Subsurface Structure Analysis Using HVSR Inversion in the Musi Ujan Mas Kepahiang Hydroelectric Area

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Abstract - *Bengkulu Province is characterized by high seismic activity due to the convergence of the Indo-Australian and Eurasian plates and the presence of the active Musi Segment of the Sumatra Fault. These tectonic conditions make Kepahiang Regency particularly susceptible to shallow earthquakes, highlighting the importance of subsurface characterization for critical infrastructure such as the Musi Ujan Mas Hydroelectric Power Plant. This study aims to investigate subsurface characteristics around the hydropower plant area using microtremor measurements analyzed through the Horizontal to Vertical Spectral Ratio (HVSR) method and HVSR inversion. A total of 40 measurement points were acquired using a PASI Gemini 2 portable seismograph with a sampling frequency of 200 Hz. HVSR analysis was conducted to determine the dominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (Kg), while inversion of HVSR curves using Dinver software was applied to estimate shear-wave velocity (Vs) profiles and V_{s30} values. The results show that f_0 ranges from 1,21 to 5,77 Hz, with dominant low-frequency values indicating thick and soft sediment layers. Amplification factors vary between 1,46 and 15,01, while Kg values suggest that a large portion of the area is highly vulnerable to seismic effects. V_{s30} values range from 213,26 to 508,88 m/s, corresponding to soil classes C and B based on UBC and EC8 classifications. These findings indicate significant subsurface heterogeneity and identify areas prone to seismic amplification, providing important information for seismic hazard assessment and infrastructure planning.*

Keywords: *HVSR; Microtremor; Subsurface structure; Dinver; Musi Ujan Mas Hydroelectric Power Plant*

INTRODUCTION

Bengkulu Province is located at the intersection of the Indian-Australian and Eurasian tectonic plates (Azwar et al., 2022). In addition, the region is also traversed by the Sumatra Fault, specifically the Musi-Keruh segment, which crosses several regencies, causing frequent earthquakes, one of which occurred in the Kepahiang Regency (Yulita, Lubis, & Hidayati, 2023). These conditions cause high seismic activity, which is generally dominated by shallow earthquakes with a depth of ≤ 70 km, such as the 2007 Bengkulu earthquake (Mw 8.4) (Hutchings & Mooney, 2021). According to data from Meteorology, Climatology, and Geophysics Agency (BMKG), over the past five years (2020–2024), the Bengkulu region has recorded around 400–500 earthquakes each year. The high number of earthquakes in Bengkulu has the potential to have a major impact on vital infrastructure such as hydroelectric power plants (HPP).

Understanding subsurface structures is an important aspect in supporting the construction of large infrastructure such as hydroelectric power plants (HPP). The Musi Kepahiang HPP is one of the strategic projects that requires a detailed understanding of the geological conditions and physical properties of the subsurface layers. According to (Nakamura, 2000), the geological characteristics of an area can be obtained through microtremor measurements, particularly Horizontal-

Vertical Spectral Ratio (HVSR) analysis. Microseismic measurement is a passive seismic method that records vibrations originating from natural surface activity and human activity. This method is used to identify subsurface conditions by analyzing dominant frequencies and amplification factors (Arintalofa, Yulianto, & Harmoko, 2020).

In this study, HVSR analysis was not only used to observe the spectral response of the soil, but also to perform inversion to obtain a shear wave velocity (Vs) model as a representation of the subsurface structure. Through HVSR inversion, the measurement curve obtained in the field was converted into a Vs velocity profile against depth. The Vs value is closely related to geological conditions, as changes in velocity indicate differences in lithology, sediment thickness, and bedrock depth. Thus, HVSR inversion results can be used to interpret subsurface structures in greater detail and accuracy, as well as to determine the V_{s30} value, which is useful in site classification and seismic microzonation (Zuhair et al., 2023).

In this study, several key parameters obtained from the HVSR analysis, namely the dominant frequency (f_0), amplification factor (A_0) and seismic fragility index (Kg) as well as shear wave velocity (Vs), subsurface layer thickness, impedance contrast, and V_{s30} values from inversion results. All of these parameters are used to comprehensively describe the subsurface structure.

The objective of this study is to determine the subsurface characteristics around the Musi Ujan Mas Kepahing Hydroelectric Power Plant through microtremor measurements analyzed using the HVSR method.

The results of this analysis are expected to provide information on the dominant frequency (f_0), amplification factor (A_0), seismic vulnerability index (Kg), and V_{s30} estimates, which aim to minimize losses due to earthquakes and support sustainable development.

Based on the geological map of the study area (Figure 1), the Kepahiang region consists of hilly terrain dominated by material resulting from the eruption of a young Quaternary volcano. These rock units include pyroclastic deposits, lava flows, and tuff. The morphology, ranging from flat to undulating terrain, was formed as a result of weathering of young volcanic debris, which was then deposited to form a relatively gentler surface (Sihombing et al., 2024). The geological structure in the Kepahiang region shows that this area is dominated by the presence of an active fault system. Regionally, the faults in Kepahiang are part of the Sumatra Fault, known as one of the most active tectonic structures in Indonesia (Supartoyo & Litman, 2018). Structurally, the alignment pattern on the geological map confirms the dominance of tectonic elements in the form of the Sumatra Fault, particularly the Musi Segment, which is oriented relatively northwest-southeast. The Musi Segment has been reported as one of the active segments with a high degree of deformation in the Great Sumatra Fault (GSF) system. The research location in the Musi Ujan Mas hydroelectric power plant area is in a zone relatively close to the Musi Segment, so these active tectonic conditions greatly influence the subsurface characteristics of the research area. This fault activity makes Kepahiang Regency a region with a high level of vulnerability to geological disasters, especially earthquakes. One of the main sources of earthquakes in this region originates from the Musi Segment, which is one of the active segments of the Sumatra Fault that has the potential to produce significant deformation.

The rock formations in the Kepahiang area are dominated by volcanic rocks, so that in Kepahiang Regency, igneous rock are commonly found due to its proximity to volcanoes such as Bukit Kaba and the foothills of Bukit Kaba (Firdasari, 2018). At the research site, the rock formation is dominated by volcanic kaba.

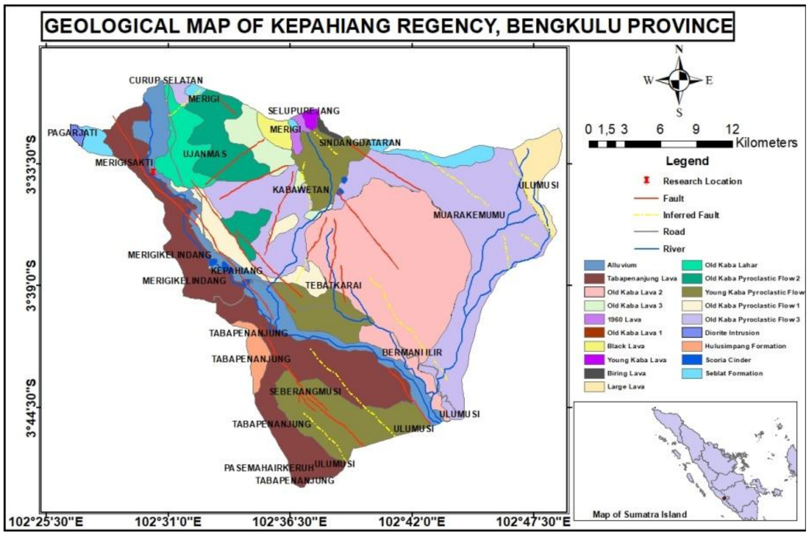

Figure 1. Geological Map of Kepahiang Regency, Modified from (Gafoer, Amin, & Pardede, 2007) and (Irwanto et al., 2013).

RESEARCH METHODS

Microtremor data was collected at 40 measurement points around the hydroelectric power plant area using a Seismograph Portable short period (PASI Mod Gemini 2 Sn-1405) seismometer with a sampling frequency of 200 Hz and a measurement duration of 30 minutes at each point in accordance with the guidelines from (SESAME, 2004).

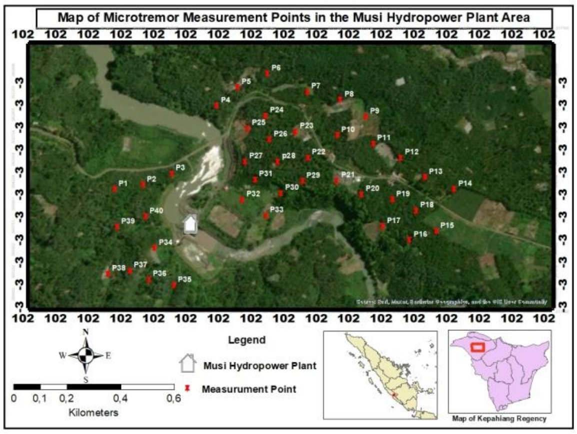

Figure 2. Map of Research Location

The Horizontal-Vertical Spectrum Ratio (HVSR) method is a geophysical technique that compares the horizontal spectrum and vertical spectrum of recorded microseismic events. The concept behind the HVSR method is to assume that microseismic waves mainly consist of shear waves and eliminate surface waves. HVSR is an analysis method based on observing the propagation of shear waves caused by seismic events for various geological conditions. The HVSR method can also be used to determine the amplification factor and dominant period of a location; these values can be estimated from the peak of the HVSR curve. The amplification factor and dominant period can be obtained through data processing using geophysical software (Nurwidyanto et al., 2023).The HVSR formula is expressed as follows (Nakamura, 1989):

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

where $H_{NS}^2(f)$ and $H_{EW}^2(f)$ are the amplitude spectra of the north-south and east-west horizontal components, respectively, and *V(f)* is the amplitude spectrum of the vertical component at frequency *f*. The peak of this HVSR curve refers to the maximum value of the HVSR ratio to frequency, which indicates the local dominant frequency (f_0) associated with ground resonance, and the relative amplification factor (A_0) which indicates the magnitude of amplification at that dominant frequency (Wintoro et al., 2025).

The Horizontal to Vertical Spectral Ratio (HVSR) method is used to determine the dominant frequency (f_0) and maximum amplification factor (A_0), These parameters are then used to calculate the seismic vulnerability index (Kg). In general, the equation for calculating the seismic vulnerability index refers to the formulation proposed by (Nakamura, 1997) is:

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

In addition, HVSR curve inversion was performed using Dinver software to obtain a subsurface shear wave velocity model. Inversion in the HVSR method is a mathematical process to obtain subsurface physical parameters based on observation data, where the measured HVSR curve (observed) is compared with a synthetic curve calculated from the initial model. In this study, several types of seismometers were used, so the instrument response on each seismogram was eliminated first before the inversion process.

The inversion process is performed using the Monte Carlo algorithm or conditional neighborhood algorithm available in Dinver. The initial steps include inputting the H/V curve from the measurement results and initial model parameters such as P-wave velocity (Vp), S-wave velocity (Vs), Poisson's ratio, and density. The best velocity model is determined based on the misfit value, which is a measure of the difference between the observed and synthetic data. A model is considered good if it meets the criteria of 0 < misfit < 1. If the misfit value is still high (> 1), the initial model parameters must be adjusted and the inversion process repeated. The misfit value is calculated using the following equation:

$$\sqrt{\frac{1}{N}\sum_{1}^{N}\frac{(Di-Mi^2}{\sigma i}} \tag{3}$$

N is the amount of data, Di is the inverse result, Mi is the model parameter, and σ is the standard deviation (Tawakal et al., 2020).

From the inversion results, a model of the shear wave velocity structure at each measurement point was obtained. This model was then used to calculate the average shear wave velocity to a depth of 30 meters (V_{s30}) using the following formula:

$$V_{s30} = \frac{30}{\sum_{i=1}^{N}\frac{Hi}{Vsi}} \tag{4}$$

where H_i s the thickness of layer i and V_{si} is the shear wave velocity in layer i. This calculation is performed by summing the thickness and velocity ratios of each layer until the total depth reaches 30 meters. This approach is commonly used in soil classification analysis based on shear wave velocity.

RESULTS AND DISCUSSION

In this study, subsurface conditions in the study area were analyzed using dominant frequency maps (f_0), amplification factors (A_0), soil vulnerability indices (Kg), and average shear wave velocities to a depth of 30 meters (V_{s30}). All of these parameters were obtained through HVSR data processing and inversion, thereby providing a more detailed description of the spatial distribution of subsurface characteristics.

1. Dominant Frequency (f_0)

The dominant frequency is the frequency at which the soil or soil layer experiences maximum amplification when exposed to seismic vibrations (Candraningtyas & Budi Susanti, 2024). The results of the dominant frequency (f_0) analysis using the HVSR method with Geopsy software show that the dominant frequency values vary across the various research locations. The distribution of the dominant frequency (f_0) values can be seen in Figure 3.

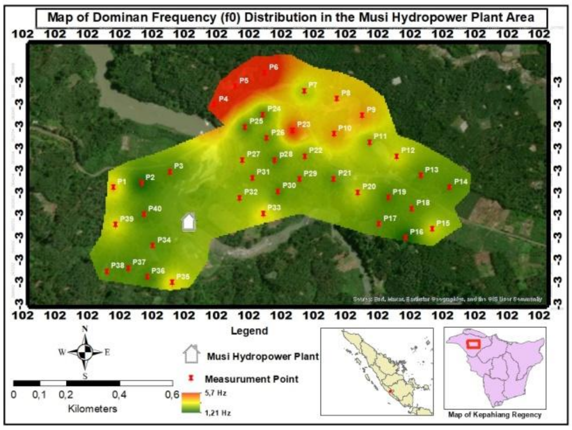

Figure 3. Peta Sebaran f_0

Based on the data obtained, the dominant frequency value (f_0) in the Musi Ujan Mas Kepahiang hydroelectric power plant area is in the range of 1,21 to 5,77 Hz. Based on Kanai (1998) classification in Siregar & Madlazim (2017), the study area is classified as soil type II to IV, which indicates a predominance of alluvial sediment material and soft soil layers with a thickness of 10 to more than 30 meters.

The dominant frequency distribution map shows that areas with high frequency values (4 to 5,77 Hz) belonging to soil type II are scattered across the northern to central parts of the study area, marked in red, indicating a thin surface sediment layer (approximately 5 m) or shallow bedrock depth. In other words, high f_0 values indicate that the subsurface is dominated by hard rock. Points marked in yellow-orange belong to soil type III, which dominates the central-eastern area with frequency values ranging from 2,5 to 4 Hz where the thickness of the surface sediment is in the thick category of 10-30 m. Conversely, low dominant frequencies indicate very thick sediment layers and show that the subsurface is composed of soft rocks such as alluvial deposits or fine sediments, as seen on the map where most of the area is marked in green, representing low dominant frequencies (< 2,5 Hz).

Statistically, approximately 65% of points are at frequencies < 2,5 Hz (Type IV), 25% of points are at 2,5 to 4 Hz (Type III), and 10% of points show values > 4 Hz (Type II). No f_0 values > 6,67 Hz representing hard rock (Type I) were found, so it can be concluded that the Musi hydroelectric power plant area is generally dominated by medium to thick alluvial sediment layers. This dominant frequency (f_0) is influenced by the shear wave velocity (Vs) and sediment layer thickness (h) (Syahputri & Sismanto, 2020).

2. Soil Amplification (A_0)

The amplification values in the Musi Ujan Mas Kepahiang Hydroelectric Power Plant area range from 1,46 to 15,01, as shown in Figure 4.

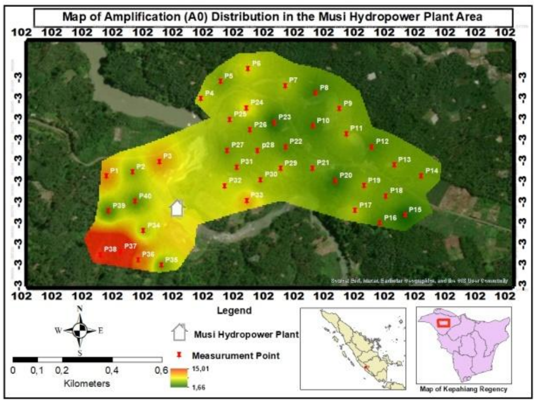

Figure 4. Map of soil amplification distribution

In the distribution map, it can be seen that the low zone is colored green according to the classification (Maulana et al., 2025), which states that low amplification factor values are less than three. This zone is generally located in areas with relatively denser or thinner sediments so that seismic wave amplification is not too large. Furthermore, the medium zone is marked in yellow according to the classification (Maulana et al., 2025) and has an amplification value ranging from ($3 \leq A < 6$) This zone is spread across several points in the western and central areas and describes a layer of sediment with a medium thickness that can still provide significant wave amplification to structures on the surface. The red zone in the southwest has a very high amplification value, reaching around 15,01 which falls into Zone 4 (Very High) according to (Maulana et al., 2025) This value is well above the threshold of 9, indicating that this area is highly vulnerable to seismic wave amplification. Geologically, this zone coincides with a relatively gentle river valley filled with very thick (>30 m). fine alluvial deposits. The very thick and soft sediment layer causes earthquake wave energy to be trapped and amplified before reaching the surface, resulting in a much greater vibration response on the surface compared to areas with thin sediments. This phenomenon is consistent with the results of previous dominant frequency (f_0) analysis, in which this region also has a low f_0 value (< 2,5 Hz), indicating very thick sediment. This correlation confirms that areas with very high amplification values tend to be located in zones with low f_0 due to the great depth of the sediment layer. Thus, the red zone in the southwest is the area most at risk of earthquake wave amplification, so mitigation aspects must be considered, especially for foundation planning and the selection of building structure types.

Statistically, the distribution of amplification classifications in the study area shows that approximately 25% of points are in the low zone, 60% are in the moderate zone, 10% are in the high zone, and 5% are in the very high zone. These proportions show that most of the Musi hydroelectric power plant area is still dominated by soil conditions with low to moderate amplification potential, but the existence of a very high zone in the southwest remains a priority area in the evaluation of local seismic hazards.

3. Seismic Vulnerability Index (Kg)

The Seismic Vulnerability Index (Kg) can be used to assess the level of vulnerability and potential damage caused by ground movement.

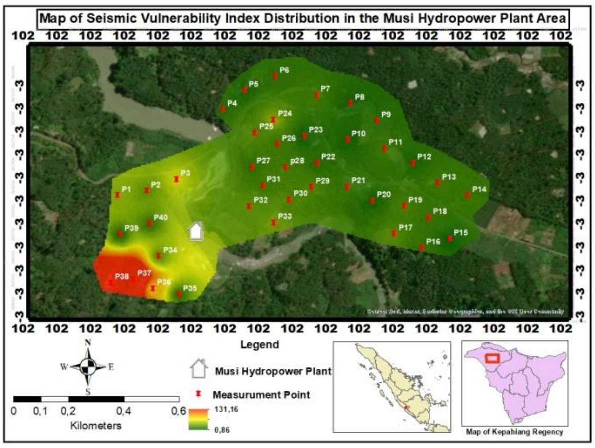

Figure 5. Map of Seismic Vulnerability Index Distribution (Kg)

Based on the seismic vulnerability index (Kg) distribution map in the Musi Hydroelectric Power Plant area, it can be seen that the Kg value varies between 0,86 and 131,16. This variation illustrates the difference in the level of soil vulnerability to seismic wave amplification at each measurement point. Based on the classification (Dewi et al., 2023), values of Kg < 3 are categorized as low zone, 3 < Kg < 6 are categorized as moderate zone, and Kg > 6 are categorized as high zone. Spatially, zones with low vulnerability values (green) dominate most of the northern to central regions, indicating relatively dense soil conditions with thin sediment thickness. These areas tend to have small amplification values (A_0) and higher dominant frequencies (f_0) indicating that the subsurface layers are sufficiently rigid that they do not easily amplify earthquake vibrations. Meanwhile, moderate zones (yellow) are scattered in the central to western parts of the study area. The Kg values in this zone range from 3 to 6, indicating that this area has a sediment layer with medium thickness and moderate compactness, so that it can still experience earthquake wave amplification within reasonable limits. The high zone (red) appears concentrated in the southwest, particularly around points P37, P38, and P39, with the highest Kg value reaching 131,16. This area coincides with a valley and thick fine alluvial deposits, which tend to trap seismic wave energy and cause significant amplification. This condition is consistent with the results of the previous amplification analysis (A_0) where this area also showed high (A_0) values, confirming a direct relationship between sediment thickness and seismic vulnerability.

Based on statistical calculations from 40 measurement points, it was found that 20% of the area is classified as low zone ($Kg < 3$), 20% is classified as medium zone ($3 < Kg < 6$), and the remaining 60% is classified as high zone ($Kg > 6$). Thus, although most of the Musi Hydroelectric Power Plant area is still considered safe from earthquake amplification, there are areas with high vulnerability potential in the southwest that need special attention. This zone should be taken into consideration in construction planning, especially for building foundations or hydroelectric power plant facility structures, so that they have better resistance to the local effects of earthquakes.

4. V_{s30}

The shear wave velocity (Vs) is obtained from the analysis of the H/V curve using the ellipticity curve (inversion) method in the Dinver program with predetermined parameters. The ellipticity curve in Dinver is the result of calculating the ratio between the vertical and horizontal components of Rayleigh waves propagating on the surface. This concept is important because the elliptical shape of particle movement in Rayleigh waves is greatly influenced by the properties of the subsurface layer, as can be seen in Figure 6.

The results of the HVSR curve inversion process are the shear wave velocity (Vs) soil profiles. The red line in the soil profiles (Figure 7) shows the model with the best mismatch value of 0,3. This value represents the best fit between the measured curve and the theoretical curve obtained as a result of the inversion process.

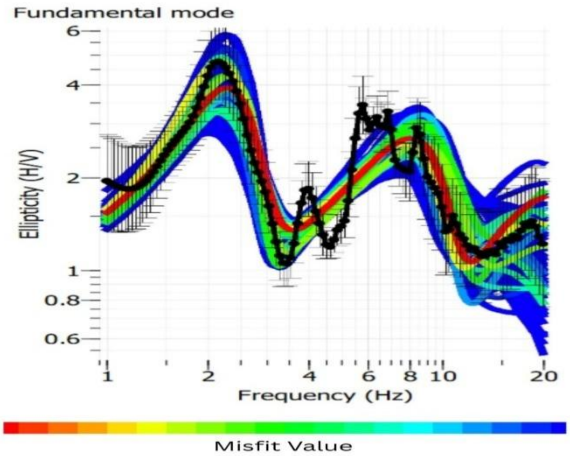

Figure 6. Ellipticity Curve

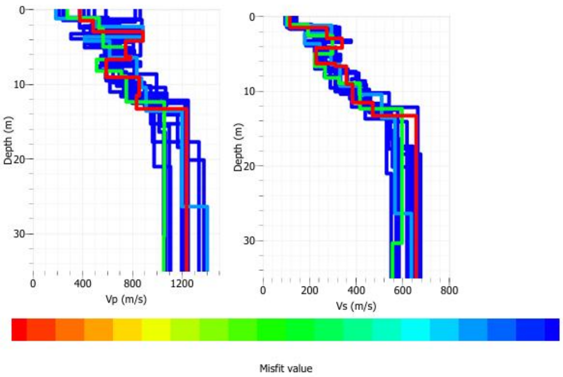

Figure 7. Final ground profile results

The shear wave velocity value at a depth of 30 meters (V_{s30}) is very important and is the most frequently used value in geophysical methods to measure the properties of subsurface structures down to a depth of 30 meters. This value can be used to classify rocks based on the strength of earthquake vibrations caused by local effects and can also be used when planning earthquake-resistant buildings. Figure 8 shows a map of the distribution of V_{s30} in the study area.

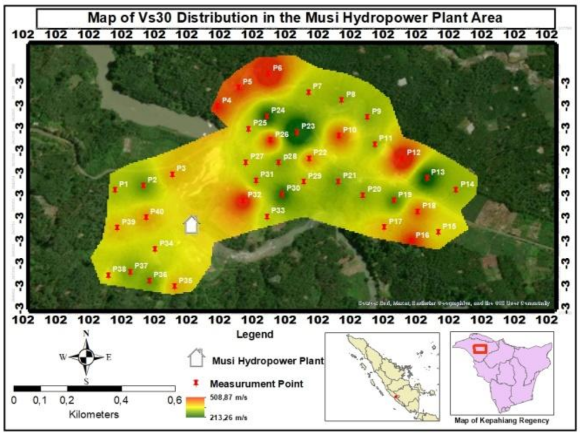

Figure 8. Map of V_{s30} Distribution

Based on the distribution map of shear wave velocity (V_{s30}) values in the Musi Hydroelectric Power Plant area V_{s30} values ranging from 213,26 m/s to 508,88 m/s. were obtained. Referring to soil classification based on the Uniform Building Code (UBC) and Eurocode 8 (EC8) (Jamaluddin et al., 2018) , these V_{s30} values fall into two soil classes, namely class C (SD) with a velocity range of 180–360 m/s, and class B (SC) with a range of 360–760 m/s. There are No V_{s30} values smaller than 180 m/s, so there are no areas classified as class D (soft soil), and there are also no V_{s30} values greater than 760 m/s so there are no areas classified as class A in this study area.

Spatially, areas with low V_{s30} values (213–360 m/s) are shown in green on the map, scattered across the central to southwestern parts of the study area. This zone is classified as class C (medium or stiff soil), which is generally composed of medium to slightly soft sedimentary material with considerable thickness. Meanwhile, areas with high V_{s30} are indicated by yellowish red colors, scattered in the north, east, and a small part of the west, which are categorized as class B (very dense soil or soft rock). This zone describes denser soil or rock conditions with thinner sediment thickness, resulting in lower amplification capacity for seismic waves.

Based on calculations from 40 measurement points, approximately 60% of the study area is classified as class C, and the remaining 40% is classified as class B. This indicates that most of the Musi hydroelectric power plant area is located on medium soil types that are still susceptible to seismic amplification due to medium sediments. This condition is consistent with the results of the dominant frequency (f_0), and amplification factor (A_0), analyses, where areas with lower V_{s30} values tend to have smaller f_0 and larger A_0 indicating thicker sediments and stronger vibration responses to seismic waves.

Thus in general, the Musi Hydroelectric Power Plant area is dominated by class C and B soils, which indicate medium to dense soil characteristics. Although there are no very soft soils (class D), mitigation of wave amplification still needs to be considered, especially in class C zones that have the potential for greater vibration response during seismic activity.

CONCLUSION

Microtremor analysis using the HVSR method and inversion in the Musi Hydroelectric Power Plant area reveals subsurface structures that meet the research objectives. Dominant frequency (f_0) values range from 1,21–5,77 Hz, with most of the area showing low f_0, indicating thick, soft sediments, especially in the west–southwest zone. Amplification factor (A_0) values

(1,66–15,01) mostly fall within moderate to high levels, producing high seismic vulnerability index (Kg) values (0,86–131 ,16) in about 60% of the area. These conditions show that thick sediment zones have higher earthquake amplification potential.

HVSR inversion results confirm variations in subsurface geology through shear wave velocity (Vs) and layer thickness profiles. Lower Vs correlates with thicker sediments and stronger seismic responses. V_{s30} values (213,261–508,875 m/s) indicate dominance of medium soil (SD/C) with partial hard soil (SC/B). Low V_{s30} aligns with low f_0 and high A_0 in the west–southwest region, supporting the presence of softer subsurface layers and higher amplification risk. Overall, the interated parameters (f_0, A_0, Kg, V_{s30}) indicate heterogeneous subsurface conditions; the southwest region is the most earthquake-prone area in the study area due to the combined effects of thick sedimentary deposits and moderate to high magnification factors. These geological conditions may increase structural response and potential damage during strong ground shaking events.

Based on these results, it is recommended that earthquake-resistant structural design be prioritized in the Musi Ujan Mas Hydroelectric Power Plant area, particularly in areas characterized by low f_0, low V_{s30}, and high amplification factors. Engineering assessments should include appropriate seismic load calculations, foundation reinforcement, and soil improvement techniques in areas with thick sediment deposits. Furthermore, periodic structural reviews and routine maintenance of critical infrastructure components are essential to ensure long-term resilience to potential ground amplification due to earthquakes. Continuous geotechnical and microtremor monitoring is also recommended to support risk mitigation and sustainable operation of the hydropower plant.

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