

Seismic Vulnerability Analysis using Microseismic Methods in Kepahiang District, Bengkulu

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Abstract

This study aims to analyse subsurface geological conditions and seismic vulnerability levels using the microseismic method with 17 measurement points to obtain the Seismic Vulnerability Index (SVI) and shear wave velocity (V_s) parameters. The analysis results show a strong correlation between these two parameters in identifying weak subsurface zones that have the potential for earthquake wave amplification. High SVI values indicate significant vibration amplification potential. The V_s results reinforce these findings, with point 3 having the highest V_s value of 1,491.99 m/s (Hard Rock/SA), indicating dense and compact rock, while point 14 has the lowest V_s value (Soft Soil/SE), reflecting a soft layer with high amplification potential. The integration of SVI and V_s parameters confirms that point 14 is a critical zone with the highest seismic vulnerability, requiring special attention in disaster mitigation, spatial planning, and infrastructure development.

Keywords: Microseismic, Seismic Vulnerability Index, V_s , Kepahiang

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INTRODUCTION

Kepahiang Regency, Bengkulu Province, Indonesia, is located in the convergence zone of the Indo-Australian and Eurasian tectonic plates (Yulita et al., 2023). The northward movement of the Indo-Australian Plate and the southward movement of the Eurasian Plate generate compressional forces that form the Sumatra Fault Zone (SFZ). The SFZ, which stretches along the island of Sumatra, consists of 19 main segments ranging from 35 to 200 kilometres in length, each exhibiting varying rates of displacement. This variation contributes to different levels of seismic activity, thereby increasing the potential for earthquakes in the Sumatra region, including Kepahiang (Lubis et al., 2020).

The Indo-Australian tectonic plate generates tectonic energy and the highest strain rate in Bengkulu Province, including Kepahiang Regency (P. A. Sihombing et al., 2024). This condition causes seismic activity in the region to be higher than in other regions on the island of Sumatra. Kepahiang Regency is also crossed by the Musi Sumatra Fault and a number of secondary faults located directly beneath it (Daswita et al., 2023). The existence of these faults increases vulnerability to ground movement during earthquakes. Based on the top and bottom of the fault based on variations in subsurface resistivity, estimates of the rate of displacement, faults, and seismic moment, large earthquakes with a magnitude above 7 tend to occur more frequently along these faults, especially in Bengkulu Province (Margiono et al., 2021). This condition confirms the high risk of earthquakes in Kepahiang Regency.

The presence of the Musi Fault in Sumatra and secondary faults in Kepahiang Regency increases the risk of earthquakes, especially in densely populated areas. Seismic data from 1971 to 2011 in coordinates 2°S–3°S and 102°E–103°E around the Musi Fault recorded 12 shallow earthquakes with a magnitude of ≥ 5 . One major event occurred on 15 December 1979, with an earthquake measuring 6.6 (depth 33 km) at coordinates 3.299°S, 102.712°E, which destroyed nearly 500 houses and caused significant ground cracks (Lubis et al., 2019). The proximity of fault zones to residential areas necessitates the implementation of earthquake-resistant building designs, despite the increased construction costs. The impacts of earthquakes include loss of life, property damage, and damage to public infrastructure. Therefore, urban planning must prioritise earthquake-resistant building standards, especially in earthquake-prone areas (Wicaksana & Rosyidah, 2021). As a developing region, Kepahiang Regency requires medium- and long-term development plans that focus on reducing earthquake risk through resilient infrastructure and strategic planning (Azuwandri, 2022). This approach will minimise the impact of disasters and improve public safety.

The Musi Fault, one of the main segments in the Sumatra Fault Zone (SFZ), plays an important role in determining the level of earthquake risk in the Sumatra region, particularly in Kepahiang Regency (Lubis et al., 2019). As an active fault, the Musi Fault experiences continuous tectonic movement due to compressional forces between the Indo-Australian and Eurasian plates. This movement causes seismic energy to accumulate beneath the surface, which is often released in the form of earthquakes (Refrizon et al., 2013). This condition raises a number of major issues related to earthquake risk in the region. One of the main issues is the high level of seismic activity around the Musi Fault. Tectonic movements along this fault often trigger shallow earthquakes with significant magnitudes, which have the potential to damage infrastructure and cause casualties (Aslamia & Supardi, 2022). The area around the fault line is a zone with a high risk of earthquakes. In addition, the local geological structure, including the presence of soft soil or clay, exacerbates the impact of earthquakes through seismic wave amplification (Mokodenseho et al., 2023). This condition increases damage, especially in densely populated areas or areas with buildings that do not meet earthquake resistance standards. This vulnerability is exacerbated by the proximity of the fault to important infrastructure such as settlements, roads, bridges, and other public facilities. Damage to this infrastructure can cause significant social and economic disruption. The lack of understanding among

the community and relevant parties about the potential dangers of earthquakes caused by the top and bottom of the Musi Fault is another challenge. The lack of information and awareness of these risks often hinders effective mitigation efforts. In addition, spatial planning that does not take into account the existence of active faults further increases the vulnerability of the region, especially for settlements and public facilities located in high-risk zones (Aulia et al., 2021). In addition, the Musi Fault has a history of triggering major earthquakes, such as the 6.6 magnitude earthquake in 1979 that caused massive damage in the Bengkulu Province. The frequency of these major earthquakes adds to the complexity of managing risk in the fault zone. These issues underscore the importance of detailed mapping of earthquake risk zones around the Musi Fault. This mapping aims to identify risk levels in various areas, while supporting disaster mitigation-based development planning. With this step, the social and economic impacts of earthquakes can be minimised, creating a safer and more resilient environment for local communities. Earthquake risk analysis aims to determine the threshold intensity of earthquakes based on the probability of occurrence or exceedance within a certain period of time (Litman, 2021). In addition, this analysis includes an assessment of the potential damage and losses caused by earthquakes in the future. In this study, the earthquake risk caused by the Musi Fault was analysed using various key parameters, including resistivity, Seismic Vulnerability Index (SVI), and shear wave velocity (V_s). These parameters provide a comprehensive picture of the level of vulnerability and potential impact of earthquakes in the study area.

The studies conducted are still limited and do not accurately describe the subsurface conditions. However, the results from geoscience are sufficient to support the physical parameters required for the numerical model to be developed. Previous research has been conducted by (Ardiansyah, 2018) The results obtained indicate that the series of earthquakes that occurred in the Kepahiang Regency, when viewed from the location of the epicentre and the depth of the hypocentre, are strongly suspected to have been caused by local fault activity in the Kepahiang Regency, namely the Musi Fault. However, this research needs to be developed further. Therefore, research needs to be conducted to determine the impact of earthquakes caused by the Musi Fault using the microtremor method, which is an effective geophysical approach for identifying active faults that have the potential to cause earthquakes. The microtremor method captures the dynamics of movement around faults (Mokodenseho et al., 2023). The results obtained are more complete data for earthquake risk identification, thus providing a solid basis for disaster mitigation and risk management in earthquake-prone areas.

Regional Geology

The Kepahiang region, Bengkulu Province, is located in the central eastern part of the province. Tectonically, Kepahiang is very interesting because of its location close to the Great Sumatran Fault (GSF), particularly the Musi segment, and its location in the Bukit Barisan mountain range in the Kaba Volcano complex. Its landscape shows a diversity of volcanoes ranging from Tertiary to Quaternary (Putri & Daud, 2023). The geological characteristics of this area are dominated by volcanic and sedimentary formations resulting from volcanic activity due to its proximity to Mount Kaba. The main geological structure is characterised by the presence of a northwest-southeast fault, which is parallel to the Musi Fault line. This structure is marked by the presence of fumaroles, hills, waterfalls, fractures, and intrusions of igneous rock. These characteristics reinforce the indication that Kepahiang Regency is located in an active tectonic zone (Hamdhan & Pratiwi, 2017).

Stratigraphically, the Kepahiang Regency area is composed of Tertiary to Quaternary rocks. In the Tertiary section, the Hulusimpang Formation (Tomh), Seblat Formation (Toms), Granite (Tmgr), Lemau Formation (Tml), and Simpangaur Formation (Tmps) are found (Figure 1). Of these units, the Hulusimpang Formation (Tomh) is the oldest sedimentary rock formation developed in the Bengkulu Basin, dating from the Late Oligocene to the Late Miocene (Farid et al., 2021; Heryanto, 2006). The lithology of this formation is dominated by andesite to basalt lava, volcanic breccia, and

hydrothermally altered tuff, containing quartz, veins, and sulphide minerals (R. B. Sihombing et al., 2018).

Meanwhile, Quaternary rocks in Kepahiang consist of the Bintunan Formation (QTb), Old Volcanic Rocks (Qv), Bukit Kaba volcanic breccia (Qhvk), Swamp Deposits (Qas), and Alluvial (Qal) (Hadi et al., 2025). From this unit, the Old Volcanic Rock Formation (Qv) is an important formation because it dates from the Pleistocene to Holocene periods and consists of andesite-basalt lava, tuff, and volcanic breccia. The formation is approximately 300 metres thick and is mainly found in the northwestern part of the Bukit Barisan zone (Firdasari & Idarwati, 2017). The presence of young volcanic lithology in Tertiary rocks indicates the influence of active fault movement, which in the context of Kepahiang can be linked to the activity of the Musi segment of the GSF. The northwest–southeast trending fault zone that developed in this region is thought to be part of the Musi Fault deformation (Raharjo et al., 2022).

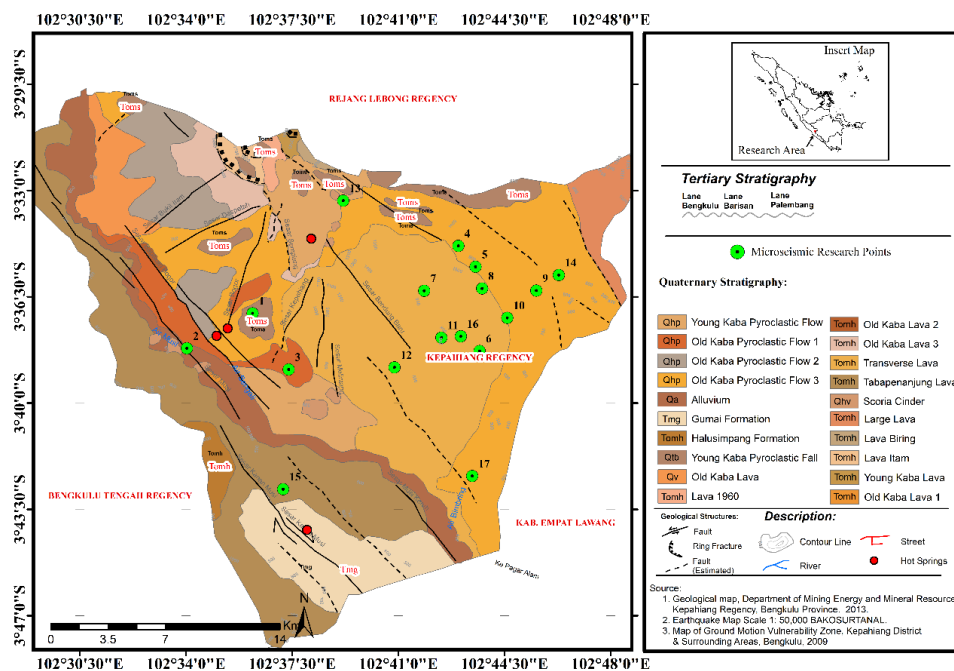


Figure 1. Geological map study area (Gafoer, s., T.C. Amin., 2007)(Irwanto et al., 2013)

Thus, based on its geographical location, stratigraphic conditions, and observed geological evidence, it can be interpreted that Kepahiang Regency is one of the areas directly affected by the Musi Fault, making it an important area for tectonic studies and earthquake hazard potential in Bengkulu Province.

METHOD

This study utilised two main geophysical methods, namely the Microtremor Method (HVSR) (Figure 1), to obtain a subsurface image in order to identify regional geological conditions and indications of active structures such as the Musi Fault. Microtremor measurements are conducted to identify the characteristics of natural ground vibrations and obtain the dominant frequencies associated with subsurface structures (Hadi, Farid, et al., 2024). Data acquisition was carried out using a short-period broadband seismometer, namely a PASI Gemini-2 triaxial geophone, with a total of 17 measurement points. Each point was recorded for 30 minutes using the Ambient Excitation method, which recorded three main wave components, namely North–South (N–S), East–West (E–W), and Up–Down (U–D).

The data processing stages begin with the selection of stable signal segments using the windowing technique, followed by transformation to the frequency domain using Fast Fourier Transform (FFT). The horizontal spectrum (U–S and E–W components) is calculated and averaged, then compared with the vertical spectrum (U–D) to obtain the H/V ratio. The resulting H/V ratio curve is then smoothed using a method to reduce spectrum fluctuations (Sugianto & Refrizon, 2021). Microtremor data is analyzed using TerraWareHV software. According to the Diffuse Field Assumption (DFA) theory, seismic energy is evenly dispersed throughout the subsurface medium (Ba et al., 2021). The dominant soil frequency (f_0) and peak amplification factor (A_0) are ascertained using the Horizontal-Vertical Spectral Ratio (HVSr) curve produced by this investigation. The thickness of the overburden layer and the impedance difference between the bedrock and sediment layers regulate the properties of local resonance (Arisona; et al., 2024), (SESAME, 2004). The inversion process is carried out iteratively until a modelling curve with the smallest misfit value is obtained, ensuring optimal conformity between the observational results and the theoretical model.

The conceptual framework for parameter integration in this study is based on the causal relationship between the ground seismic response from local resonance to shallow deformation. The HVSr parameter, which identifies resonances induced by impedance contrast in subsurface materials (Wahyuni et al., 2025), is used to calculate the SVI (Seismic Vulnerability Index), a metric for amplification potential. Shear wave velocity (V_s) profiles (Dialosa et al., 2012). show how subsurface characteristics control waves propagation and amplitude. Earthquake susceptibility zoning is a physical interaction of resonance, amplification, shock strength and soil deformation response rather than an overlap of discrete parameters in the spatial sense. Equation (1) (Nakamura, 2008) s used to calculate the Seismic Vulnerability Index (SVI) based on the values of f_0 and A_0 :

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

Seismic waves can be significantly amplified by soft soil conditions with a high SVI value (Wahyuni et al., 2025). The HVSr curve was then verified using Simulated Annealing inversion within the DFA framework to obtain the shear wave velocity (V_s) profile and layer thickness, which were used in location classification in accordance with SNI 1726:2019 in Table 1. The interpretation of the inversion model has inherent limitations, including assumptions of one dimensional layering and a decrease in resolution at greater depths, so the results are considered to be the most likely physical representation, not a unique geological solution.

Table 1. Classification of location categories based on V_s values according to SNI 1726.

Location Classification	Shear Wave Velocity V_s (m/s)
Hard Rock (SA)	$V_s > 1500$
Rock (SB)	$750 < V_s \leq 1500$
Very dense soil and soft rock (SC)	$350 < V_s \leq 750$
Medium soil (SD)	$175 < V_s \leq 350$
Soft soil (SE)	$V_s \leq 175$

RESULTS AND DISCUSSION

The Kepahiang region is part of the complex Kaba Volcano system. The products of this volcano are broadly divided into two parts, namely the products of the Old Kaba eruption and the products of the Young Kaba eruption, which are surrounded by other volcanic units, such as Bukit Lumut in the northwest, Taba Pananjung in the southwest, and Bukit Malintang in the southeast. The constituent rock units consist of dacitic, andesitic, and basaltic andesite lava, pyroclastic fall and flow deposits, as well as lahar deposits and surface deposits (Herlambang & Novranza, 2016). Tectonically,

this region is influenced by the Musi Fault, which is part of the Sumatra Fault Zone (Gafoer, S., Amin, T.C., 2012). This fault activity plays an important role in rock deformation, the formation of regional morphology, and the potential for earthquakes. Therefore, identifying the existence and distribution of the Musi Fault is crucial in efforts to mitigate geological disasters, particularly earthquakes in the Kepahiang Regency and surrounding areas. The process of heat conductivity and tectonic pressure along the fault indicates ongoing geodynamic activity (Saraswati et al., 2019). These activities not only affect slope stability, but can also cause secondary hazards such as ground movement, surface cracks, and changes to the hydrological system.

Previous studies have also shown that the Kepahiang area has indications of a shear zone that correlates with fault activity. Thus, identifying the Musi Fault through geological and geophysical approaches is a strategic step in spatial planning and disaster mitigation. Information on fault structures can be used to map earthquake-prone zones and reduce risks to infrastructure and communities in the Kepahiang region. The Seismic Vulnerability Index (SVI) can be used to determine the level of vulnerability and potential damage to land movement (Wibowo & Huda, 2020). Based on the Seismic Vulnerability Index (SVI) obtained, it can be seen that the study area has a low Seismic Vulnerability Index (SVI) value range, as indicated by the dark green colour. This means that the study area has a fairly thin sediment layer, but there are also areas with moderate to high values, indicated by blue to red colours, which indicate the thickness of the existing sediment layer. The distribution of the Seismic Vulnerability Index (SVI) is shown in Figure 2.

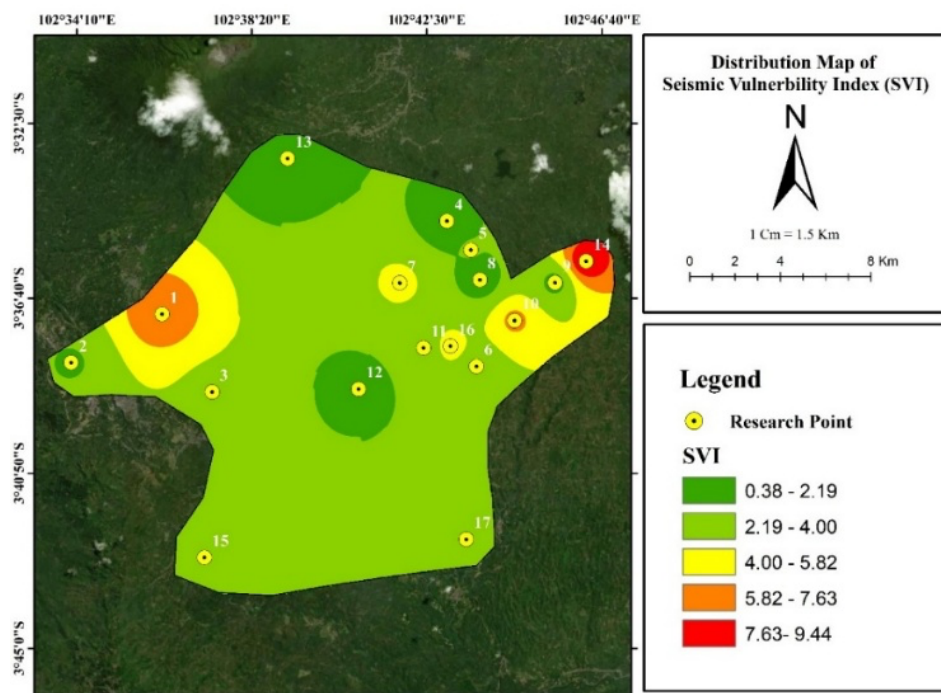


Figure 2. Map of Seismic Vulnerability Index (SVI) distribution

Based on measurement data taken at 17 measurement points, the Seismic Vulnerability Index (SVI) values in the study area ranged from 0.38 to 9.44. Areas with high seismic vulnerability indices were indicated by Points 1, 10 and 14, which had values ranging from 5.82 to 9.44. At Point 14, the high Seismic Vulnerability Index (SVI) value is due to its position being in a straight line with the estimated fault line. Faults are weak zones in the earth's crust where earthquake energy accumulates and is released (Crisanti Uduk et al., 2025). When a point is located directly above or parallel to a fault line, seismic waves travelling through the ground will experience greater amplification due to changes in the physical properties of the rock and subsurface structure around the fault.

The Seismic Vulnerability Index (SVI) can indicate the vulnerability of an area affected by tremors or rock layer movements (Satria et al., 2020). The higher the seismic vulnerability index of an area, indicated by the colour red, the more vulnerable the area is to the impact of tremors (Nadzir et al., 2024). Based on the data obtained, areas that are vulnerable to shocks or rock layer movements are referred to as weak zones. The highest seismic vulnerability index was observed at Point 14, with an SVI value of 9.4 (Figure 1). This high value indicates a greater potential for seismic wave amplification and suggests that the area may be more susceptible to earthquake-induced ground shaking and damage than other measurement points. However, the relationship between Point 14 and the nearby fault zone cannot be conclusively established based solely on the microseismic data used in this study and requires further investigation using additional subsurface structural or geophysical data.

The high SVI (Seismic Vulnerability Index) value reinforces the interpretation that point 14 is the area with the highest seismic vulnerability among the other observation points. A high SVI value indicates that the ratio between horizontal and vertical vibration amplitudes (H/V) is quite large, indicating significant seismic wave amplification (site amplification) at the surface. This is consistent with the subsurface geological conditions dominated by fault zones, where fractures and rock dislocations can accelerate the transmission and amplification of seismic waves.

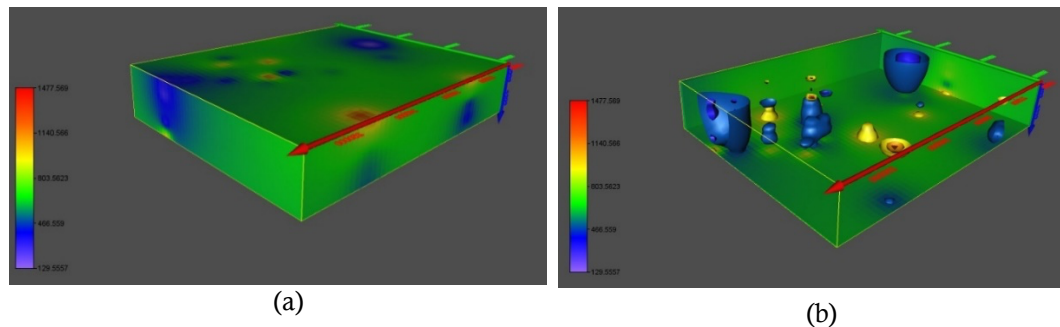


Figure 3. a) Three-dimensional modeling of (Vs) value solid rock. b) volumetric modeling of (Vs) value assumed to be solid

Softer rock materials generally have a relatively lower shear wave velocity (V_s) compared to harder rocks. This is due to the fact that shear wave velocity is directly proportional to the density and compactness of the rock. Thus, a decrease in rock density will result in a decrease in the shear wave velocity within that medium. Therefore, the V_s parameter is often used as one of the main indicators in interpreting subsurface lithology, as well as a basis for rock type classification (Arisona et al., 2024).

In the context of this study, the V_s values obtained showed significant variation at each measurement point. Based on the analysis results, the highest V_s value was recorded at point 3, which was 1491.99 m/s, which falls into the Hard Rock (SA) category according to the classification of rock types based on shear wave velocity (Wibowo & Huda, 2020). This value represents rock with a high degree of compactness and density, which is generally associated with solid igneous rock or massive volcanic rock (Rabbani et al., 2025). Conversely, the lowest V_s value was obtained at point 1, which was classified as Soft Soil (SE). This category describes geotechnical and geotechnical conditions in which the subsurface constituent materials are relatively soft, loose, and have low density, such as water-saturated clay layers, loose sand, or young alluvial sediments (Hadi, Sunaryo, et al., 2024).

In general, the range of V_s values obtained in this study indicates complex subsurface lithological variations, consistent with local geological conditions dominated by volcanic and Quaternary sedimentary materials. The presence of fairly large V_s values at most measurement points reinforces the interpretation that the study area is dominated by dense volcanic rocks, while low V_s values at several points reflect the presence of weathering zones or loose surface deposits. Thus, the

distribution of Vs values from all observation points provides a comprehensive picture of subsurface heterogeneity, which is very important in seismic vulnerability analysis and earthquake disaster mitigation planning in the study area.

CONCLUSION

Thus, the microseismic method provides a comprehensive understanding of the subsurface geological conditions and their potential vulnerability to earthquake shocks. Based on the combined analysis results, point 14 was consistently identified as the most vulnerable area, both in terms of geological structure and seismic dynamics. Geologically, the high SVI (Seismic Vulnerability Index) value at this point indicates significant earthquake wave amplification, suggesting that the ground surface in the area is more susceptible to amplifying vibrations caused by seismic waves. This condition is reinforced by the results of shear wave velocity (Vs) analysis, which shows variations in subsurface lithology. In general, the highest Vs value was measured at point 3 at 1,491.99 m/s, which is classified as Hard Rock (SA), indicating that the location is dominated by solid and compact rock, thus having better resistance to earthquake shocks. Conversely, the lowest Vs value was found at point 1, which falls into the Soft Soil (SE) category. This condition reflects a soft surface layer with low density and a higher potential for vibration amplification during an earthquake. The variation in Vs values across all observation points illustrates the heterogeneity of the subsurface lithology, where areas with low Vs, such as at point 14, are strong indications of weak zones that are susceptible to seismic deformation. Based on the two main parameters, SVI and Vs, it can be concluded that point 14 is a critical zone with the highest level of seismic vulnerability in the study area. This zone is thought to be directly associated with the active Kepahiang fault, which has the potential to increase the risk of earthquake wave amplification. Therefore, this area needs special attention in seismic disaster mitigation efforts, particularly in spatial planning, infrastructure development, and earthquake hazard analysis in the region.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The authors states that there is no conflict of interest in the publication of this article.

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