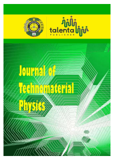
Journal of Technomaterial Physics
Journal homepage: https://talenta.usu.ac.id/JoTP



Analysis of Rock Layering Structure Using Shear Wave Velocity from HVSR Inversion

Delpa Astuti[1], Refrizon[1]*, Arif Ismul Hadi[1], Muhammad Najib Syami Muqtadir[2]
[1] *Department of Physics, Faculty of Mathematics and Natural Sciences, University of Bengkulu, Bengkulu, 38371, Indonesia.*
[2] *Kepahiang Geophysical Station, Meteorology, Climatology, and Geophysics Agency (BMKG), Kepahiang, Bengkulu, 38221, Indonesia.*

*Corresponding Author: refrizon@unib.ac.id

ARTICLE INFO

Article history:
Received 13 April 2026
Revised 02 May 2026
Accepted 08 May 2026
Available online 11 May 2026

E-ISSN: 2656-0755
P-ISSN: 2656-0747

How to cite:
D. Astuti, Refrizon, A. I. Hadi, and M. N. S. Muqtadir, "Analysis of Rock Layering Structure Using Shear Wave Velocity from HVSR Inversion," Journal of Technomaterial Physics, vol. 08, no. 01, pp. 68–82, Feb. 2026, doi: 10.32734/jotp.v8i1.25203.

ABSTRACT

The Musi Ujan Mas Hydropower Plant (HPP) area in Kepahiang lies within an active tectonic zone influenced by the Sumatra Fault, making it prone to earthquakes. This study aims to analyze subsurface rock structures and seismic vulnerability using shear wave velocity derived from the Horizontal to Vertical Spectral Ratio (HVSR) inversion method with TerraWareHV software. Microtremor data were collected at 40 measurement points, each recorded for approximately 30 min. HVSR analysis was used to derive the dominant frequency (f_0) and amplification factor (A_0), which were subsequently used to generate shear wave velocity models V_{s0}, V_{s10}, V_{s20}, V_{s30}. The results show that the f_0 values range between 1.28 and 5.55 Hz, with most locations characterized by low frequencies associated with thick sediment layers and weak soil materials. The A_0 values vary between 2.99 and 16.86, with higher amplification observed in areas composed of less compact lithology. The inversion results indicate noticeable variations in shear wave velocity with depth, suggesting heterogeneous subsurface conditions. The study area is predominantly composed of thick sediment layers with moderate to high amplification potential. These findings provide valuable insights into local site effects and support seismic hazard assessment and infrastructure development in the region.

Keywords: Amplification, Dominant Frequency, Sediment Thickness, Seismic Vulnerability, Sumatra Fault

ABSTRAK

Kawasan Pembangkit Listrik Tenaga Air (PLTA) Musi Ujan Mas di Kepahiang terletak di dalam zona tektonik aktif yang dipengaruhi oleh Sesar Sumatra, sehingga rentan terhadap gempa bumi. Penelitian ini bertujuan untuk menganalisis struktur batuan bawah permukaan dan kerentanan seismik menggunakan kecepatan gelombang geser yang diperoleh dari metode inversi Rasio Spektral Horizontal-ke-Vertikal (HVSR) dengan perangkat lunak TerraWareHV. Data mikrogetaran dikumpulkan di 40 titik pengukuran, masing-masing direkam selama sekitar 30 menit. Analisis HVSR digunakan untuk menentukan frekuensi dominan (f_0) dan faktor amplifikasi (A_0), yang kemudian digunakan untuk menghasilkan model kecepatan gelombang geser V_{s0}, V_{s10}, V_{s2} , V_{s30}. Hasil menunjukkan bahwa nilai f_0 berkisar antara 1,28 dan 5,55 Hz, dengan sebagian besar lokasi ditandai oleh frekuensi rendah yang terkait dengan lapisan sedimen tebal dan material tanah yang lemah. Nilai A_0 bervariasi antara 2,99 dan 16,86, dengan amplifikasi yang lebih tinggi teramati di area yang terdiri dari litologi yang kurang padat. Hasil inversi menunjukkan variasi yang signifikan pada kecepatan gelombang geser seiring dengan kedalaman, yang mengindikasikan kondisi bawah permukaan yang heterogen. Wilayah studi sebagian besar terdiri dari lapisan sedimen tebal dengan potensi amplifikasi sedang hingga tinggi. Temuan ini memberikan wawasan berharga mengenai efek lokasi lokal dan mendukung penilaian bahaya seismik serta pengembangan infrastruktur di wilayah tersebut.

Kata kunci: Amplifikasi, Frekuensi Dominan, Ketebalan Sedimen, Kerentanan

http://doi.org/10.32734/jotp.v8i1.25203

Seismik, Sesar Sumatra

1. Introduction

Geologically, Indonesia's high tectonic activity is influenced by its location at the convergence of three major tectonic plates the Indo Australian, Eurasian, and Pacific plates [1]. This condition causes most of Indonesia to experience high levels of seismic activity, including Bengkulu Province, which is crossed by the subduction zone and the Sumatra Fault, particularly the Musi Segment that stretches across Kepahiang Regency [2]. For example, an earthquake with a magnitude of approximately 6.3 occurred on May 23, 2025, off the southwest coast of Bengkulu, indicating uplift fault activity in the subduction zone [3]. This makes the region highly vulnerable to earthquakes. Therefore, seismic studies are needed as a mitigation measure against potential disasters [2].

One important area that has become the focus of research is the area around the Musi Ujan Mas Hydropower Plant (HPP) in Kepahiang. This HPP serves as vital infrastructure in providing electricity to the community. Therefore, the stability and safety of its construction must be thoroughly considered. Given that the Musi HPP is located near the Sumatran Fault, specifically the Musi Segment, the proximity of these faults to this critical infrastructure increases the region's vulnerability to strong earthquakes that could disrupt the power supply. Subsurface geological conditions significantly influence the ground's response to seismic vibrations, where certain soil layer characteristics can amplify or dampen seismic waves spreading to the surface. Therefore, geophysical studies around the Musi HPP are crucial for gaining a deeper understanding of the potential earthquake hazards.

Various studies have demonstrated the effectiveness of the Horizontal-to-Vertical Spectral Ratio (HVSR) method in evaluating subsurface conditions and seismic trace effects. Ahmad Zaenudin et al. [4] applied HVSR inversion to estimate shear wave velocity (V_s) structures and identified subsurface layers and geological features. Similarly, Mita Uthaman et al. [5] utilized HVSR analysis for site characterization, demonstrating its ability to classify soil conditions based on V_s profiles. Furthermore, YiFan Yang et al. [6] demonstrated that the dominant frequency (f_0) obtained from HVSR can be effectively used to estimate sediment thickness and spatial variability in earthquake hazard assessment.

In addition, microtremor-based studies conducted in the Kepahiang region, such as those reported by Arif et al. [7] and related investigations [8], have demonstrated that HVSR analysis is effective in identifying subsurface structures, dominant frequency, and amplification characteristics associated with local geological conditions. These studies indicate that variations in dominant frequency and amplification are strongly influenced by sediment thickness, lithology, and subsurface heterogeneity. Furthermore, the geological setting of Kepahiang is influenced by volcanic activity, particularly from Mount Kaba, and is characterized by volcanic rocks, alteration zones, and fault structures that control subsurface properties and seismic response [7], [8]

However, most previous studies in the Kepahiang region have focused on regional-scale analyses and have not provided a detailed picture of subsurface characteristics specific to locations near critical infrastructure such as the Musi HPP. Consequently, the application of the HVSR method combined with inversion techniques in this region remains limited.

In this study, the use of TerraWareHV with the Diffuse Field Assumption (DFA) approach enables a more comprehensive analysis by considering multiple wave types (P, S, Rayleigh, and Love), resulting in a more reliable shear wave velocity (V_s) model. This approach offers a more detailed characterization of subsurface conditions and seismic vulnerability compared to previous studies.

Analysis of subsurface conditions and seismic vulnerability levels in the Musi HPP area was conducted using microtremor method through the Horizontal Vertical Spectral Ratio (HVSR) approach developed by Nakamura [9]. This method utilizes natural ground vibrations to obtain key parameters, such as dominant frequency (f_0) and wave amplification (A_0). These parameters are then used to estimate the seismic vulnerability index (K_g), which indicates the relative potential for damage in a given area during a seismic event. Furthermore, the outcomes of the HVSR method are combined to estimate V_{s0}, V_{s10}, V_{s2} , V_{s30}, corresponding to the average shear wave velocities at depths of 0, 10, 20, and 30 m, respectively, which serve as international standards for soil classification [10]. This study also produced a three-dimensional

(3D) model of shear wave velocity (V_s) based on the results of microtremor inversion. This 3D model illustrates the variation in V_s values, providing a clearer visualization of the subsurface structure.

In this research, the inversion process was carried out using TerraWareHV, Python 3.7.x-based software developed by Geotem Ingeniería. This program calculates the H/V spectral ratio and performs inversion by applying the Diffuse Field Assumption (DFA) approach, which considers all types of seismic waves, namely P, S, Rayleigh, and Love waves [11], thereby producing a more accurate subsurface structure model. TerraWareHV was chosen because of its easy-to-understand interface, support for automatic and manual inversion modes, and the ability to visualize results that can be viewed immediately. Through the inversion process, the resulting H/V spectral ratio is converted into a shear wave velocity (V_s) model that characterizes the subsurface structure. These advantages make TerraWareHV a reliable and efficient tool for estimating the subsurface structure of rock layers, utilizing shear wave velocities V_{s0}, V_{s10}, V_{s20}, V_{s3} and seismic vulnerability analysis.

The objective of this study is to analyze the subsurface structure and seismic vulnerability in the area surrounding the Musi Hydropower Plant using HVSR inversion, as well as to estimate shear wave velocity parameters V_{s0}, V_{s10}, V_{s20}, V_{s3} .

2. Materials and Methods

Microtremor data acquisition for this research was conducted at 40 recording points distributed across the Musi HPP area, Ujan Mas District, Kepahiang Regency. This research was conducted on May 1-4 and 11, 2025, in the Ujan Mas District, Kepahiang Regency, Bengkulu Province. The device used was a PASI Mod Gemini 2 Sn-140S short-period portable seismometer with a sampling frequency of 200 Hz. The distribution of recording points is shown in Figure 1. At each point, passive recording was carried out for approximately 30 min to ensure signal stability and minimize the influence of external interference. The measurement points were selected to represent variations in local geological conditions, allowing the HVSR analysis to better characterize the subsurface structure.

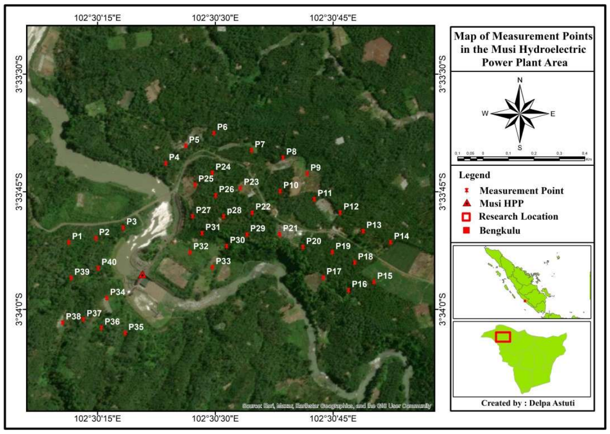


Figure 1. Measurement Point Map.

According to the geological map of Kepahiang Regency (Figure 2), the Kepahiang area consists of Quaternary volcanic rocks, diorite intrusions, and Tertiary sedimentary and volcanic rock formations, including the Gumai Formation, Hulusimpang Formation, and Seblat Formation, with the addition of the Kaba Volcano unit. Quaternary volcanic rocks and Kaba Volcano are generally composed of lava, breccia, and tuff that are still young and easily weathered, while diorite is more compact and stable [12]. Tertiary sedimentary formations are dominated by sandstone, claystone, shale, and limestone with varying degrees of compactness. These geological conditions form the morphology of hills to mountains with varying susceptibility to erosion, landslides, and earthquakes.

The research location is indicated by a green triangle symbol on the map. The area is located in a zone dominated by Quaternary volcanic rocks. These conditions have the potential to produce subsurface characteristics with relatively low to moderate shear wave velocity (V_s) values, due to the reduced compactness of the rock material. In addition, the research location is close to geological structures and active faults that develop in the Bengkulu region, so that tectonically, the area has the potential for greater shock amplification when seismic activity occurs. Therefore, understanding the geological conditions around the study site is important in interpreting subsurface parameters, disaster mitigation, and geotechnical analysis for infrastructure development in Kepahiang Regency [7].

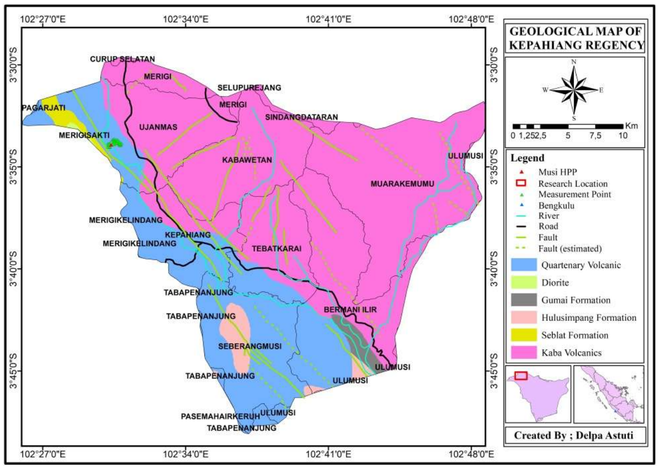
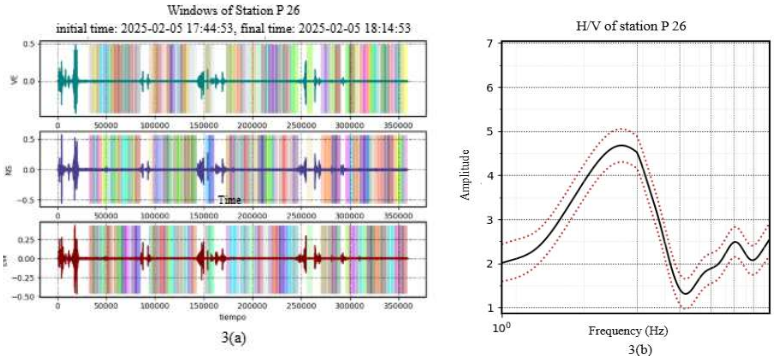


Figure 2. Geological Map of Kepahiang, Bengkulu Province, modified from [13], [14].

Microtremor data processing is performed using TerraWareHV software through several stages. First, the data recorded by the seismometer is entered into the TerraWareHV software. This data consists of three components (N–S, E–W, and Z), which are displayed in the form of a time series. Next, adjustments are made to the processing parameters available in TerraWareHV, including the type of frequency normalization (Normalization), the type of taper window (Window), the taper window function (Taper window), the window length (Window length), and the HVSR analysis frequency range (Frequencies for HVSR). Other processes, such as signal trend removal (Remove trend), One-bit normalization, and the application of Konno-Ohmachi smoothing, can be performed as needed to smooth the spectrum.

After the parameters are determined, the software segments the signal into multiple windows based on the selected window length, then computes the horizontal-to-vertical spectrum ratio (HVSR). The results are displayed in the form of an HVSR curve showing the dominant frequency value (f_0) at the peak of the curve, and the amplification factor (A_0), an example of the windowing process and the HVSR curve resulting from processing using TerraWareHV can be seen in Figure 3. (a) and (b).



3(a)

3(b)

Figure 3. (a) Example of the windowing process and (b) example of the HVSR P26 curve resulting from processing using TerraWareHV

The HVSR method, introduced by Nakamura [9], is an approach that utilizes the spectral ratio of the horizontal and vertical components of microtremor signals. Microseismic activity refers to continuous ground vibrations of very small amplitude that originate from various sources, including both human activities and natural processes [15]. This approach is applied to determine the horizontal-to-vertical component ratio (HVSR) from microtremor recordings at a specific site, thereby representing the dynamic properties of the surface layer. As formulated in Equation (1) [16], this method can reveal a strong correlation between the dominant frequency and the condition of the subsurface layer, especially in soft soil environments.

$$HVSR(f) = \frac{\sqrt{H_{NS}^2(f) + H_{NW}^2(f)}}{V(f)} \tag{1}$$

From the HVSR curve results, two main parameters can be obtained, namely the dominant frequency (f_0), which indicates the thickness and properties of the sediment layer, and the amplification factor (A_0), which describes the level of seismic wave amplification at that location. Furthermore, these two parameters are used to calculate the seismic vulnerability index (K_g) formulated in Equation (2) [17].

$$K_g = \frac{A_0^2}{f_0} \tag{2}$$

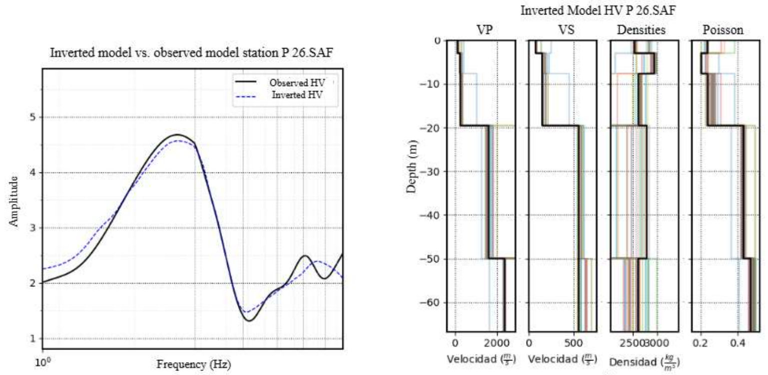
The seismic vulnerability index (K_g) represents a parameter used to assess the susceptibility of the surface soil layer to deformation induced by earthquake ground motion [18]. This parameter can be determined through microearthquake data analysis and is used to represent the capacity of near-surface soil layers to respond to or resist deformation caused by earthquakes [19]. Where A_0 is the amplification factor and f_0 is the dominant frequency.

Microtremor data processing was carried out using TerraWareHV software. The HVSR curves were obtained by dividing the horizontal spectral component by the vertical component of ground motion. The data processing parameters included a window length of 40 s, a frequency range of 2-20 Hz, a KonnoOhmachi smoothing coefficient of 20-30, and the application of a 40% cosine taper to minimize spectral leakage. These parameters were selected to ensure stable and reliable HVSR curves.

The next step is to invert the observed HVSR curve. At this stage, the HVSR curve is compared with the theoretical curve based on the initial model, which includes the layer thickness and shear wave velocity for each subsurface layer. The calculation of the theoretical HVSR curve in TerraWareHV is carried out based on the Diffuse Field Assumption (DFA) approach, where the HVSR value is expressed as the ratio of horizontal and vertical wave energy through the imaginary part of the Green's function, as stated in Equation (3).

$$H/V(x,\omega) = \frac{Im[G_{11}(x,x;\omega] + Im[G_{22}(x,x;\omega]}{Im[G_{33}(x,x;\omega]} \tag{3}$$

This formula is based on the DFA theory proposed by [11], which is implemented in the software to generate HVSR curves from subsurface models, which are then compared with the observed curves. Iterations are performed until the smallest misfit value between the observational data and the theoretical model is obtained, resulting in a subsurface shear wave velocity (V_s) model, as shown in Figure 4. (a) and 4(b).



4(a) 4(b)

Figure 4. (a) An example showing the comparison of the observed HVSR curve with the inversion results, along with (b) the HVSR inversion model obtained from data processing using TerraWareHV.

Figure 4. (a) presents a comparison of the recorded HVSR curve (shown as a black line) and the modeled HVSR curve (displayed as a blue dashed line). The recorded curve reflects the original spectral response of

microtremor signals obtained during field measurements, whereas the modeled curve represents the outcome of the inversion process used to derive the most suitable subsurface structure. The similarity between the two curves indicates that the inversion model is able to represent the subsurface geological conditions well. Figure 4. (b) shows the HVSR inversion model consisting of P-wave velocity (V_p), S-wave velocity (V_s), rock density, and Poisson's ratio versus depth. In this study, the V_s value is the basis for determining parameters such as V_{s0}, V_{s10}, V_{s20}, V_{s30} in the Musi HPP area.

Based on the inversion results obtained, the average shear wave velocity values at various depths (V_{s0}, V_{s10}, V_{s20}, V_{s30}) were calculated using the thickness and velocity parameters of the modeled layers. To calculate these values, equations referring to the Uniform Building Code were used according to [20], [21], [22].

The average shear wave velocity at depths of 10, 20, and 30 m (V_{s10}, V_{s20}, V_{s30}) was derived from the HVSR inversion results using the layer thickness and velocity parameters, as expressed in Equations (4), (5), dan (6).

$$V_{s10} = \frac{10}{\sum_{i=1}^{n} \frac{di}{Vsi}} \tag{4}$$

$$V_{s20} = \frac{20}{\sum_{i=1}^{n} \frac{di}{Vsi}} \tag{5}$$

$$V_{s30} = \frac{30}{\sum_{i=1}^{n} \frac{di}{Vsi}} \tag{6}$$

where di is the thickness of the i th layer and Vsi is the shear wave velocity of each layer.

In addition, distribution maps of the HVSR parameters (f_0, A_0, and K_g) were created using ArcGIS software. A three dimensional shear wave velocity model (V_s 3D) was constructed by interpolating the inversion results at all measurement points to visualize variations in subsurface conditions down to a depth of approximately 60 m.

3. Result and Discussion

This study analyzes the subsurface conditions of the study area through four main parameters, namely dominant frequency (f_0), amplification factor (A_0), soil vulnerability index (K_g), and average shear wave velocity (V_s to depths of 0, 10, 20, and 30 m). These values were obtained from microtremor data processing using the HVSR method, followed by an inversion process to derive the shear wave velocity profile. The analysis map provides a comprehensive overview of subsurface characteristics and seismic vulnerability level, and is able to describe the soil layer configuration in more detail in the area around the Musi HPP, which can be used as a basis for consideration in infrastructure planning and disaster mitigation efforts in the area around the Musi HPP.

3.1. Dominant Frequency (f_0)

The dominant frequency refers to the frequency at which the soil layer experiences the highest vibration amplification when exposed to seismic waves [23]. The results of HVSR analysis performed using TerraWareHV software show that, different f_0 values were obtained at each measurement point. In this study, the classification of f_0 values refers to the division proposed by Kanai (1957) to group soil layer conditions based on their frequency response. The results of the HVSR analysis obtained using TerraWareHV indicate that the dominant frequency (f_0) in the Musi Ujan Mas Kepahiang hydroelectric power plant area ranges from 1.28 to 5.55 Hz. Low f_0 values (around 1–2 Hz), shown in green, dominate about 70% of the study area, indicating the presence of very thick and soft surface sediments, generally exceeding 30 m in thickness. Moderate f_0 values (2.5–4 Hz), shown in light green, cover about 20% of the area and reflect relatively thick sediment layers (10–30 m). Meanwhile, higher f_0 values (4–5.55 Hz), shown in orange and covering about 10% of the area, indicate thinner and relatively stiffer sediment layers. Table 1 shows the distribution of dominant frequency classifications based on the values obtained, which are visualized with a distribution map in Figure 5.

Table 1. Soil Classification Based on Dominant Frequency Values according to Kanai [24].

Classification Type	Land Type	f_0 (Hz)	References	Point	Percentage
IV	I	6,67–20	Siregar and Madlazim, 2017		
IV	II	4 - 6,67	Siregar and Madlazim, 2017	P4 P5 P6 P23	10%
III	III	2,5 – 4	Siregar and Madlazim, 2017	P1 P8 P9 P10 P15 P33 P35 P39	20%
II	IV	<2,5	Siregar and Madlazim, 2017	P2 P3 P7 P11 P12 P13 P14 P16 P17 P18 P19 P20 P21 P22 P24 P25 P26 P27 P28 P29 P30 P31 P32 P34 P36 P37 P38 P40	70%

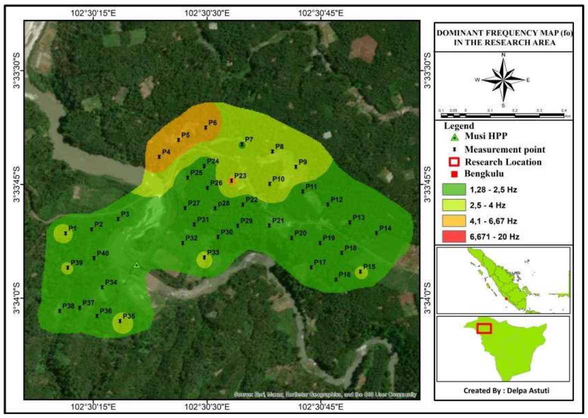


Figure 5. Distribution Map f_0.

The results of this study are consistent with previous studies. A study by Siregar and Madlazim [24] showed that microtremor analysis using the HVSR method can identify soil structure characteristics based on dominant frequency and amplification values, where variations in these values reflect differences in geological conditions and the degree of seismic wave amplification at a given location. Furthermore, Yang et al. [6] state that the dominant frequency obtained from HVSR analysis is correlated with sediment thickness, and can therefore be used to estimate the distribution of sediment thickness.

Geologically, these variations in f_0 values reflect local geological conditions in the Ujan Mas area, as indicated by geological maps showing the presence of Quaternary volcanic rocks, particularly alluvial materials composed of loose to unconsolidated sediments. Low f_0 values suggest the presence of thick, soft sedimentary layers, which have the potential to increase seismic wave amplification and a location's vulnerability. Nevertheless, this interpretation must be approached with caution, given the presence of local heterogeneity and measurement conditions that can also influence HVSR analysis results.

In general, the variation in the value of f_0 is influenced by the factors of subsurface shear wave velocity (V_S) and sediment layer thickness (h). This relationship is consistent with the soil layer resonance theory, in which the dominant frequency is directly proportional to shear wave velocity and inversely proportional to sediment layer thickness [25]. Thus, the thicker the sediment and the softer the material, the lower the dominant frequency value produced, and vice versa.

3.2. *Soil Amplification (A_0)*

The seismic amplification factor indicates the level of vibration amplification due to differences in rock layer characteristics. The amplification factor tends to be higher in weathered rocks than in rocks that are still relatively compact or medium. The greater the amplification factor value, the stronger the seismic wave amplification, especially in rocks that have undergone weathering, fracturing, or other physical changes [17]. Table 2 shows the distribution of Soil Amplification classifications based on the values obtained, which are visualized with a distribution map in Figure 6.

Table 2. Classification of Amplification Factors [26].

Classification	Amplification Value	Reference	Point	Percentage
Very Low	$\boldsymbol{A_0}$<3	Tohari and Wardana, 2018	P15 P20 P23 P39	10%
Low	$3 \leq \boldsymbol{A_0} < 6$	Tohari and Wardana, 2018	P2 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14 P16 P17 P18 P19 P21 P22 P24 P25 P26 P27 P28 P29 P30 P31 P32 P34 P35 P40	75%
Moderate	$6 \leq \boldsymbol{A_0} < 9$	Tohari and Wardana, 2018	P1 P3 P33	7,5%
High	$9 \leq \boldsymbol{A_0} < 12$	Tohari and Wardana, 2018	P36	2,5%
Very High	$\boldsymbol{A_0}$ >12	Tohari and Wardana, 2018	P37 P38	5%

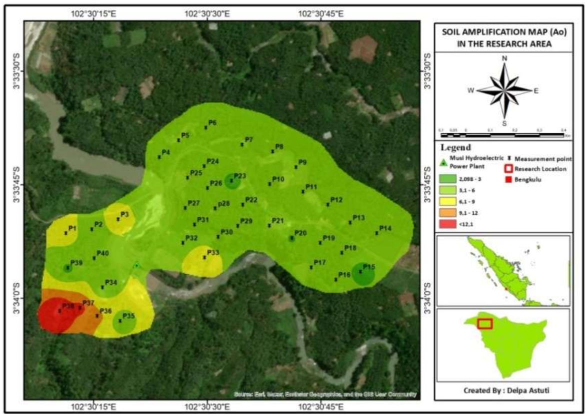


Figure 6. Distribution Map A_0

The results of the HVSR analysis obtained using TerraWareHV indicate that the seismic amplification factor (A_0) in the Musi Ujan Mas Kepahiang hydroelectric power plant area ranges from 2.99 to 16.86. High amplification values (10–16.86), shown in dark red and orange, are concentrated around measurement points P36, P37, and P38 and cover approximately 7.5% of the study area (high and very high zones). These high A_0 values indicate the potential for strong seismic wave amplification, which is generally associated with soft soil conditions and thick sediment layers. Moderate amplification values (5.33–10.20), shown in yellow and scattered across several points such as P1 and P3, also cover approximately 7.5% of the study area and reflect intermediate site response characteristics. Meanwhile, the majority of the study area—approximately 85% (low and very low zones) is characterized by low amplification values (A_0 < 6), shown in green and light green, indicating relatively denser subsurface conditions with lower amplification potential

The results of this study are consistent with previous studies. Mita Uthaman et al. [5] stated that high amplification is associated with unconsolidated sediments and low V_s, whereas low amplification reflects denser material. YiFan Yang et al. [6] demonstrated that variations in amplification are influenced by sediment thickness and subsurface heterogeneity. Additionally, Tohari et al. [26] revealed that high amplification correlates with zones of significant building damage, particularly in alluvial deposits

Analysis results indicate that the obtained amplification patterns align with the regional geological conditions of the Kepahiang area. Based on the geological map by S. Gafoer et al. [13], the study area is dominated by alluvial deposits and sediments consisting of clay, silt, and sand. These unconsolidated materials are characterized by low shear wave velocities and high impedance contrast, which amplify seismic waves. The presence of localized high A_0 zones indicates variations in sediment thickness and composition, likely controlled by depositional processes and structural influences.

In theory, the value of A_0 is influenced by the physical properties of the soil layer, including shear wave velocity (V_s), density, and sediment thickness [10]. The greater the A_0 value, the higher the potential for amplification during an earthquake, so it is vulnerability and requires more extensive disaster mitigation planning. Therefore, information on the A_0 value is important as a basis for seismic. Risk analysis in research.

3.3. Seismic Vulnerability (K_g)

The seismic vulnerability index is the degree of vulnerability the susceptibility of near-surface soil layers to deformation under ground vibrations. The seismic vulnerability index may be identified using the Microtremor method. The seismic vulnerability index indicates the ability of the surface soil layer to withstand deformation [19]. The seismic vulnerability index (K_g) indicates the degree of susceptibility of soil layers to earthquake shaking. The higher the K_g value, the greater the susceptibility of the surface soil layer to landslides. Conversely, a lower K_g value indicates a lower level of susceptibility [27]. The seismic vulnerability index is calculated using the amplification (A_0) with a dominant frequency value (f_0) [17]. Table 3 shows the distribution of Seismic Vulnerability classifications based on the values obtained from the calculations, which are visualized with a distribution map in Figure 7.

Table 3. Seismic Vulnerability Classification (K_g) [28].

Vulnerability Index	Classification	Reference	Point	Percentage
$\boldsymbol{K_g} \leq 3$	Low	Akkaya, 2020	P15 P23 P39	7,5%
$3 < \boldsymbol{K_g} \leq 5$	Medium	Akkaya, 2020	P5 P8 P10 P20	10%
$5 < \boldsymbol{K_g} \leq 10$	High	Akkaya, 2020	P4 P6 P9 P11 P12 P14 P22 P31 P34 P35 P40	27,5%
$\boldsymbol{K_g} \geq 10$	Very High	Akkaya, 2020	P1 P2 P3 P7 P13 P16 P17 P18 P19 P21 P24 P25 P26 P27 P28 P29 P30 P32 P33 P36 P37 P38	55%

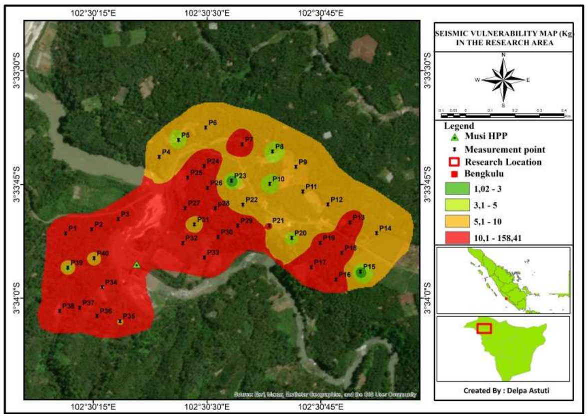


Figure 7. Distribution Map K_g.

The HVSR analysis results show that K_g values in the Musi Ujan Mas Kepahiang HPP areas range from 1.02 to 158.49, indicating significant spatial variation in seismic vulnerability. Based on the classification results, approximately 55% of the study area falls into the very high vulnerability category (red), followed by 27.5% in the high category (orange), 10% in the medium category (light green), and only 7.5% in the low category (green).

High K_g values are generally associated with areas that exhibit high amplification (A_0) and low dominant frequency (f_0), indicating thick and soft sediment layers that are highly responsive to seismic waves. Conversely, low to moderate K_g values (approximately 17.5% of the area) are typically found in zones with stiffer subsurface materials or shallow bedrock, resulting in lower amplification potential and reduced seismic vulnerability.

These findings are consistent with previous studies. İlker Akkaya [26] demonstrated that high K_g values are closely associated with soft soil conditions and an increased potential for earthquake damage. Similarly, Yutaka Nakamura [9] emphasized that the combination of high amplification and low dominant frequencies reflects a strong site effect.

Geologically, the distribution of high K_g values aligns with the regional conditions of the Kepahiang area, which is dominated by unconsolidated alluvial sediments [9]. These materials, characterized by low shear wave velocities and high impedance contrast, enhance seismic wave amplification. However, high K_g values must be interpreted with caution, as they can also be influenced by local site conditions, disturbances, and the limitations of the HVSR method. Therefore, validation using independent geological or geotechnical data is necessary to improve reliability.

3.4. Terrawarehv Optimization Model Convergence Process

The data processing using TerraWareHV was performed iteratively to obtain smaller error values. Each iteration produces a specific error value, and the result are plotted against the number of.iterations, as shown in Figure 8.

High value the pattern in Figure 8 shows the relationship between the Root Mean Square (RMS) value and the number of iterations during the microtremor inversion process. Each line represents the inversion results from 40 measurement points. In the initial iterations (iterations 1–5), the RMS value is relatively high, ranging from 0.1 to more than 0.4. This indicates that in the early stages, the inversion model does not yet match the observation data. However, as the number of iterations increases, the RMS value decreases significantly. Almost all curves show a downward convergence pattern, where after approximately 15 to 20 iterations, the RMS value begins to stabilize in the range of 0.01–0.05.

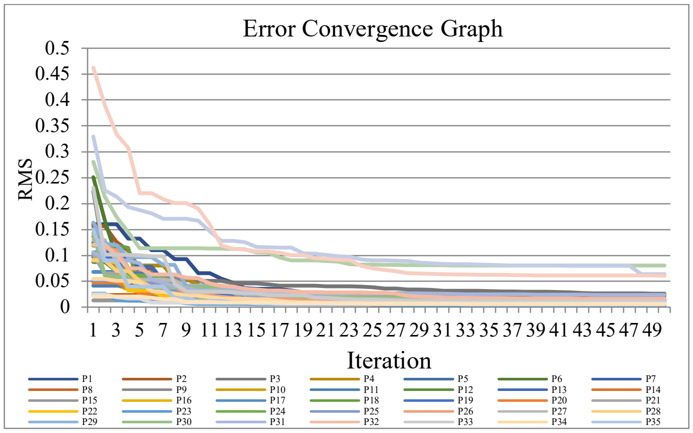


Figure 8. Error Convergence Graph.

At the early stage of the iteration (iterations 1–3), there was one point that had the highest misfit value, namely point 38, which reached around 0.45. This point was the highest error value that appeared in all the data. In addition, there are several other points that also show a fairly high misfit at the beginning of the iteration, in the range of 0.25–0.35 namely points 33, 36, and 37, before then experiencing a significant decline and beginning to approach a stable condition.

In the iteration range of 30–50, almost all points have reached a relatively small misfit value, ranging from 0.02 to 0.1. From this pattern, it can be interpreted that the final average misfit of all points is in the range of 0.05. The pattern shows that the inversion process successfully found a subsurface model that matches the microtremor measurement data. The low RMS value (<0.05 indicates that the fit between the observed data and the modeling results is quite good, so that the model obtained can be considered representative.

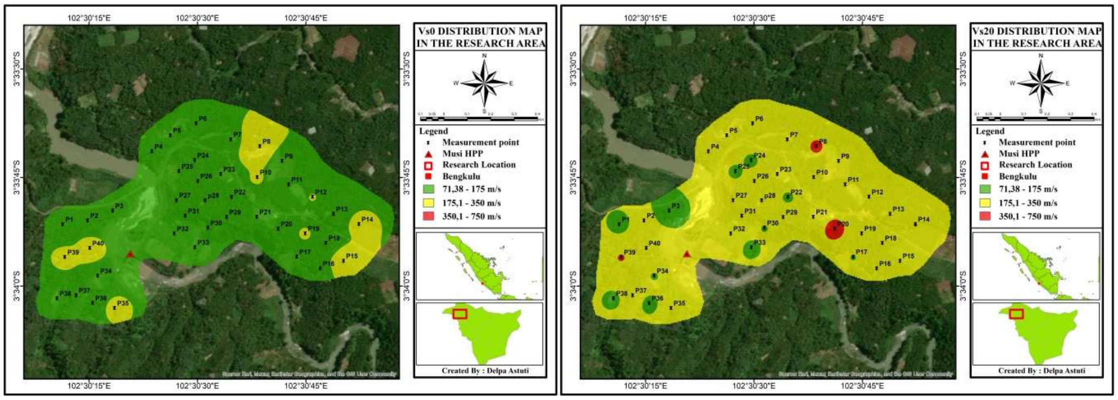
However, it should be noted that low RMS values do not necessarily guarantee the uniqueness or correctness of the subsurface model. Different subsurface configurations may produce similar HVSR curves. Therefore, the interpretation must be supported by geological information. Overall, the convergence pattern indicates that the inversion process has reached a stable solution, which supports the reliability of the subsurface interpretation based on HVSR analysis.

3.5. Shear Wave Velocity (V_s)

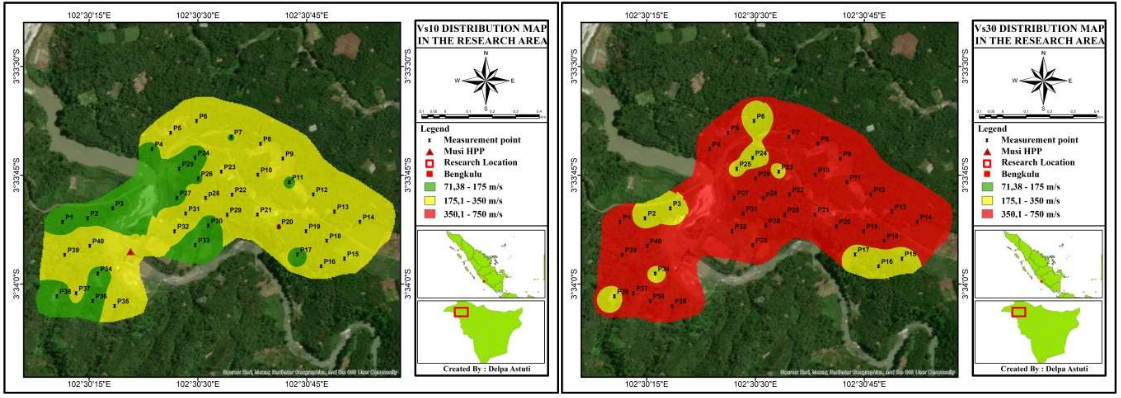
Shear wave velocity (V_s) is used as the primary parameter in determining the dynamic properties of soil related to stiffness and subsurface conditions [16]. Based on the results of microtremor inversion using the Horizontal to Vertical Spectral Ratio (HVSR) method, V_s values were obtained at various depths, reflecting variations in sediment layers to bedrock. These values are used to calculate the average shear wave velocity (V_{s0}, V_{s10}, V_{s20}, V_{s3}), which is a reference in soil type classification [20]. In addition, the inversion results are visualized in a three-dimensional (3D) model to identify weak zones and potential seismic wave amplification.

The spatial distribution of V_s values (Figure 9) shows a clear increase in velocity with depth. At the surface layer (Figure 9a), the study area is predominantly characterized by low V_s values (175–261 m/s), indicated by green colors, signifying that the surface layer is dominated by loose materials such as alluvium, loose sand, and soil or soft sediments. At a depth of 10 m (Figure 9b), the yellow zone with medium V_s values (261–350 m/s) begin to dominate, This indicates that at a depth of about 10 m, the soil layer experiences an increase in density due to natural compaction processes. This trend continues at depths of 20 m (Figure 9c), where medium to high V_s values (yellow) are more evenly distributed, indicating that the subsurface structure at a depth of approximately 20 m is dominated by more compact sediments.

Meanwhile, Table 4 shows the distribution of V_{s30} and Figure 9(d) the V_{s30} map shows a predominance of red in most of the study area, indicating that the study area is dominated by the SC class (very dense soil and soft rock) with V_{s30} values between 350–750 m/s, covering 72.5% of the total measurement points. This condition indicates a relatively compact soil layer with moderate seismic wave amplification potential. Meanwhile, the SD class (medium soil) with V_{s30} values between 175–350 m/s covers 27.5% of the study area, indicating softer soil material with higher vibration amplification potential compared to the SC class.



9(a). Distribution Map V_{s0} 9(c). Distribution Map V_{s20}



9(b). Distribution Map V_{s10} 9(d). Distribution Map V_{s30}

Figure 9. Distribution Map (a) V_{s0}, (b) V_{s10}, (c) V_{s20}, (d) V_{s3} .

Based on the variation in V_s values at depths of 0–30 m, the study area falls into the SE (Soft Soil), SD (Medium Soil), and SC (Very Dense Soil and Soft Rock) categories according to the Soil Classification standard (Badan Standardisasi Nasional, 2019). The zone dominated by low to medium V_s values at the surface layer leads to a soft soil (SE) classification, which has a high potential for earthquake amplification. At medium depths where V_s values increase and distribution is more even, the conditions correspond to the characteristics of medium soil (SD). Meanwhile, high V_s values at a depth of around 30 m indicate the presence of hard soil (SC) and medium soil (SD) layers.

From a geological perspective, the observed V_s distribution is in agreement with the regional geological conditions of the Kepahiang area. Based on the geological map by S. Gafoer et al. [9], the study area is dominated by alluvial and sedimentary deposits at shallow depths, underlain by more compact formations at greater depths. These conditions explain the low V_s values observed near the surface and the gradual increase in V_s with depth.

Table 4. Soil Classification V_{s30} [20].

V_{s30} (m/s)	Clasification	Referens	Point	Percentage
SA (Hard rock)	>1500	(BSN, 2019)		
SB (Rock)	>750 – 1500	(BSN, 2019)		
SC (Very dense soil and soft rock)	>350-750	(BSN, 2019)	P1 P4 P5 P7 P8 P9 P10 P11 P12 P13 P14 P18 P19 P20 P21 P22 P26 P27 P28 P29 P30 P31 P32 P33 P35 P36 P37 P39 P40	72,5%
SD (Soil of medium hardness)	175-350	(BSN, 2019)	P2 P3 P6 P15 P16 P17 P23 P24 P25 P34 P38	27,5%
SE (Soft soil)	<175	(BSN, 2019)		

To facilitate understanding of the 3D model, Figure 10 shows an example of a V_s profile from point 1. This 1D profile illustrates the vertical variation in shear wave velocity vertically from the ground surface down to a depth of 60 m. This information forms the basis for the interpolation process and the compilation of the 3D model.

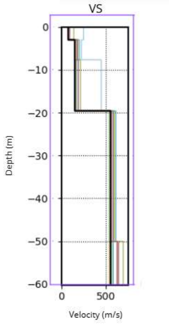
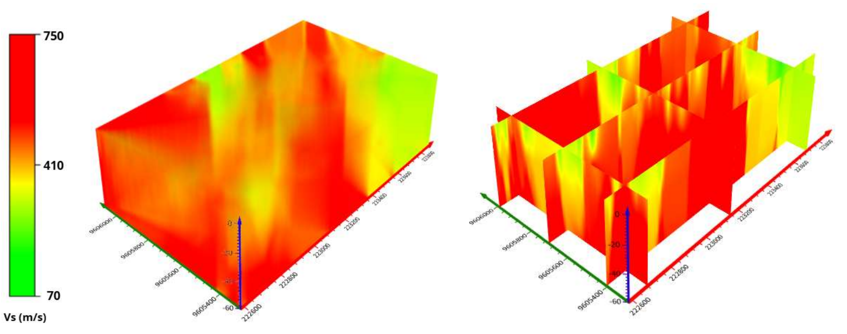


Figure 10. 1D profile of shear wave velocity (V_s) at point 1 to a depth of 60 m.

3D modeling of the study area was created to facilitate interpretation of subsurface lithology to a depth of 0-60 m using shear wave velocity values obtained from HVSR curve inversion, and the visualization is shown in Figure 11.



11(a) 11(b)

Figure 11. 3D V_s Modeling (a) Geological Map of the Study Area (b) Vertical Slice 3D V_s Model.

The three-dimensional (3D) V_s model (Figure 11) further confirms this pattern shows a significant pattern of change in the area around the Musi HPP. Red dominates most of the subsurface characteristics with V_s values above 410 m/s, indicating zones composed of dense soil layers and relatively soft rock formations. The yellow to orange areas, with values in the middle range (250-410), describe a transition zone generally associated with fairly consolidated material, but not as dense a transition zone generally associated with fairly consolidated material, but not as dense as the layer with the highest values. Meanwhile, the more limited presence of green indicates lower values (70–250), suggesting layers with lower compactness or looser materials. The vertical cross-section also shows a consistent increase in V_s with depth, reflecting increasing material stiffness due to compaction.

However, the interpretation of V_s results should be approached cautiously. Although the inversion results show consistent trends, HVSR-based inversion is inherently non-unique, meaning that multiple subsurface models can produce similar responses. Therefore, additional validation using geological or geotechnical data is necessary to improve the reliability of the subsurface interpretation.

4. Conclusion

Based on the results of microseismic analysis obtained using the HVSR method with TerraWareHV around the Musi Hydroelectric Power Plant, located in Ujan Mas Subdistrict, Kepahiang Regency, it was found that subsurface conditions exhibit significant variations. The dominant frequency (f_0) varies between 1.28 and 5.55 Hz; the amplification factor (A_0) ranges from 2.99 to 16.86; the seismic vulnerability index (K_g) varies between 1.02 and 158.49, and the average values of shear wave velocityV_{s0}, V_{s10}, V_{s20}, V_{s30} [16] show a consistent increase with increasing depth, indicating an increase in the density and degree of consolidation of subsurface materials.

Subsurface conditions in the Musi Ujan Mas Hydroelectric Power Plant area are dominated by alluvial deposits and unconsolidated sediments of considerable thickness, which overlie denser layers at certain depths. This indicates significant geological heterogeneity. Interpretation of HVSR parameters (f_0 and A_0), the seismic vulnerability index (K_g), and shear wave velocity (V_s) indicates that the near-surface layers are soft and have the potential to amplify seismic waves, whereas deeper layers exhibit higher stiffness and relatively stable conditions.

Seismically, these conditions suggest that zones composed of alluvial deposits exhibit higher susceptibility to ground motion amplification, thereby potentially increasing risks to infrastructure. Therefore, local site effects must be considered in spatial planning and engineering design, particularly in earthquake-prone areas.

However, these results must be interpreted with caution because HVSR inversions are non-unique and can yield more than one subsurface model with similar responses. Therefore, additional validation using independent data such as borehole data, MASW, seismic refraction, or other geotechnical investigations is required to enhance the reliability of subsurface condition interpretations and seismic vulnerability assessments

Acknowledgments

The author would like to thank his family for their support, motivation, and prayers. He would also like to thank the BMKG Class III Geophysical Station in Bengkulu, Kepahiang, for the facilities and technical guidance provided during data processing. Sincere thanks are extended to the supervising lecturer for the guidance, direction, and valuable input. As well as the Physics Study Program, for the guidance and opportunity that enabled the successful completion of this research. The author also thanks all parties who have helped.

References

[1] F. D. Cahyo, F. Ihsan, R. Roulita, N. Wijayanti, and R. Mirwanti, “Kesiapsiagaan Bencana Gempa Bumi Dalam Keperawatan: Tinjauan Penelitian,” *JPP (Jurnal Kesehat. Poltekkes Palembang)*, vol. 18, no. 1, pp. 87–94, 2023, doi: 10.36086/jpp.v18i1.1525.

[2] A. I. Hadi and K. S. Brotopuspito, “Estimasi Kedalaman Bidang Batas Sesar dari Data Gravitasi di Daerah Rawan Gerakan Tanah (Studi Kasus: Sesar Sumatra Segmen Musi Bengkulu),” *SIMETRI, J. Ilmu Fis. Indones.*, vol. 2, no. 2, pp. 2207-37:2207-42, 2016.

[3] K. E. dan S. D. M. Badan Geologi, “Analisis geologi kejadian gempa bumi di barat daya Bengkulu tanggal 23 Mei 2025,” Kementerian ESDM. [Online]. Available: https://geologi.esdm.go.id/media-center/analisis-geologi-kejadian-gempa-bumi-di-barat-daya-bengkulu-tanggal-23-mei-2025

[4] A. Zaenudin, A. Farduin, G. I. B. Darmawan, and Karyanto, “Shear wave velocity model using HVSR inversion beneath Bandar Lampung City,” *Earthq. Sci.*, vol. 37, no. 4, pp. 337–351, 2024, [Online]. Available: https://doi.org/10.1016/j.eqs.2024.04.004

[5] M. Uthaman, C. Singh, and A. Singh, “Site characterization of Sikkim Himalaya using HVSR,” *Seismica*, vol. 3, no. 2, 2024.

[6] Y. Yang, L. Shi, and J. Huang, “Regional mapping of sediment thickness using microtremor HVSR spatial variability,” *Discov. Geosci.*, vol. 3, no. 73, 2025.

[7] A. I. Hadi *et al.*, “Seismic microzonation of kepahiang regency , Indonesia using the HVSR method : enhancing Urban resilience to mitigate earthquake vulnerability,” *Indian Geotech. J.*, no. 1, 2025, doi: 10.1007/s40098-025-01299-z.

[8] M. R. Rabbani, A. I. Hadi, B. Harlianto, M. Farid, H. Raihana, and A. P. Anggi, “HVSR Microtremor Analysis to Assess Subsurface Fault Characteristics and Geothermal Potential in Kepahiang,” *J. Geocelebes*, vol. 9, no. 2, pp. 157–170, 2025, doi: 10.70561/geocelebes.v9i2.43347.

[9] Nakamura, “A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface,” *Q. Rep. RTRI*, vol. 30, no. 1, 1989.

[10] G. Vessia, G. Laurenzano, A. Pagliaroli, and M. Pilz, “Seismic site response estimation for micro zonation studies promoting the resilience of urban centers. Engineering Geology, 284, 106031.,” *Eng. Geol.*, vol. 284, 2021, [Online]. Available: https://gfzpublic.gfz-potsdam.de/rest/items/item_500678

[11] J. P. Flores *et al.*, “The inversion of spectral ratio H/V in a layered system using the diffuse field assumption (DFA),” *Geophys. J. Int.*, vol. 208, no. 1, pp. 577–588, 2017, doi: 10.1093/gji/ggw416.

[12] A. Firdasari, “Geologi Dan Karakteristik Petrografi Batuan Vulkanik Formasi Hulusimpang Daerah Temdak Dan Sekitarnya, Kabupaten Kepahiang, Provinsi Bengkulu,” Skripsi, Universitas Sriwijaya, 2018.

[13] T. C. . P. Gafoer, S.; Amin, “Geological Map of Bengkulu Quadrangle, Sumatra,” Bandung, 2007.

[14] A. I. Hadi, K. S. Brotopuspito, S. Pramumijoyo, and H. C. Hardiyatmo, “Regional Landslide Potential Mapping in Earthquake-Prone Areas of Kepahiang Regency,” *Geosciences*, 2018, doi: 10.3390/geosciences8060219.

[15] A. Satria, I. L. Resta, and N. Muchtar, “Analisis ketebalan lapisan sedimen dan indeks kerentanan seismik kota jambi bagian timur,” *J. Geofis. Eksplor.*, vol. 6, no. 1, pp. 18–30, 2020, doi: 10.23960/jge.v6i1.

[16] R. Mianshui, F. Li-Yun, S. S. Francisco José, and S. Weijia, “Joint inversion of earthquake-based horizontal-to-vertical spectral ratio and phase velocity dispersion: Applications to Garner Valley,” *Front. Earth Sci.*, vol. 10, no. August, pp. 1–18, 2022, doi: 10.3389/feart.2022.948697.

[17] D. M. Jannah *et al.*, “Analisis Indeks Kerentanan Seismik Berdasarkan Nilai Vs30 Pada Zona Terdampak Gempa Bumi,” *Kurvater*, vol. 9, no. 2, pp. 107–116, 2024, doi: 10.33579/krvtk.v9i2.4972.

[18] N. B. Wibowo and I. Huda, “Analysis of Amplification , Seismic Vulnerability Index and Soil Clasification Based on Vs30 in Yogyakarta,” *Bull. Meteorol. Klimatologi, dan Geofis.*, vol. 1, no. 2, pp. 21–31, 2020.

[19] F. Anjelina and A. F. Pohan, “Indeks Kerentanan Seismik Daerah Perbukitan dan Permukiman di Bukit Nobita Kota Padang Menggunakan Data Mikrotremor,” *J. Fis. Unand*, vol. 13, p. 6, 2024.

[20] Badan Standardisasi Nasional, “SNI 1726-2019: Indonesia Seismic Resistance Design Guideline for Buildings and Other Structures (in Indonesian),” 2019, [Online]. Available: www.bsn.go.id

[21] A. I. Hadi *et al.*, “Zonation of Seismic Vulnerability Levels in South Bengkulu Regency , Indonesia for Disaster-Based Regional Planning,” *Udar. Zb. (The Mining-Geology-Petroleum Eng. Bull.*, pp. 133–148, 2024, doi: 10.17794/rgn.2024.2.11.

[22] E. Hadi, A. I., Sunaryo., Farid, M., Refrizon., Harlianto, B., Fadli, D. I., Putriani., “Analysis of earthquake-prone areas based on the seismic wave velocity, Young’s modulus, shear modulus, and Poisson’s ratio for disaster risk reduction in Bengkulu city, Indonesia,” *Nat. Hazards*, vol. 120, no. 15, 2024, doi: 10.1007/s11069-024-06827-3.

[23] L. I. Juarzan, W. A. W. Jafar, L. H. Hamimu, and I. Indrawati, “Analisis Ketebalan Lapisan Sedimen Menggunakan Metode Horizontal to Vertical Spectral Ratio (HVSR) di Wilayah Pesisir Kecamatan Moramo Kabupaten Konawe Selatan,” *J. Rekayasa Geofis. Indones.*, vol. 5, no. 03, pp. 137–145, 2023, doi: 10.56099/jrgi.v5i03.27.

[24] I. S. Siregar and Madlazim, “Analisis mikrotremor dengan metode hvsr untuk mengetahui zona penguatan gempa bumi di wilayah stasiun seismik jawa timur,” *IFI (Jurnal Fis. Indones.*, vol. 06, pp. 33–38, 2017.

[25] A. Ariyanto *et al.*, “Pemetaan Kerentanan Seismik Melalui Analisis Mikrotremor Hvsr Di Wilayah Kecamatan Kemiling Dan Sekitarnya,” *JGE (Jurnal Geofis. Eksplorasi)*, vol. 10, no. 2, pp. 82–99, 2024, doi: 10.23960/jge.v10i2.393.

[26] A. Tohari and D. D. Wardhana, “Mikrozonasi Seismik Wilayah Kota Padang Berdasarkan Pengukuran Mikrotremor,” *Ris. Geol. dan Pertamb.*, vol. 28, no. 2, p. 205, 2018, doi: 10.14203/risetgeotam2018.v28.984.

[27] Airunnisa, I. L. Resta, and Ngatijo, “Analisis Data Mikrotremor Untuk Mengetahui Nilai Indeks

Kerentanan Seismik Di Kecamatan Jambi Luar Kota),” *J. Geofis.*, vol. 22, no. 01, pp. 21–25, 2024.
[28] İ. Akkaya, “Availability of seismic vulnerability index (Kg) in the assessment of building damage in Van, Eastern Turkey,” *Earthq. Eng. Eng. Vib.*, vol. 19, no. 1, pp. 189–204, 2020, doi: 10.1007/s11803-020-0556-z.