulnerability map shows that regions with high vulnerability (45.93–76.13 in DFA and 25.17–41.72 in Geopsy) demand special attention in development and disaster mitigation planning. Meanwhile, areas with lower vulnerability values (0.65–45.93 in DFA and 0.34–25.17 in Geopsy) are more stable and thus safer for large-scale infrastructure. Overall, the differences in frequency, amplitude, and seismic vulnerability index values between DFA and Geopsy are relatively minor, indicating consistency between both methods.

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