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Local Seismic Response and Earthquake Vulnerability Zoning around the Bogor Fault, Kepahiang Regency, Bengkulu

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Abstract

Kepahiang Regency, Bengkulu Province, is located in the active tectonic zone of the Sumatran Fault System (Musi Segment), with the Bogor Fault running near residential areas, potentially increasing the risk of local earthquakes. This study aims to analyze local seismic response and map earthquake-vulnerability zones along the Bogor Fault using microseismic measurements from 40 observation points. This analysis integrates the parameters f_0, A_0, SVI, PGA, GSS, and Vs to evaluate the structural influence of the Bogor Fault on seismic response and earthquake vulnerability. The results show a range of values for f_0 of 1.64–17.97 Hz, A_0 of 2.15–9.15, SVI of 0.91–35.52, PGA 0.12–0.41 g, GSS 1.01 × 10^{-5}–1.97 × 10^{-4}, and Vs 183–2700 m/s, with location classes ranging from SA to SE according to SNI 1726:2019. Areas with low Vs values exhibit higher SVI, PGA, and GSS values, indicating stronger seismic amplification and greater potential for deformation. The distribution of these parameters aligns with the orientation of the Bogor Fault, suggesting a structural influence on the local seismic response. A comprehensive analysis of f_0, A_0, SVI, PGA, GSS, and Vs identified three vulnerability zones: high vulnerability along the central-to-northeastern corridor of the Bogor Fault and low vulnerability in the western and southwestern sectors. Microzonation mapping resulted in categorizing the study area into low-, moderate-, and high-vulnerability zones. This study revealed that the level of earthquake vulnerability in Kepahiang is largely determined by geological conditions, including the presence of faults, which can guide earthquake hazard mitigation efforts and the development of risk-based spatial planning.

Introduction

The province of Bengkulu lies within an active convergence zone between the Indo-Australian and Eurasian plates, where earthquakes are generated by the offshore subduction system and the Sumatra land-based strike-slip fault [1]. One of these active structures affects the

Kepahiang Regency area across the Kabawetan District, where faults close to settlements and intensively farmed land increase the risk of local earthquakes.

According to seismic data, the Musi segment has proven to be a significant source of seismic activity, with moderate-magnitude events recorded in 1979 (Mw 6.0) and 1997 (Mw 5.0) [2]. It is known that the Bogor Fault runs through an area with settlements and intensive agricultural activity; therefore, understanding the local seismic response in the vicinity of the fault corridor is essential for assessing potential ground amplification and seismic hazard vulnerability.

Records of earthquake distribution from 2009 to 2022 indicate a high level of seismic activity in this study area. These seismic zones are clustered along the path of a regional tectonic structure that is part of the Sumatra Fault System, specifically the Musi Segment, which passes through the Kepahiang Regency administrative region [1], [2]. These conditions suggest that the study area is still under the influence of active tectonic dynamics. Considering the arguments presented above, A detailed assessment of the local characteristics of seismic response and an evaluation of the varying potential for earthquake vulnerability along the Bogor Fault are considered of utmost urgency and require immediate implementation. Figure 1 shows that the earthquake epicenters are concentrated along a regional tectonic structure associated with the Musi Segment of the Sumatra Fault System. This distribution also shows that seismic activity in the study area is influenced by the Sumatra Fault System and the marine subduction zone. However, this study focuses on the Bogor Fault, as it runs through the study area and is considered to have the strongest influence on local conditions

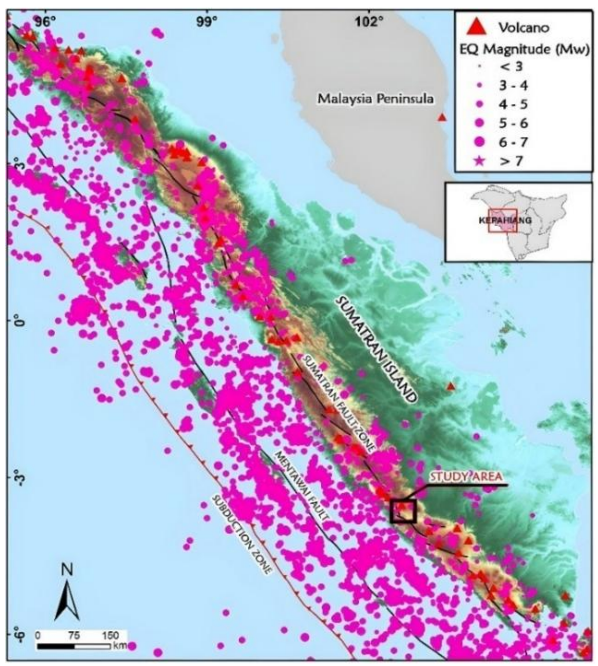

Figure 1. Map of Earthquake Activity with Magnitudes >2 from 2009 to 2022 (BMKG) Using Reference Data [1]. Adapted from [3].

Surface conditions and soil characteristics significantly impact seismic response at the local scale [4]. To determine the dominant soil frequency, seismic wave amplification, and soil sensitivity indices, the microzonation method is commonly used, employing microseismic analysis with the horizontal-to-vertical spectral ratio (HVSR) technique [5]. representing the dynamic properties of the ground and potential deformations caused by an earthquake include the dominant frequency (f_0), amplification factor (A_0), seismic vulnerability index (SVI), shear wave velocity (Vs), peak ground acceleration (PGA), and ground shear strain (GSS) [5].

Based on previous geophysical studies conducted in the Kepahiang region, it was found that the Bogor Fault is associated with a zone of low resistivity [6]. According to the results of magnetotelluric surveys, this zone is characterized by a weak structure [6]. Furthermore, microseismic studies conducted in the same area by [4]. revealed significant differences in the dominant ground frequency and amplification factor. This finding indicates that changes in subsurface conditions can lead to uneven wave amplification across different points. The results of these studies reveal the complex nature of the subsurface conditions in the Kepahiang region and indicate spatial variation in the local seismic response [7].

Many studies conducted in Indonesia have used the HVSR method to assess regional seismic response and seismic vulnerability. In their study, Hadi et al [3] performed seismic microzonation in Kepahiang Regency using parameters such as dominant frequency, amplification, and the seismic vulnerability index. Siburian et al. [7] investigated the impact of site-specific seismic microzonation in Rejang Lebong using ambient vibration measurement techniques, while Ardiansyah et al [8]. Conducted seismic sensitivity mapping in Wonosobo based on HVSR data. These studies proved useful for identifying differences in subsurface conditions and zones that may be vulnerable to greater ground motion during an earthquake. However, most of these studies focus on the distribution of seismic parameters within administrative regions, rather than examining their relationship to specific active fault structures.

Nevertheless, most previous studies have focused primarily on the distribution of seismic parameters at the administrative scale and have not specifically analyzed how the structure of active faults influences seismic response at the local scale. In the Kepahiang region, various geophysical studies have confirmed the existence of the Bogor fault along with its subsurface characteristics through microseismic and magnetotelluric surveys [4],[6]. Although this fault has been identified, its relationship to the spatial distribution of seismic response parameters, such as the dominant frequency (f_0), amplification factor (A_0), seismic vulnerability index (SVI), peak ground acceleration (PGA), ground shear strain (GSS), and shear wave velocity (Vs) has not yet been thoroughly investigated. As a result, the extent to which the Bogor Fault influences seismic sensitivity patterns in this region remains unclear. Previous studies have also evaluated individual parameters such as SVI, PGA, and Vs, but these parameters are typically interpreted separately rather than integrated into a fracture-controlled microzonation framework. Furthermore, no studies have yet been conducted linking local seismic response parameters (f_0 and A_0) with technical parameters such as SVI, PGA, GSS, and Vs to map seismic vulnerability zones along the Bogor Fault corridor. These limitations underscore the need for an integrated approach that combines fault geometry with various seismic response parameters.

This study was conducted along the Bogor fault to examine the actual distribution of seismic responses in the area and to assess the seismic hazard. The novelty of this study is the integration of measurements derived from HVSR (f_0 and A_0), the Seismic Vulnerability Index (SVI), and the Peak Ground Acceleration (PGA), Ground shaking intensity (GSS), and ground shaking velocity (Vs) to assess the potential for shaking-induced damage along a recurring fault. Unlike previous studies, which have focused primarily on administrative-scale microzoning, this study assesses earthquake vulnerability along the Bogor Fault by integrating f_0, A_0, SVI, PGA, GSS, and Vs into a fault-based framework.

Regional Geology

The Kepahiang Regency area is part of a Quaternary volcanic rock complex and lies within the active volcanic zone of the Bukit Barisan Mountains. Changes in the mechanical properties of the rocks and in the thickness of surface sediments are believed to influence the region's local seismic response, which is directly related to the dynamic structure and geological characteristics of the area [9]. The dominant lithological formations in the study area include alluvial deposits, pyroclastic deposits, pyroclastic flows of various ages, and andesitic–basaltic lava rocks. The thickness and physical properties of the sediments vary both laterally and vertically due to changes in rock types and deposition patterns that are generally non-uniform. A fault system that remains active to this day cuts across the study area, extending from northwest to southeast and from north to south. Local segmentation and the formation of deformation zones with fractures, brecciation, and severe weathering are characteristics of this system [10]. (Figure 2) Weak subsurface zones with a high seismic impedance contrast are produced by deformation zones that develop parallel to fault lines. Volcanic activity and fault structures regulate the formation of shallow basins and the buildup of loose sediments of different thicknesses. Seismic wave amplification may be higher in regions with thicker sediments and lower stiffness. As a result, four key factors influencing the dynamic behavior of the ground include lithological heterogeneity, fault segmentation, weak areas adjacent to faults, and variations in sediment thickness. Seismic microzonation is a spatial assessment technique that uses subsurface, geotechnical, and geological features to separate a region into zones with different seismic response levels. This technique aims to identify variations in ground-motion amplification and site-specific dynamic behavior, particularly in structurally controlled areas. These factors underlie the analysis of site response and regional seismic microzonation.

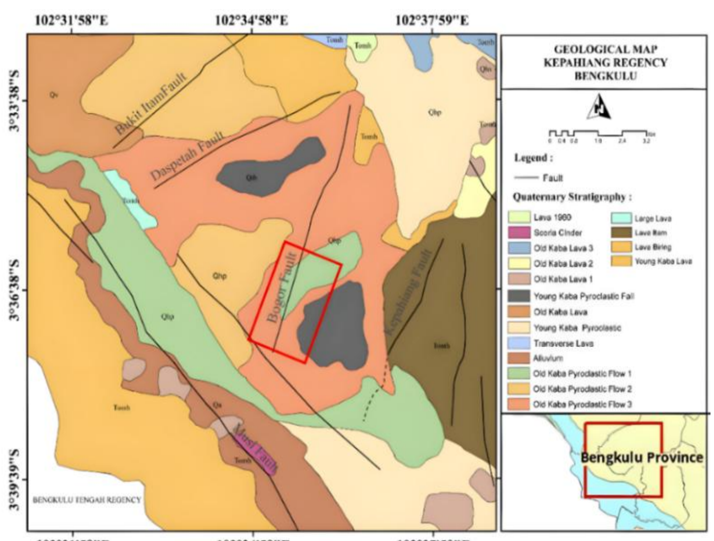

Figure 2. Geological Map of Kepahiang Regency, Bengkulu Province [11], Based on References [11], [12] and [13].

Experimental Method

This study was conducted in an active tectonic zone, specifically in the Kepahiang Regency of Bengkulu Province, which is influenced by the regional fault structures of the Sumatra Fault System. The geological conditions of this area result in high sensitivity to earthquakes, since variations in the characteristics of rocks and sedimentary materials in near-surface layers have the potential to influence ground behavior during seismic activity [14]. Based on these conditions, this study examines the characteristics of the dynamic ground response and the spatial distribution of seismic vulnerability using a quantitative geophysical approach combined with microtremor techniques. Microtremor data were collected using a portable Gemini-2 SN-1405 seismometer, which recorded ambient vibrations for approximately 45 minutes at each measurement point [15]. The Gemini-2 SN-1405 portable seismometer has high sensitivity, enabling the recording of low-amplitude environmental vibrations. This device can record low-amplitude environmental microseismic signals, making it suitable for reliable HVSR analysis and site response characterization [15]. These specifications make this device an ideal choice for microseismic research. Furthermore, this instrument can detect very low-amplitude ground vibrations resulting from both natural and anthropogenic activities, strongly supporting the application of HVSR-based microseismic analysis methodologies. During field data collection, the device is connected to a real-time monitoring system to maintain data quality and ensure signal stability throughout the acquisition. This instrumentation records ground motion simultaneously in three principal components: vertical (Z), north–south (N–S), and east–west (E–W), which are essential parameters for HVSR analysis and site response characterization.

Figure 3. Documentation of Field Activities for Micro-Vibration Data Acquisition Using the Gemini-2 SN-1405 Instrument

Figure 3 documents the data collection process at the micro-vibration survey site. The Gemini-2 SN-1405 portable seismometer was placed directly on the ground surface and connected to a real-time monitoring system designed to ensure signal stability throughout the measurement period. The location was chosen to minimize the impact of external factors and to ensure the quality of the data collected on environmental vibrations. During field data collection, the researchers followed standard procedures for measuring environmental vibrations to reduce noise levels around the site and improve data quality. The selection of areas for data collection was based on flat, open terrain with minimal human activity. There are 40 measurement stations distributed across the study area at intervals of 200 to 300 meters, intended to reflect the diversity of geological conditions and areas adjacent to the Bogor fault.

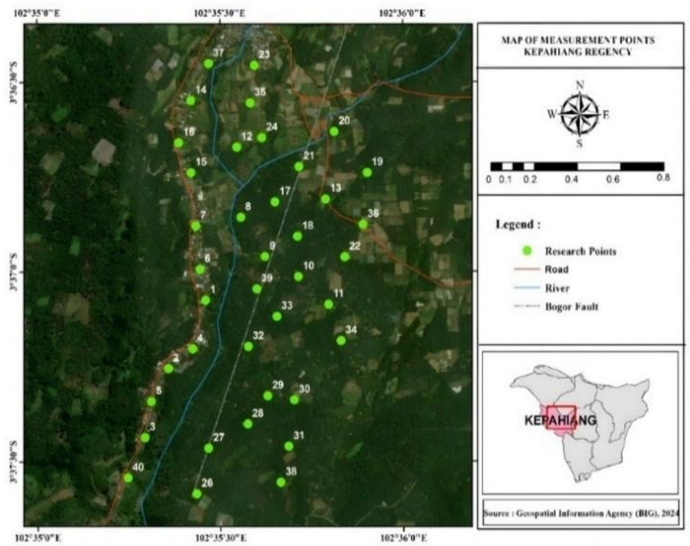

Figure 4. Spatial Distribution of Microseismic Measurement Points in the Study Area

Figure 4 shows the spatial distribution model of the microseismic measurement points used in this study. These observation points were selected based on the diversity of geological conditions and their relative distance from the Bogor fault. The distribution was designed to identify spatial variations in site-specific characteristics and seismic response across the entire study area.

The analysis of microtremor data was performed using the TerraWareHV application. According to the Dispersed Field Assumption (DFA) theory, seismic energy is distributed uniformly throughout the subsurface environment [16]. The natural frequency of the ground (f_0) and the maximum amplification factor (A_0) were obtained from the Horizontal-to-Vertical Spectral Ratio (HVSR) curve. The depth of the surface layer and the impedance contrast between the bedrock and the sedimentary material determine the local resonance characteristics [17]. Ground motion is recorded in three orthogonal components: north–south (N–S), east–west (E–W), and vertical (Z), as shown in Figure 5. Figure 5 illustrates an example of a microseismic signal recorded in these three components. The recorded traces were then processed using the HVSR technique to identify the dominant frequency (f_0) and the amplification factor (A_0) for the subsurface layers

Figure 6 shows the HVSR curves representing data from several measurement stations. The highest frequency on each curve indicates the dominant frequency (f_0), while the greatest amplitude corresponds to the amplification factor (A_0). Changes in peak position and amplitude among stations indicate differences in subsurface conditions and impedance contrasts throughout the study area. These parameters are then used to calculate SVI, PGA, and GSS values.

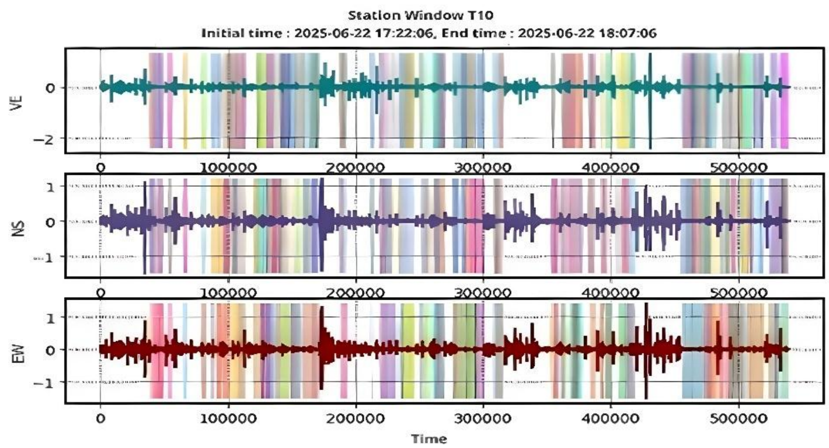

Figure 5. Documentation of Ground Vibrations in the N–S, E–W, and Z Components

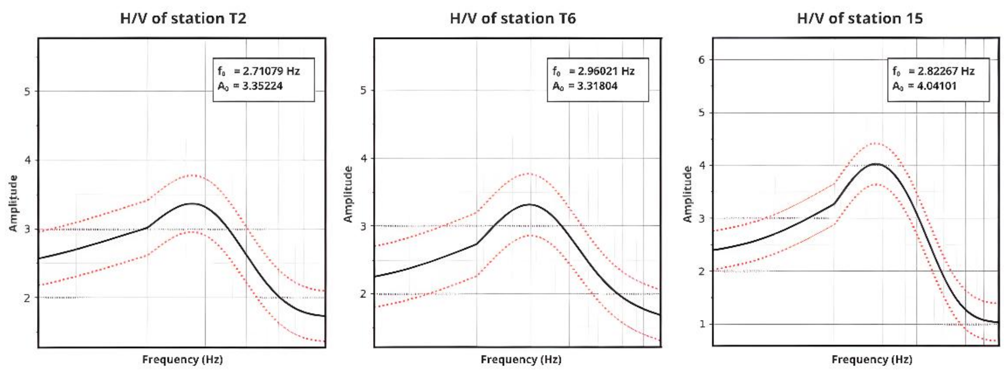

Figure 6. Representation of the H/V Spectrum Curve at Various Study Points

The conceptual framework for integrating parameters in this study is based on the cause-and-effect relationship between the ground's seismic response, generated by local resonance, and shallow deformation. HVSR parameters, which reveal resonance resulting from impedance contrasts in subsurface materials [18], are used to generate SVI (Seismic Vulnerability Index) values, a metric that indicates amplification potential. The peak ground acceleration (PGA) reflects the intensity of seismic loading, while ground shear displacement (GSS) describes the ground's behavior during deformation. Shear wave velocity (Vs) profiles [19]. Demonstrate how subsurface characteristics control the propagation and strengthening processes of waves. Therefore, the seismic vulnerability zoning in this study reflects the interaction among resonance, amplification, seismic loading, and soil deformation response, rather than solely the spatial overlap of parameters. Equation (1) [20] was 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 [18].

The primary indicator of the highest surface ground vibration intensity is peak ground acceleration (PGA) [21]. The Kanai empirical equation was used in this study to calculate PGA values. The dominant ground period, hypocenter distance, and earthquake magnitude are all integrated in this formula. This equation was selected because it explicitly accounts for the impact of site conditions on seismic response by using the dominant soil period determined by microtremor analysis. Therefore, this formula can be used to assess the impact of local sites on environments with shallow sediment. Microzonation seismic studies based on microtremors in Asia have extensively used Kanai's formulation. To empirically determine the relationships among ground vibration intensity, soil properties, and earthquake source parameters, [22] first used this approach, which was later improved by [23]. In Equation (2), T_0 represents the dominant ground period obtained from HVSR analysis, M is the earthquake magnitude, and R is the hypocentral distance. These parameters were used to estimate peak ground acceleration, accounting for both local site conditions and earthquake source characteristics. Equation (2) can be used to calculate the PGA value:

$$a_g = \frac{5}{\sqrt{T0}} 10^{0,61M - \left(1,66 + \frac{3,6}{R}\right) \log R + 0,167 - \frac{1,83}{R}} \quad (2)$$

The PGA value is first converted from gallons to g to aid in technical interpretation and comparison with structural resistance levels.

Maximum acceleration intensity and local amplification parameters are combined to calculate shear strain (GSS) [24]. Because strain has a stronger correlation with the extent of soil damage than acceleration alone, these parameters were chosen. Equation (3) can be used to obtain GSS values.

$$\gamma = \left(\frac{{A_0}^2}{f_0}\right)\left(\frac{1}{\pi^2 V_b}\right) a_{max} \quad (3)$$

where A_0 is the amplification factor, f_0 is the dominant frequency, V_b is the bedrock shear-wave velocity, and amax is the peak ground acceleration. These parameters collectively represent the amplification characteristics and deformation potential of the near-surface materials. Particularly in soft soils, high GSS values suggest possible nonlinear soil response, including local shear failure, permanent deformation, and stiffness reduction [25].

The HVSR curve was then verified using Simulated Annealing inversion within the DFA framework to obtain the shear wave velocity (Vs) profile and layer thickness, which were used to classify locations in accordance with SNI 1726:2019 (Table 1). The interpretation of the inversion model has inherent limitations, including assumptions of one-dimensional layering and a decrease in resolution with depth, so the results are considered the most likely physical representation, not a unique geological solution. The Vs values obtained by the researchers were then grouped according to the site categorization criteria outlined in SNI 1726:2019, as shown in Table 1.

Table 1. Site Categories Based on Vs Values in Accordance with SNI 1726.

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

According to SNI 1726:2019, site classification (SA–SE) is determined based on the shear wave velocity (Vs), which indicates the stiffness of near-surface materials and affects the propagation of seismic waves. Shear wave velocity (Vs) is widely regarded as the primary parameter for characterizing a site, as it reflects the material's stiffness near the surface and influences the propagation of seismic waves [26]. Changes in the Vs value reflect variations in impedance contrast between sedimentary layers and the bedrock, which determine the local near-surface resonance characteristics. This concept is consistent with the HVSR theory, which states that impedance contrast controls both the resonance frequency and the amplification of seismic waves [18]. In this study, seismic susceptibility is understood through a physics-based framework that links subsurface characteristics with seismic response mechanisms. Changes in impedance contrast, resulting from variations in Vs values, control the dominant frequency (f_0), an indicator of resonance, which, in turn, influences the amplification factor (A_0). These parameters then determine the value of the Seismic Vulnerability Index (SVI), while the Peak Ground Acceleration (PGA) and Ground Surface Shifting (GSS) reflect the intensity of the ground motion and the resulting deformational response.

The general SA–SE classification is used to describe the spatial distribution of subsurface stiffness, rather than focusing exclusively on specific soil categories. Lower Vs values generally correlate with stronger amplification (higher A_0), higher SVI values, and greater deformation potential, especially in sedimentary areas subjected to structural deformation along the Bogor Fault, which is the primary factor determining subsurface heterogeneity and seismic response. For spatial microzoning purposes, this analysis combines the parameters f_0, A_0, SVI, PGA, GSS, and Vs to describe the integrated interaction between subsurface conditions and seismic response. Softer materials (low Vs values) consistently show a correlation with lower f_0 values but higher A_0, SVI, PGA, and GSS values, whereas stiffer materials exhibit a more consistent response. This integrated framework enables earthquake vulnerability zoning to represent the subsurface behavior governed by physical principles under seismic loading, rather than simply representing the spatial distribution of parameters [27]. A similar approach has been used in previous HVSR-based microzonation studies to assess local seismic response and vulnerability to earthquakes [3], [20].

Result and Discussion

The findings of this study reveal that the local seismic behavior around the Bogor fault is not randomly distributed but rather exhibits a distinct spatial pattern shaped by the fault's geometry and segmentation. The areas located along the fault line are characterized by relatively high amplification factors (A_0 = 2.15–9.15), seismic vulnerability indices (SVI = 0.91–35. 52), and ground shear stress values (GSS = 1.01×10^{-5}–1.97×10^{-4}), accompanied by lower shear wave velocity (Vs) values and a predominance of SD–SE location categories. These conditions indicate a mechanically weaker subsurface material with greater potential for earthquake wave amplification. Variations in the seismic response, influenced by similar fault activity, have also been reported in studies [3],[4], and [7], which show that structural heterogeneity, lithological variations, and fault-related deformation have a significant impact on the spatial distribution of seismic parameters. The consistent correspondence between high-vulnerability zones and the orientation of the Bogor fault indicates that local geological conditions, including sediment thickness, material heterogeneity, and tectonic deformation, contribute more significantly to earthquake vulnerability than regional earthquake sources. Therefore, the observed distribution pattern reinforces the idea that the geometric configuration and segmentation of the Bogor fault are crucial in determining the degree of earthquake vulnerability in the study area. These findings show that the Bogor Fault not only functions as a tectonic structure but also plays an important role in shaping the mechanical properties of the upper subsurface layers. As a result, the site's response is more influenced by local geological conditions than by the characteristics of regional earthquake sources.

Based on the HVSR analysis, the natural frequency (f0) values range from 1.64 to 17.97 Hz. Within the observed frequency range, low-frequency zones (1.64–4.90 Hz) indicate relatively thick sediment layers, while high-frequency zones (≥8.17 Hz) indicate shallower bedrock conditions. The following approach [28]. can be applied to theoretically derive the relationship between the natural frequency and the sediment depth (H):

$$f_0 \approx \frac{V_s}{4H} \tag{4}$$

The lowest natural frequencies (1.64–4.90 Hz) were detected primarily in the central and southern segments of the study area, where Vs inversion data indicate thicker sedimentary deposits. In contrast, higher natural frequencies (≥8.17 Hz) were observed in areas with thinner sedimentary layers. This spatial correspondence strengthens the theoretical inverse relationship between f_0 and sediment depth, as explained by the fourth-wave length resonance model [29], [30], and is consistent with the results of previous studies by [9] and [31]. The distribution of low-f_0 forms follows a pattern parallel to the Bogor Fault and coincides with areas of thicker sediment accumulation, indicating that fault-induced deformation has influenced the formation of shallow sedimentary basins. Therefore, changes in the natural frequency are considered a reflection of changes in subsurface configuration and sediment depth associated with structural evolution processes along the Bogor Fault. These results show that changes in the resonance frequency are primarily influenced by sediment thickness and subsurface stratigraphy; consequently, areas with low f_0 values are more prone to resonance during strong ground shaking

The amplification factor (A_0) in this study area ranges from 2.15 to 9.15, with the highest values concentrated along the Bogor Fault. Observations reveal that regions with lower Vs values tend to exhibit higher amplification levels, indicating a significant impedance contrast between unconsolidated sedimentary material and the underlying bedrock. The clustering of high-amplification values along the Bogor Fault line indicates that tectonic deformation associated with fault activity has altered the configuration of shallow surface structures, thereby increasing the amplification of seismic waves and the level of local ground motion. A similar relationship between amplification factors, impedance contrast, and sedimentary structures influenced by faulting has also been documented in studies [32] and [3]. These results indicate that impedance contrast plays an important role in amplifying seismic waves, with softer sediments overlying stiffer materials producing stronger ground motion in zones controlled by fractures.

The Seismic Vulnerability Index (SVI) values obtained through calculations based on the parameters f_0 and A_0 range from 0.91 to 35.52, as shown in Figure 7. The central and eastern regions exhibit high values, while most measurement points have low to moderate values, following a pattern parallel to the Bogor Fault. There is a positive spatial correlation between SVI values and PGA, with points with higher SVI values generally corresponding to higher predicted ground accelerations. This relationship arises because SVI is influenced by amplification factors and natural frequencies. Areas characterized by high amplification values and considerable sediment thickness tend to accumulate and amplify seismic energy more efficiently, making them more susceptible to pronounced seismic responses. Such observations are consistent with findings previously reported by researchers [3],[33], and [34], who concluded that the seismic vulnerability index serves as a reliable reflection of the dynamic characteristics of near-surface materials when subjected to seismic loading. The high SVI values observed along the Bogor fault indicate that subsurface conditions associated with the fault increase local seismic sensitivity by enhancing both seismic wave resonance and amplification. The seismic vulnerability index values obtained in this study were analyzed using the classification criteria developed by [34] and subsequently applied by [3], as shown in Table 2.

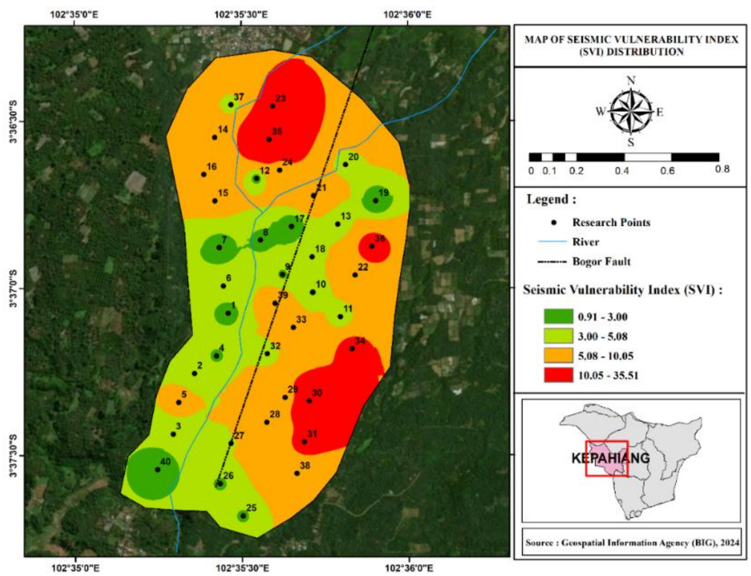

Figure 7. Mapping of SVI Value Distribution

Figure 7 shows that the highest SVI values are primarily concentrated along the Bogor fault corridor, indicating that subsurface conditions associated with this fault enhance local seismic amplification. This distribution is consistent with the HVSR concept proposed by Nakamura [18] and aligns with the findings of previous microzonation studies [3].

Table 2. Categories of the Seismic Vulnerability Index Used in This Study (Based on References [34], [3]

Vulnerability Level	SVI Value	Research Points
Low	SVI < 3	P1, P4, P7, P8, P9, P10, P12, P17, P19, P25, P26, P40
Moderate	3 ≤ SVI < 5	P2, P3, P6, P11, P13, P18, P20, P32, P37
High	5 ≤ SVI < 10	P5, P14, P15, P16, P21, P22, P24, P27, P28, P29, P33, P38, P39
Very High	SVI ≥ 10	P23, P30, P31, P34, P35, P36

The classification results show that areas with high and very high SVI values are mainly concentrated around the Bogor Fault. This distribution suggests that the geological conditions associated with this fault play an important role in determining local seismic vulnerability. Based on the classification results, 12 monitoring points fell into the low weakness category, 9 into the medium category, 14 into the high category, and the remaining 5 into the very high category. The high and very high weakness categories were mainly concentrated along the Bogor fault line, indicating a significant influence of fault-related geological conditions on the local seismic response. A similar spatial correlation between the fault corridor and high-vulnerability zones has also been documented in studies [3], [4], and [7].

PGA (Peak Ground Acceleration) values calculated using Kanai's empirical method range from 0.12 to 0.41 g (Figure 8). The distribution of high PGA values extends toward the northeastern sector, parallel to the orientation of the Bogor fault, indicating that subsurface conditions influenced by fault activity contribute to variations in the spatial distribution of ground-motion intensity. Areas characterized by lower Vs values and stronger impedance contrast generally experience greater amplification of seismic energy, resulting in higher predicted PGA values. The spatial correlation between high PGA values, High SVI, and low Vs values indicates that subsurface conditions at specific locations significantly influence the ground response to earthquakes. Similar correlations have also been documented in studies [3], [4] and [35]. There is a direct link between the intensity of surface vibrations and the potential for local amplification, as evidenced by the spatial correlation between areas with high SVI values and the largest predicted PGA values [36]. Surface acceleration is generally higher in areas where impedance variations lead to effective resonance. This model reinforces the view that vulnerability indices constructed with HVSR parameters accurately describe dynamic responses influenced by structural control of active faults, rather than being merely theoretical figures. These findings indicate that the predicted ground acceleration is influenced not only by the earthquake's magnitude, but also by local site conditions, particularly the geological characteristics of near-surface materials. The PGA values obtained from the Kanai equation were analyzed using the classification criteria developed by [13] and then applied to the Kepahiang seismic microzonation study by [3] The classification categories used in this study are shown in Table 3.

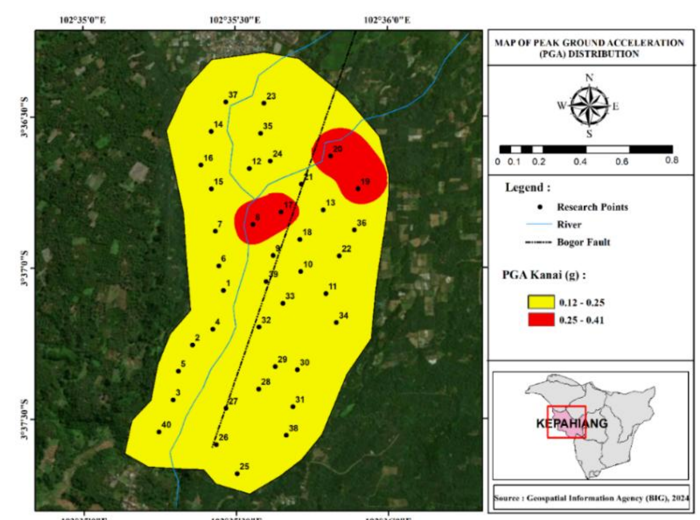

Figure 8. Kanai PGA value distribution map (g)

As shown in Figure 8, relatively high PGA values are concentrated in the northeastern part of the study area, in line with the direction of the Bogor Fault. This distribution indicates that subsurface conditions associated with the fault contribute to increased ground acceleration, which is consistent with previous studies [3], [35].

Table 3. The PGA classification criteria used in this study were adopted from previous studies [13],[3]

Vulnerability Level	PGA (g) Value	Research Points
Low	PGA < 0,26	P1, P2, P3, P4, P5, P6, P7, P9, P10, P11, P12, P13, P14, P15, P16, P18, P21, P22, P23, P24, P25, P26, P27, P28, P29, P30, P31, P32, P33, P34, P35, P36, P37, P38, P39, P40
Moderate	0,26 ≤ PGA < 0,48	P8, P17, P19, P20
High	0,48 ≤ PGA ≥ 0,79	-
Very High	PGA ≥ 0,79	-

Most monitoring stations fall into the low PGA category, while only a few fall into the moderate category. This pattern suggests that local site conditions play a greater role in determining spatial variations in PGA than the regional seismic loading alone. The soil shear stress (GSS) values range from 1.01×10^{-5} to 1.97×10^{-4} (Figure 9). Moderate to high GSS zones are most common in the central to eastern regions. Geographically, low-VS zones and high-SVI and PGA zones are near one another. When exposed to seismic energy, soils with lower stiffness typically undergo greater shear deformation. This link is clearly evident in the relationship between areas with low Vs values and relatively higher GSS values. The study's results show that a decrease in shear wave velocity (Vs) correlates with an increase in GSS values. Ground materials with low Vs values are more susceptible to deformation under seismic loading due to their lower dynamic shear modulus. A similar relationship between low Vs values, increased shear deformation, and greater potential for deformation has also been documented in studies [3] and [20]. This relationship indicates that low-ductility materials are more prone to deformation under seismic loading. The spatial distribution pattern, which is parallel to the orientation of the Bogor fault, indicates that the weakening of shallow mechanical properties is influenced by structural deformation processes occurring in deeper layers. Figure 10a further supports this analysis by showing that the maximum deformation zone occurs at depths of about 20–50 m, a region where material with low Vs values transitions into a more compact subsurface layer. In this depth range, changes in mechanical properties lead to deformation concentration and amplify seismic waves. These conditions indicate that the observed distribution of the GSS is influenced not only by the ground characteristics in the upper layers but also by structural conditions at depth related to the Bogor fault. These findings suggest that areas with higher GSS values are more prone to permanent ground deformation during strong earthquakes because of their lower mechanical stiffness. Table 4 presents the Ground Shear Spectrum (GSS) classification criteria adopted from previous studies [13], [3] which are used as a reference for interpreting the potential for ground deformation in the study area.

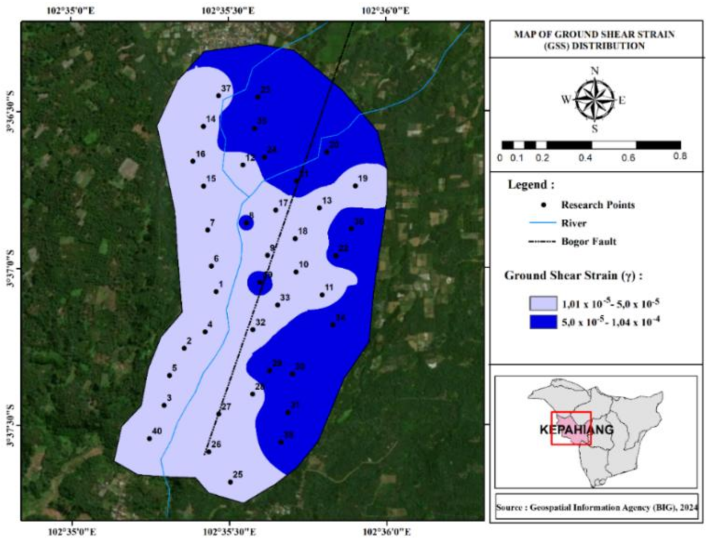

Figure 9. Mapping of Ground Shear Strain Distribution (γ)

Figure 9 shows that the highest GSS values are largely concentrated along the Bogor Fault, where relatively soft subsurface material is associated with greater deformation potential. This pattern is consistent with previous findings reported by [3] and [20].

Table 4. Classification of Soil Shear Strain (GSS) Criteria Applied in This Study, Based on References from Previous Investigations [13], [3]

Vulnerability Level	GSS (γ) Value	Research Points
Low	GSS < 10^{-5}	P1, P2, P3, P4, P5, P6, P7, P9, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19, P25, P26, P27, P28, P29, P32, P33, P37, P40
Moderate	$10^{-5} \leq$ GSS < 10^{-4}	P8, P20, P21, P22, P23, P24, P30, P31, P34, P35, P36, P38, P39
High	$10^{-4} \leq$ GSS < 10^{-3}	-
Very High	GSS ≥ 10^{-3}	-

In accordance with SNI 1726:2019, the HVSR inversion data show Vs values ranging from approximately 183 to 2700 m/s, which fall within the SE to SA soil categories. The areas with low Vs values form linear, parallel patterns along the Bogor Fault and are generally concentrated in the upper subsurface. This distribution corresponds to the spatial distribution of SVI, PGA, and GSS, indicating that the weakening of mechanical properties in the shallow upper layers is significantly influenced by structural control at depth. Although the penetration depth of the HVSR study remains limited to about 160 m, the spatial correlation of various seismic parameters indicates that the Bogor Fault influences the formation of the upper subsurface material. As a result, areas near the fault typically exhibit lower Vs values with greater potential for amplification. Similar observations were also found in studies [4] and [7], which identified areas with low Vs characteristics associated with deformation due to fault activity and accompanied by increased seismic strengthening. The spatial distribution shown in Figure Vs indicates that deformation associated with cracks has significantly affected the mechanical properties of the shallow subsurface layers.

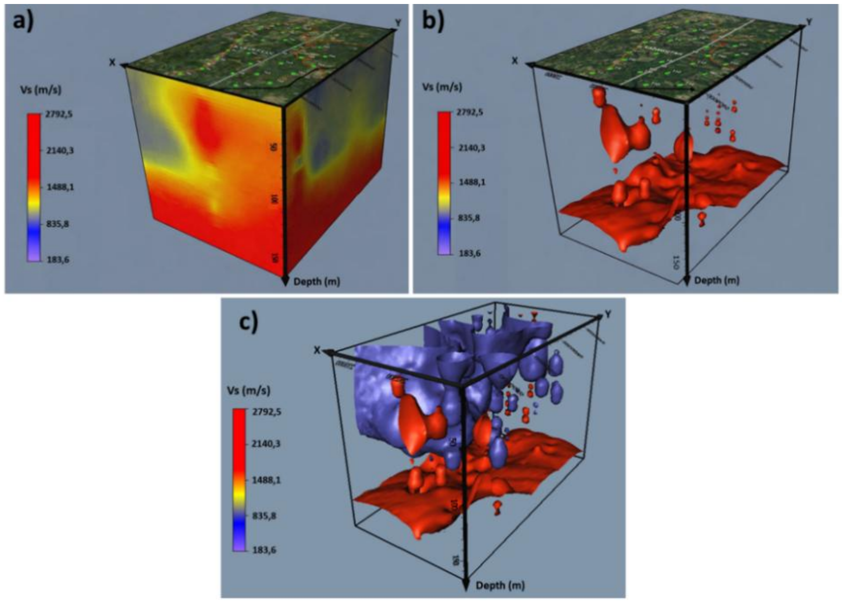

Figure 10. shows (a) a three-dimensional model of the shear wave velocity (Vs) distribution with depth within the study area, (b) a three-dimensional view of the shear wave velocity (Vs) isosurface, where higher values indicate areas of dense subsurface material, (c) a three-dimensional model of the transition from low shear wave velocity (Vs) to higher values, illustrating the boundary between subsurface material that tends to be softer and denser material.

Figure 10 shows that low V_s values are concentrated along the Bogor Fault, while higher V_s values are associated with denser subsurface material. This distribution shows that the fault-influenced geological conditions have a strong impact on the local seismic response. The 3D model shows that low-velocity zones are concentrated in the central and northeastern segments of the study area and are distributed along the Bogor Fault. These areas are associated with unconsolidated sedimentary material and material with weak mechanical properties; in contrast, the high velocity (Vs) isosurfaces represent denser, stronger subsurface formations. The transition between low and high-velocity materials becomes increasingly apparent at depths of around 20–50 m, corresponding to areas with increasing GSS values. This correlation indicates that contrasts in the mechanical properties of the subsurface play an important role in determining local reinforcement and deformation patterns. These results further strengthen the idea that the Bogor Fault not only influences the subsurface structural configuration but also the distribution of materials that govern seismic wave propagation and deformation.

An integrated analysis of the parameters f_0, A_0, SVI, PGA, GSS, and Vs identified three earthquake vulnerability zones within the study area. The low vulnerability zone is located mainly in the western and southwestern segments, characterized by relatively high Vs values, low reinforcement factors, and low deformation potential. The moderate vulnerability zone occupies a transition area along the fault line. The high-vulnerability zone is concentrated in the central to northeastern segments, which correspond to the direction of the Bogor fault, characterized by low Vs values, high amplification factors, increasing SVI values, the largest predicted PGA values, and higher GSS values. This zonation indicates that earthquake vulnerability is strongly influenced by geological structures associated with fault activity and related subsurface conditions.

Table 5. Summary of Seismic Parameters from the Study

Parameter	Minimum	Maximum
f_0 (Hz)	1.64	17.97
A_0	2.15	9.15
SVI	0.91	35.52
PGA (g)	0.12	0.41
GSS	1.01 x 10^{-5}	1.97 x 10^{-4}
Vs (m/s)	183	2700

Table 5 summarizes the seismic variables obtained from HVSR processing and inversion. The range of values of the identified variables indicates considerable spatial variability in subsurface characteristics and seismic behavior. The model shows that higher SVI, PGA, and GSS values tend to correlate with lower Vs values, indicating potential for amplified shaking and enhanced deformation in areas under fracture control.

The spatial correlation among the parameters f_0, A_0, SVI, PGA, GSS, and Vs underscores the importance of combining different seismic indicators to achieve reliable microzoning. Areas characterized by low Vs values, high amplification, elevated SVI, and consistently high GSS correlate with high-vulnerability zones. In general, a systematic relationship was found between f_0, A_0, SVI, PGA, GSS, and Vs, demonstrating that seismic vulnerability is determined by sediment depth, impedance contrast, and variations in shear wave velocity, as documented in previous studies [3],[20] and [31]. Areas characterized by thicker sediments, lower Vs values, and stronger impedance contrast tend to exhibit lower natural frequencies, higher amplification factors, higher seismic vulnerability indices, and greater ground shear displacement values. The spatial consistency of these parameters along the Bogor fault line indicates that the geological structures associated with fault activity play a key role in determining earthquake vulnerability in the study area. The close relationship between these parameters suggests that earthquake sensitivity is influenced by the combined effects of sediment thickness, impedance contrast, and changes in shear wave velocity, rather than by any single parameter. This study shows that earthquake vulnerability in the study area is primarily determined by subsurface characteristics, particularly the presence of faults, rather than by distance from the earthquake source. Consequently, variables related to local geology should be taken into account in earthquake risk assessments and in the formulation of spatial planning policies. In comparison with previous microzonation studies conducted by other researchers in Kepahiang Regency [3], which classified vulnerability zones based on administrative factors and HVSR parameters, this study integrates fracture geometry and segmentation with assessments of f0, A0, SVI, PGA, GSS, and Vs. This different methodology resulted in a microzoning map that better illustrates the structural impacts closely associated with the Bogor Fault. -It visualizes linear vulnerability patterns that most likely would not have emerged if the researchers had used a zoning methodology based on administrative boundaries.

Some methodological limitations should be considered when interpreting this study's findings. The HVSR technique assumes a one-dimensional (1D) subsurface model, which is effective for detecting vertical impedance contrasts; however, the method's ability to map lateral heterogeneity around fracture zones remains limited. Furthermore, the Vs inversion results obtained by the researchers have not been exclusively confirmed by geotechnical data from excavations or in-situ testing. PGA estimates derived from Kanai's empirical equation [37] also do not account for three-dimensional local effects. Consequently, the interpretation of the results of this study should be understood as a characterization of shallow seismic response based on surface geophysical observations and empirical models. Future studies should include data from boreholes and geotechnical investigations to increase the reliability of the final interpretations. Based on the microzoning study conducted, the central to northeastern area of Kepahiang, which passes through the Bogor Fault, should be prioritized as the primary focus in preparing Risk-Based Spatial Planning (RTRW). Areas categorized by researchers as SD–SE type sites with high SVI, PGA, and GSS values are recommended to require the application of more stringent seismic design standards. Further investigations, such as MASW and borehole logging, are recommended to improve subsurface characterization and refine microzonation boundaries for earthquake mitigation.

Conclusion

This study shows that the local seismic behavior and earthquake vulnerability levels in the Kepahiang Regency are closely linked to the geometric configuration and fault segmentation of the Bogor Fault. Models of natural frequency distribution (f_0), amplification factor (A_0), seismic vulnerability index (SVI), peak ground acceleration (PGA), Ground shear deformation (GSS), and shear wave velocity (Vs) indicate that variations in sediment layer thickness, changes in impedance, and mechanical properties associated with the presence of faults are the primary determinants of near-surface seismic response. Based on the comprehensive assessment, three categories of seismic vulnerability zones were successfully identified: a low-vulnerability zone in the western and southwestern parts, a medium-vulnerability zone in the transitional area, and a high-vulnerability zone extending along the central to northeastern sections of the Bogor Fault. This high-vulnerability zone exhibits consistent characteristics, including low Vs values, high amplification factors, and high SVI and PGA values, as well as increased ground shear deformation. These findings highlight that a microzoning approach that accounts for fault structural control provides a framework that more accurately reflects actual conditions in earthquake vulnerability mapping than methods based on administrative boundaries. This methodology provides additional insights into the spatial characteristics of seismic response and has the potential to aid in the development of risk-based spatial planning and in implementing more effective disaster reduction strategies in the Kepahiang Regency. It should be emphasized that the researchers' findings to date are still based on surface geophysical data and empirical models. Considering this situation, the researchers suggest the need for more in-depth verification using borehole data and in-situ geotechnical test results to strengthen the reliability of interpretations of subsurface conditions and improve the quality of future seismic microzoning studies.

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