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Mapping of soil vulnerability to earthquake using the HVSR method in microtremor measurements in Marga Agung Area, South Lampung Regency

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ABSTRACT

This study was conducted in Marga Agung Village, Jati Agung Subdistrict, South Lampung Regency, using the Horizontal to Vertical Spectral Ratio (HVSR) method based on microtremor data. This study aims to analyze the characteristics of the subsurface layers and determine the soil vulnerability level in Marga Agung Village, through soil vulnerability zoning mapping based on the natural frequency (f_0), amplification factor (A_0), seismic vulnerability index (K_g), and shear wave velocity to a depth 30 meters (Vs_{30}), and examined the potential level of building damage as a basis for earthquake disaster mitigation efforts. The results show that f_0 values range from 0.31 Hz to 27.96 Hz, A_0 values range from 1.59 to 5.10, and K_g values range from 0.15 to 53.45, dominated by low seismic vulnerability index values. Vs_{30} values are dominated by stiff soil (Type D) and very dense and soft rock (Type C), with a range from 191.05 to 440.85 m/s. This indicates that most of Marga Agung Village has relatively low soil vulnerability to earthquake ground shaking.

INTRODUCTION

Sumatera Island is one of the main regions in Indonesia with a relatively high level of seismic activity. Geographically, it ranks as the third largest island in Indonesia, with an area of approximately 473.481 km², and is the second most populous island after Java. This phenomenon is strongly correlated with Sumatera's regional tectonic configuration, which lies within an active plate convergence zone, making the region vulnerable to earthquakes (Triyoso et al., 2024; Widiyantoro et al., 2024). Seismic activity in Sumatera is primarily influenced by the presence of a subduction zone along the western side of the island, formed by the interaction between the Indo-Australian Plate and the Eurasian Plate. In addition, the strike-slip Sumatran Fault system, which stretches from the northern to the southern part of the island, also plays a significant role in controlling the distribution and intensity of earthquakes in the region (Lubis et al., 2024).

Lampung Province is one of the regions in Sumatera Island with a relatively significant level of seismic vulnerability, particularly in South Lampung Regency (Rasimeng et al., 2022).

From a geological and tectonic perspective, this condition is influenced by its proximity to the subduction zone and the presence of the Sumatran Fault system. Furthermore, local geological structures, namely the Menanga Fault and Panjang Fault, which are located relatively close to Marga Agung Village, also increase the potential seismic hazard in this region (Mangga et al., 1993; Falah et al., 2023). Another important factor is the volcanic activity of Mount Krakatoa, located in the Sunda Strait, which has historically contributed to elevated seismic activity in South Lampung (Abdurrachman et al., 2018).

The history of seismicity in Lampung Province indicates that the region has experienced several significant earthquake events. One notable event was the Liwa earthquake, with a magnitude of 6.8 and an approximate depth of 23 km, which was classified as a shallow earthquake and resulted in more than 200 fatalities (Widiwijayanti, 1994). Bandar Lampung is located in a tectonically active region and has experienced repeated local earthquakes that may cause damage to buildings (Haerudin et al., 2020; Dani et al., 2024). This situation indicates that the Lampung region, particularly areas located near active seismic sources, possesses a potential earthquake risk that warrants further study. Therefore, research examining the resilience of Marga Agung Village to the impacts of seismic activity is important.

The response of a region to earthquake ground shaking is not only influenced by the earthquake source, but is also determined by the dynamic characteristics of the local soil (Hossain et al., 2025). Differences in the physical and mechanical properties of soil layers can cause varying levels of seismic wave amplification, resulting in different levels of damage between regions Ziar & Basari, 2026). Soil dynamic characteristics can be analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method. This method effectively represents the dynamic response of soil layers through several key parameters, including the natural frequency (f_0), amplification factor (A_0), seismic vulnerability index (K_g), and the estimated average shear wave velocity to a depth of 30 meters (Vs_{30}) (Pramatadie et al., 2023). The parameters derived from HVSR analysis are widely used for assessing soil conditions and evaluating the potential impacts of earthquake ground motion, particularly in the context of development planning and disaster mitigation. Information on natural frequency and amplification values can be used to identify areas potentially experiencing ground resonance, whereas the seismic vulnerability index and Vs_{30} values are commonly used for assessing soil type, which can be used for determining regional seismic resilience. Furthermore, HVSR-based mapping results can support spatial planning that incorporates disaster risk into considerations (Amirudin & Madrinovella, 2023).

Several previous studies had been conducted in the area surrounding the study site, particularly in the Jati Agung District. These studies indicated f_0 values ranging from 0.52 to 5.81 Hz, and A_0 values between 3.46 and 7.79. Meanwhile, K_g values varied from 2.83 to 98.09, and Vs_{30} values ranged from 68.29 to 492.9 m/s. Based on these Vs_{30} values, the study area was classified into soil types C, D, and E (Hutagalung, 2024). Other research conducted in Jatimulyo Village also showed variations in subsurface dynamic characteristics, with f_0 values between 0.51 to 22.03 Hz, A_0 values ranging 1.01 and 6.65, K_g values between 0.08 to 26.66, and Vs_{30} values ranging from 136.73 to 595.74 m/s. Based on these parameters, Jatimulyo Village is categorized as having relatively low soil vulnerability and is dominated by stiff soil (Type D) (Panggula, 2025). Overall, these previous studies demonstrate the variation in soil dynamic characteristics and vulnerability levels in the Jati Agung area, South Lampung.

Although several studies related to soil dynamic characteristics had been conducted in the surrounding area, research on soil vulnerability to earthquakes using the HVSR method in Marga Agung Village remains limited. Therefore, this study aims to complement this information by analyzing the sediment layer characteristics and the soil vulnerability levels in Marga Agung Village. The determination of soil vulnerability levels was carried out by developing a soil vulnerability zoning map based on the parameters f_0, A_0, K_g, and Vs_{30}. In addition, this study was conducted to assess the potential level of building damage as a basis for supporting earthquake disaster mitigation measures in the study area.

METHODS

This research was conducted in Marga Agung Village, South Lampung Regency, in February 2025. Microtremor data were collected at 35 stations spread across the study area. The distance between stations was set at 450 to 500 meters, with a microtremor recording duration of 45–50 minutes at each station. The number of stations, the distance between stations, and the recording duration were determined based on SESAME (2004) guidelines, ensuring that the data obtained accurately represent the geological conditions and soil dynamics characteristics in the study area.

Microtremor data acquisition was carried out using a Raspberry Shake RS3D Indoor device, a high-sensitivity seismometer designed to record low-amplitude seismic vibrations. This device records seismic signals in three main components: North–South, East–West, and vertical. By recording these three components, the response of seismic wave propagation in the soil layer can be comprehensively recorded. The resulting data, in the form of time-domain seismograms, are continuously recorded during the acquisition process and subsequently used as the primary data for analyzing soil dynamics characteristics (SESAME 2004; Molnar et al 2022).

The HVSR method is used in microtremor data processing. The initial processing stage includes signal selection and selecting a stable time window to reduce the influence of external interference. Next, a spectral transformation is performed to obtain the HVSR curve at each station. The resulting HVSR curve is then used to determine the natural frequency (f_0) and amplification factor (A_0) parameters at each station location.

The natural frequency and amplification factor values obtained through the HVSR analysis are then used to determine the seismic vulnerability index (K_g) at each station (Nakamura, 1989; Zuhair et al., 2023). This parameter is calculated by combining the natural frequency and amplification factor values to obtain the soil vulnerability to seismic shaking at each measurement location. The K_g Value in this study was calculated using Equation (1), according to Nakamura (1997).

$$K_g = \frac{{A_0}^2}{f_0} \quad (1)$$

To obtain information about subsurface conditions, the observed HVSR curves are further processed through an inversion stage. The inversion stage utilizes the Genetic Algorithm (GA) method to obtain a subsurface model that describes the variation in shear wave velocity with depth. This process is carried out iteratively by matching the observed curves with the synthetic curves generated from the model until the best match is achieved (Sahraeian et al., 2020).

The inversion results in a subsurface model that shows the variation in shear wave velocity values in each soil layer and their thicknesses. This model is then used to calculate the average shear wave velocity value down to a depth of 30 meters (Vs_{30}) at each observation station (Grutas et al., 2025). The equation for calculating Vs_{30} is presented as follows:

$$Vs_{30} = \frac{30}{\sum_{i=1}^{N}(\frac{h_i}{V_{st}})} \quad (2)$$

N is the number of layers, where h_i is the thickness of the first layer, and V_{st} is the shear wave velocity of the layer according to NHERP (2000).

All parameters resulting from the analysis, namely the natural frequency (f_0), amplification factor (A_0), seismic vulnerability index (K_g), and Vs_{30} were then spatially mapped using an interpolation method based on the observation points. The resulting parameter distribution map is used to illustrate variations in soil dynamics and subsurface characteristics in Marga Agung Village, South Lampung Regency.

RESULTS AND DISCUSSION

Microtremor data analysis was conducted through the application of the Horizontal to Vertical Spectral Ratio (HVSR) method. This procedure was originally initiated by Nogoshi & Igarashi (1971) and later refined by Nakamura (1989) as an approach for identifying the natural frequencies of the soil. The HVSR method fundamentally utilizes a comparison of the Fourier amplitude spectra of the horizontal components, specifically the (North–South and East–West), with the amplitude spectrum of the vertical component of the ambient vibration signal recorded at a single measurement point. This spectral ratio produces an HVSR curve, which is used to determine the natural frequency (f_0) and amplification factor (A_0) (Nakamura, 1989).

From the data processing results using the HVSR method, several key parameters were obtained and used to evaluate the characteristics of soil dynamics in the study area. The resulting parameters include the natural frequency (f_0), amplification factor (A_0), seismic vulnerability index (K_g), and the average shear wave velocity to a depth of 30 meters (Vs_{30}). These parameters were analyzed spatially to describe variations in subsurface conditions in Marga Agung Village, South Lampung Regency.

Natural Frequency (f_0)

The natural frequency (f_0) is the soil's natural resonance frequency for shear waves (S-waves), which is influenced by the shear wave velocity *Vs*. This parameter can be used to interpret sediment characteristics, particularly regarding layer thickness and the elastic properties of the constituent materials (Castellaro et al., 2009).

The following is a map of the distribution of natural frequency values in the research area, which is presented in Figure 1, while the classification of natural frequency values according to Kanai (1983) classification is presented in Table 1.

Table 1. Classification of Natural Frequency Values (f_0)

Type	(f_0) Hz	Description	Station
I	6,667 - 20	The sediment thickness is very thin	TL6, TL12, TL13, TL15, TL20, TL24, TL25, TL28, TL29, TL32, TL33, TL36, TL39
II	4,0 - 6,67	The thickness of the surface sediment is included in the medium category of 5 - 10 meters	TL11, TL21, TL22, TL23, TL26, TL30, TL34, TL35, TL37, TL38, TL40
III	2,5 - 4	The thickness of the surface sediment is included in the thick category, around 10 - 30 meters	TL1, TL7, TL8, TL19, TL31
IV	<2,5	The thickness of the surface sediment is very thick	TL5, TL9, TL14, TL17, TL18, TL27

Source: Authors' data; classification based on Kanai (1983).

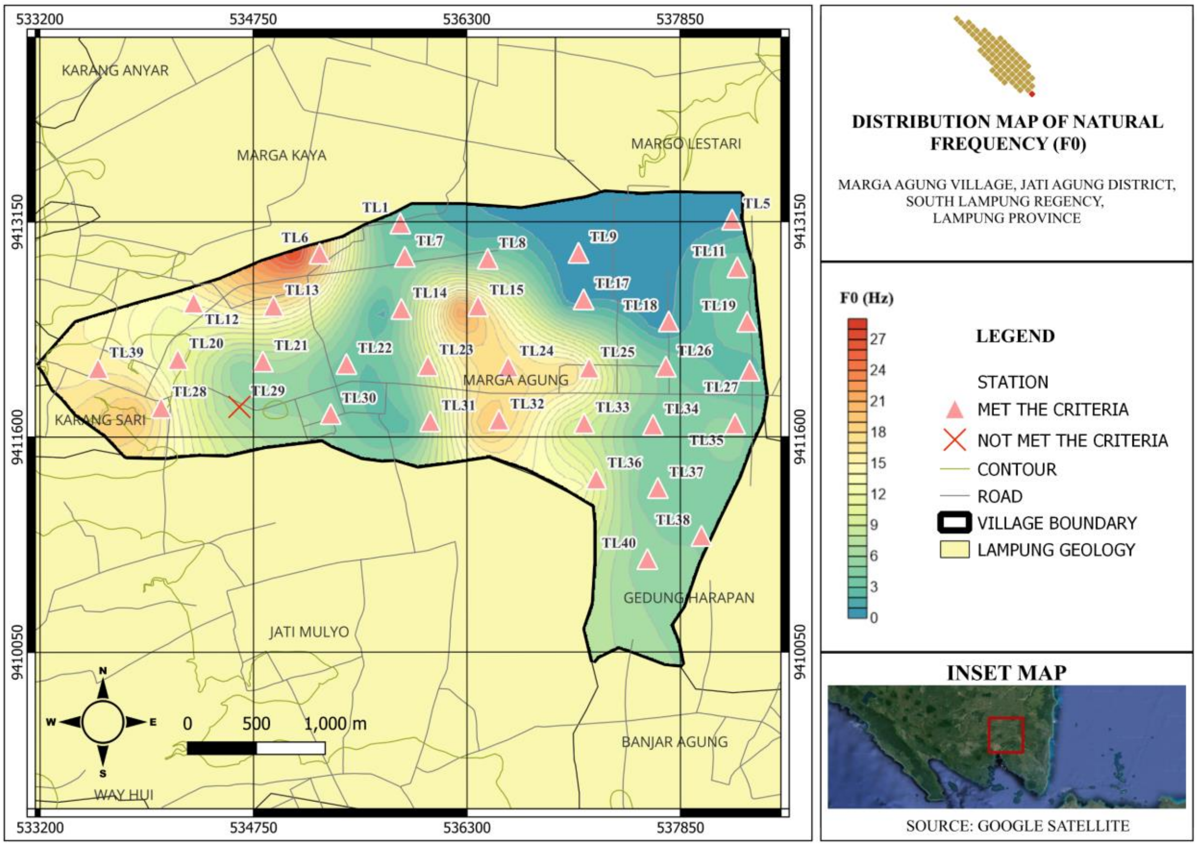

Figure 1. Map of the Distribution of Natural Frequency Values (f_0)

Referring to Figure 1, the distribution of natural frequency values in the study area is within the range of 0.31 Hz to 27.96 Hz. The highest frequency value is recorded at station TL6, at 27.96 Hz, while the lowest value is observed at station TL9, at 0.31 Hz. Furthermore, based on Kanai (1983) classification, the stations in the study area are divided into four soil types. Most of the stations fall into type I and type II, totalling to 24. Furthermore, five stations fall into type III and six into type IV.

Spatially, type I soil is generally distributed in the western to central part of the study area. Type II and type III soils tend to be found in the central to eastern parts, while type IV soils are mostly observed in the northeastern part of the study area.

The distribution of natural frequency values shows differences in the thickness of subsurface sediments in the study area (SESAME, 2004; Johnson & Lane, 2016). The relatively high natural frequency values at most stations indicate that the surface sediment layer has a relatively thin to medium thickness. Conversely, lower frequency values indicate the presence of a thicker sediment layer (Parolai et al., 2002). This distribution pattern is related to the regional geological conditions of the study area, which is are included in the Lampung Formation (QTl). This formation is composed of rhyolitic tuff, pumiceous tuff, tuffaceous claystone, tuffite compacted tuff, and tuffaceous sandstone (Mangga et al., 1993). Lithological variations in this formation cause differences in the characteristics of the subsurface layer in several locations. The presence of relatively compact layers and sediment that are not too thick in most parts of the study area contributes to the emergence of medium to high natural frequency values.

Amplification Factor (A_0)

The amplification factor indicates the degree of seismic wave amplification resulting from differences in physical characteristics between subsurface rock layers (Panjami et al., 2018). In the HVSR method, the amplification factor is derived from the ratio of the horizontal component of the spectral response to the vertical component, thus reflecting the effect of local geological conditions on seismic wave propagation (Nakamura, 2000).

The spatial distribution of amplification factor values in the research area is presented in Figure 2, while the classification of amplification values according to Setiawan (2009) is presented in Table 2.

Table 2. Classification of Amplification Factor Values (A_0)

Zone	Classification	Amplification Factor Value	Station
1	Low	$A_0 < 3$	TL1, TL6, TL7, TL8, TL11, TL12, TL13, TL14, TL15, TL19, TL20, TL21, TL22, TL23, TL24, TL26, TL27, TL29, TL30, TL31, TL32, TL34, TL35, TL36, TL37, TL38, TL40
2	Moderate	$3 \leq A_0 < 6$	TL5, TL9, TL17, TL18, TL25, TL28, TL33, TL39

Source: Authors' data; classification based on Setiawan (2009).

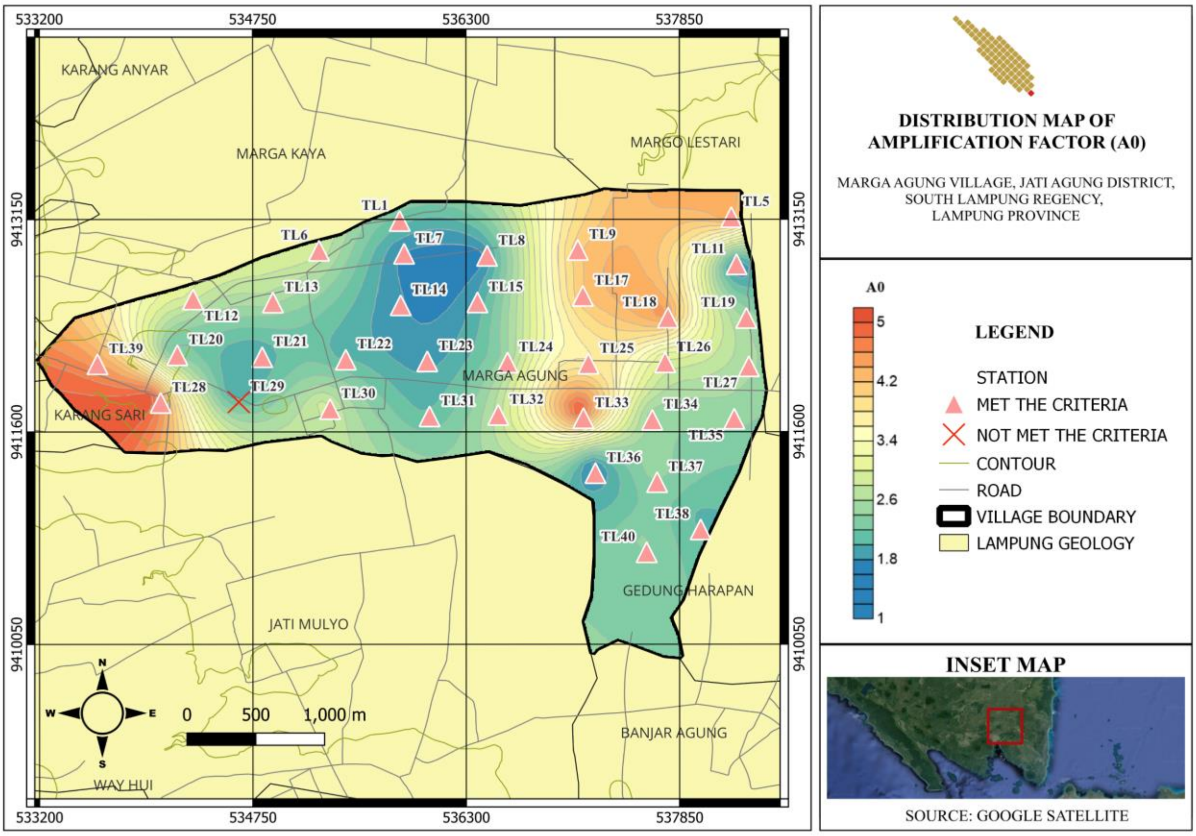

Figure 2. Distribution Map of Amplification Factor Values (A_0)

Referring to Figure 2, the amplification factor values in the study area is within the range of 1.59 to 5.10. Referring to this classification, most areas fall into the low amplification zone ($A_0 < 3$), which is found at 27 stations located in the central to eastern parts, while several points are in the southeast and south of the study area. Meanwhile, the moderate amplification zone ($3 \leq A_0 < 6$) is found at eight stations, mostly located in the central to northeastern part of the study area, with several stations located in the west.

The dominance of low to moderate amplification values in the study area indicates that the soil layers in Marga Agung Village do not produce significant amplification of seismic waves. This condition is related to the relatively small seismic impedance contrast between the sediment layers and the bedrock. Differences in physical characteristics between layers that are not highly contrasting cause seismic waves propagating toward the surface in the study area not to experience significant amplification (Sandikkaya & Dinsever, 2018). Conversely, a high A_0 value is influenced by the seismic impedance contrast between the bedrock and the overlying sedimentary layer, where a high impedance difference tends to result in greater wave amplification.

Seismic Vulnerability Index (K_g)

The seismic vulnerability index values are calculated based on the natural frequency parameters and amplification factor parameters and can be used to assess the potential earthquake hazard level in a region (Nakamura, 1997; Miezah-Adams et al., 2024). The classification of K_g values refers to Refrizon (2013) as presented in Table 3, while the distribution map of K_g values is shown in Figure 3.

Table 3. Classification of Seismic Vulnerability Index Values (K_g)

Zone	Classification	Seismic Vulnerability Index Values	Station
1	Low	$K_g < 3$	TL1, TL6, TL7, TL8, TL11, TL12, TL13, TL14, TL15, TL19, TL20, TL21, TL22, TL23, TL24, TL25, TL26, TL27, TL28, TL29, TL30, TL31, TL32, TL33, TL34, TL35, TL36, TL37, TL38, TL39, TL40
3	Moderate	$K_g > 6$	TL5, TL9, TL17, TL18

Source: Authors' data; classification based on Refrizon (2013)

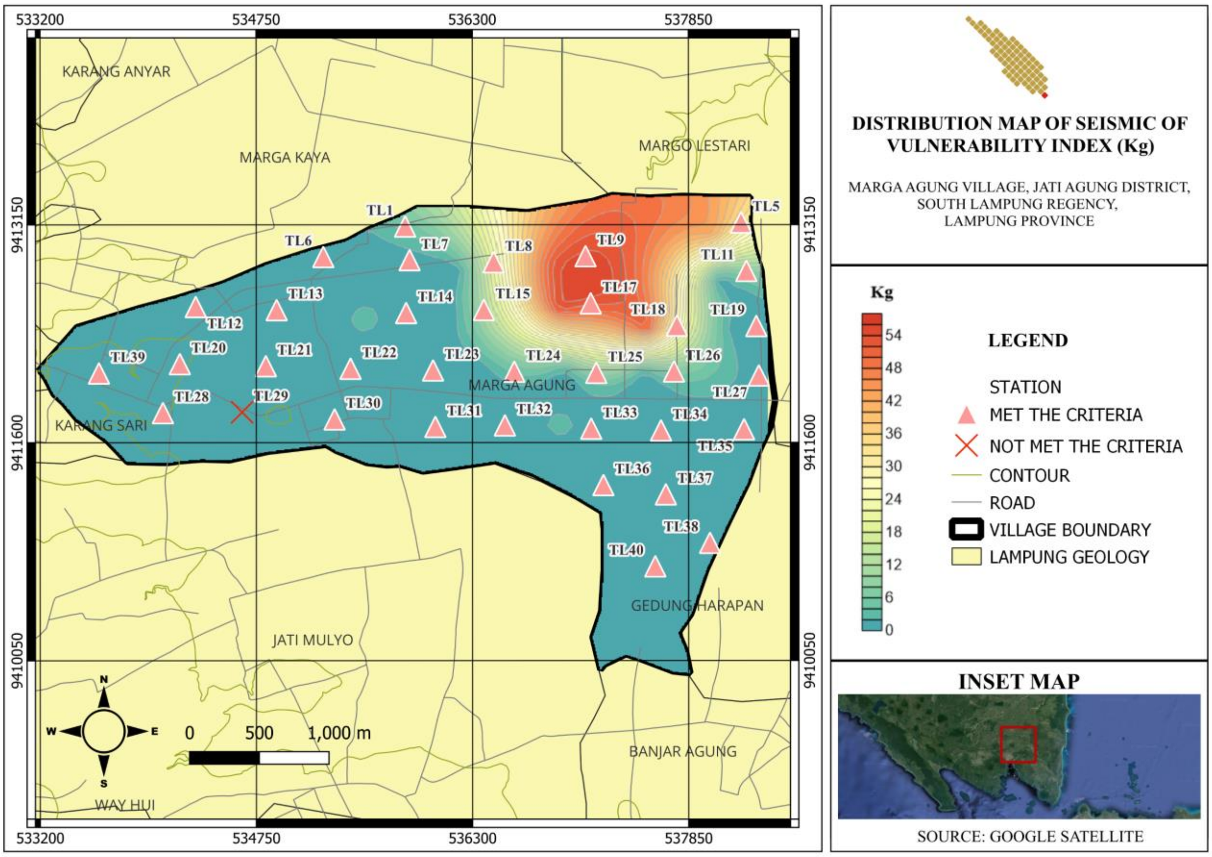

Figure 3. Map of the distribution of seismic vulnerability index values (K_g)

The calculation results indicate that the K_g values in the study area range from 0.15 to 53.45. Based on these values, the study area is classified into two main zones, the low seismic vulnerability zone (K_g < 3) and the high seismic vulnerability zone (K_g > 6). The low seismic vulnerability zone is found at thirty-one station spread across the western to southwestern regions, extending to the central to eastern areas, and from the southern to southeastern parts of the study area. Meanwhile, the high seismic vulnerability zone is found at four stations located in the northeastern part of the study area.

The dominance of low seismic vulnerability index values in the study area shows differences in characteristics of subsurface layers between soft layers and harder layers. A low seismic vulnerability index reflects a relatively low level of damage caused by earthquake shaking. This condition indicates that areas with relatively thin sediment thickness and amplification values that are not too large have a more stable level of seismic vulnerability to earthquake hazards (Hussai et al., 2021; Susilo et al., 2024). Conversely, a high seismic vulnerability index value indicates the presence of a thick sedimentary layer and a high amplification value, placing the region at greater risk of significant damage from seismic shaking (Nakamura, 2008). Furthermore, topographic conditions and land surface slope can also influence the K_g value, especially in areas with certain morphological variations (Warnana, 2011; Pischiutta et al., 2017).

The low seismic vulnerability index values in this study area correlate with the regional geological structure of Lampung, which is located in an active tectonic zone and is included in the QTL formation. The loose and unconsolidated nature of the QTL tectonic zone is included in the QTL formation. The loose and unconsolidated nature of the QTL deposits can influence the attenuation of seismic wave energy, resulting in relatively low measured ground motion amplitudes even though the area is classified as earthquake-prone (Panzera et al., 2016).

Shear Wave Velocity to a Depth of 30 meters (Vs_{30})

The Vs_{30} values are obtained through an inversion process based on the Genetic Algorithm (GA) by comparing the observed curve with the synthetic curve and evaluating their fit using an objective function until an optimum model is obtained. The model with the best fit is then retained and developed through selection, crossover, and mutation mechanisms until an optimum solution is found that more accurately represents subsurface conditions (Sambridge, 1992; Akkaya, 2020).

The inversion method based on the Genetic Algorithm is grounded in the principles of evolution and natural selection, as first proposed by Holland (1975). In HVSR analysis, each individual in the GA population represents a subsurface model composed of layer thickness and shear wave velocity (Vs) parameters.

The inversion results indicate that the observed and calculated curves have a relatively good match, with RMS error values ranging from 0.31% to 1.04%. The inverted subsurface model shows the presence of five subsurface layers with a maximum depth of approximately 80 meters.

To obtain the Vs_{30} value at each station, the calculations is carried out based on the accumulated layer thickness to a depth of 30 meters. At several stations, only the upper top two to three layers are used in the calculation according to the depth reached, which is calculated by referring to equation (2). In earthquake hazard studies, the Vs_{30} parameter is used as a primary parameter because it reflects the response characteristics of subsurface layers to earthquake shaking. This is based on the relationship between rock classification and Vs_{30} values according to NHERP (2000).

Table 4. Rock Classification Based on Shear Wave Velocity Vs_{30}

No	Type	Types of Rocks	Vs_{30}
1	A	*Hard rock*	$Vs_{30} > 1500$ m/s
2	B	*Rock*	$750 < Vs_{30} \leq 1500$ m/s
3	C	*Very dense and soft rock*	$350 < Vs_{30} \leq 750$ m/s
4	D	*Stiff soil*	$175 < Vs_{30} \leq 350$ m/s
5	E	*Soft soil*	$Vs_{30} \leq 175$ m/s

Source: NHERP (2000)

The distribution map of Vs_{30} values in the study area is presented in Figure 4, while the soil type classification refers to the NEHRP (2000) standard as presented in Table 5.

Table 5. Rock Classification Based on Shear Wave Velocity to a Depth of 30 meters Vs_{30}

No	Type	Types of Rocks	Vs_{30}	Station
1	C	*Very dense and soft rock*	$350 < Vs_{30} \leq 750$ m/s	TL6, TL12, TL13, TL15, TL24, TL25, TL28, TL32, TL33, TL36, TL37, TL39
2	D	*Stiff soil*	$175 < Vs_{30} \leq 350$ m/s	TL1, TL8, TL11, TL19, TL20, TL21, TL22, TL23, TL26, TL29, TL30, TL31, TL34, TL35, TL38, TL40
3	E	*Soft soil*	$Vs_{30} \leq 175$ m/s	TL5, TL7, TL9, TL14, TL17, TL18, TL27

Source: Authors' data; classification based on NHERP (2000)

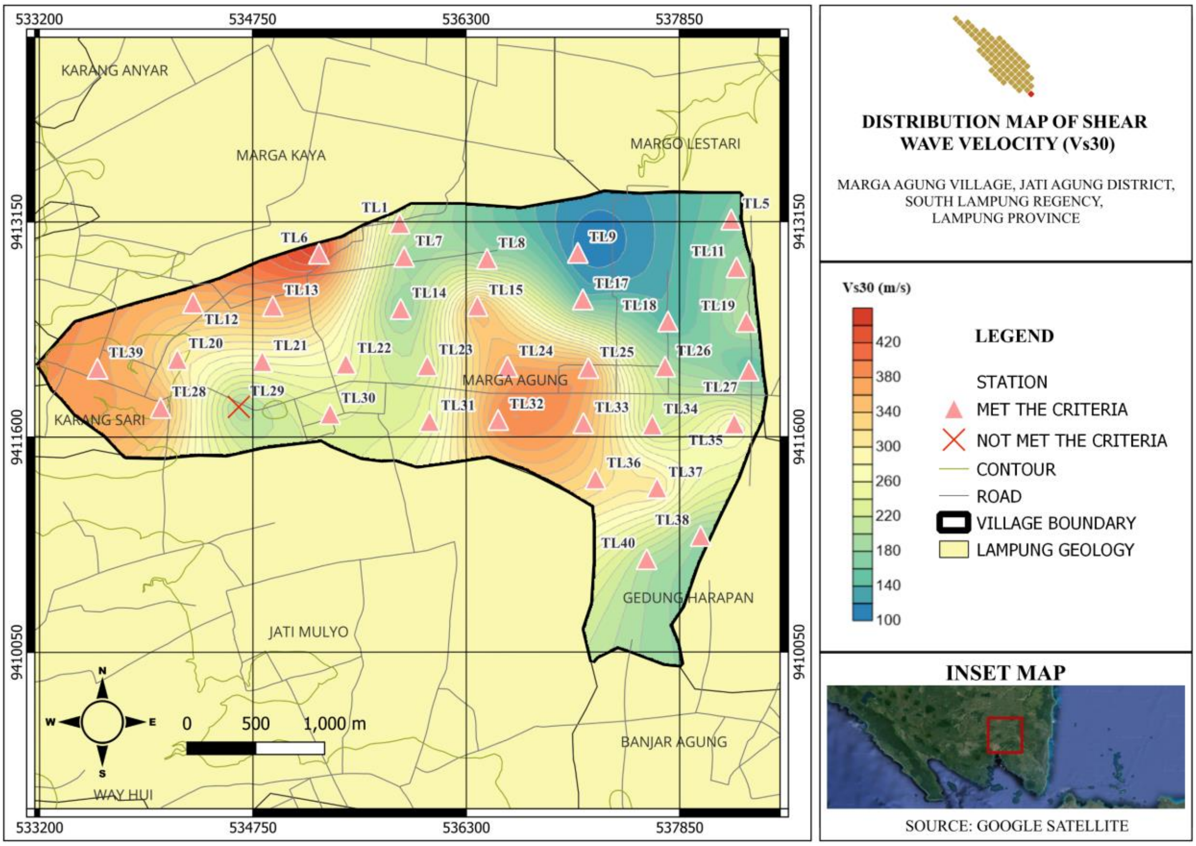

Figure 4. Map of Shear Wave Velocity Distribution to a Depth of 30 meters (Vs_{30})

Referring to the NEHRP (2000) classification, the study area is divided into three soil types, namely very dense and soft rock (Type C), stiff soil (Type D), and soft soil (Type E). Referring to Figure 4, most of the study area is dominated by stiff soil (Type D) and very dense and soft rock (Type C) with values ranging from 191.05 to 440.85 m/s, which are found at twenty-eight station that are spatially distributed, predominantly in the central to southeastern as well as western and northwestern parts of the study area. Meanwhile, soft soil (Type E) is found at several stations and is distributed in the central to eastern part of the study area, with several other stations located in the northeastern and southeastern parts.

The Vs_{30} values indicate that the Marga Agung Village area is dominated by stiff soil (Type D) and very dense and soft rock soil (Type C). This finding aligns with research by Hutagulung (2024) and Panggula (2025), which found Vs_{30} values in the stiff soil to very dense and soft rock soil category in areas with similar geological conditions. Regionally, Lampung Province is earthquake-prone due to its location in a tectonically active zone. However, this condition does not directly reflect the physical properties of the soil at a local scale. Based on the geological composition, the study area belongs to the Quaternary sedimentary unit (QTl), whose material composition indicates that the surface layer at the study site consists of relatively compact materials, thereby falling into the stiff soil to very dense and soft rock soil categories.

The dominance of stiff soil to very dense and soft rock soil in the study area has a relatively low level of vulnerability to earthquake shaking due to the relatively small potential for seismic wave amplification (Akkaya & Mert, 2022). Therefore, information regarding the distribution of Vs_{30} values and the characteristics of the subsurface layers is important for disaster mitigation efforts.

CONCLUSION

Based on data processing and analysis, the level of soil vulnerability in the study area can be identified through soil vulnerability zoning mapping. In general, the zoning results indicate that some areas are dominated by areas with relatively low to moderate soil vulnerability. Spatially, relatively stable soil conditions are found in the central to western parts of the study area, while zones with more vulnerable conditions are spread across the northeastern part of Marga Agung Village.

This condition is reflected f_0 values ranging from 0.31 Hz to 27.96 Hz. Most of the stations fall into the soil type I and II classifications according to Kanai (1983). Type I soils are generally distributed in the western to central parts of the study area, while Type II soils are found in the central to eastern parts.

In addition, A_0 values in the study area range from 1.59 to 5.10, and are dominated by the low amplification category, particularly in the central to eastern parts of the study area, with several points found in the southeast and south of the study area.

The calculated K_g values range from 0.15 to 53.45. Most of the stations have relatively low seismic vulnerability index values and are predominantly distributed in the western to southwestern parts, extending toward the central to eastern areas, as well as the southern to southeastern parts of the study area.

The parameter Vs_{30} also indicated that the area is dominated by stiff soil (Type D) and very dense and soft rock (Type C), with Vs30 values ranging from 191.05 to 440.85 m/s, found at twenty-eight station that are spatially distributed mainly in the central to southeastern parts, as well as the western and northwestern of the study area. The dominance of stiff soil to very dense and soft rock indicates that most of Marga Agung Village has a low level of soil vulnerability to seismic ground shaking. This condition indicates that the potential level of building damage is likely lower compared to areas dominated by soft soil in the event of an earthquake.

Overall, the study results indicate that the soil vulnerability condition in Marga Agung Village is relatively low. The subsurface layer, characterized by stiff soil to very dense and soft rock in the study area, does not experience significant ground motion amplification. The information on subsurface characteristics and soil vulnerability zoning obtained from this research can be used as a reference for spatial planning, building design adaptive to soil conditions, and for improving community preparedness for earthquake risks.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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