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Effect of Azimuthal Variability in Estimation of HVSR Parameters and Ground Shear Strain at Kota Baru, South Lampung, Indonesia

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Abstract: Kota Baru, a potential capital of Lampung Province in South Lampung, Indonesia, faces significant earthquake risks due to the Great Sumatran Fault and the Sumatra Megathrust. Geologically, the area is part of the Plio-Pleistocene Lampung Formation, predominantly composed of rhyolite-dacite tuff and volcanoclastic tuff, which can amplify seismic shaking. This study investigates azimuthal variations by applying rotation vectors to seismic recordings to generate Horizontal-to-Vertical Spectral Ratio (HVSR) curves at 15 locations in Kota Baru, aiming to identify their underlying causes.The results show notable changes in peak amplitude (*Ao*) and dominant frequency (*fo*) across different azimuths, with Mean Absolute Deviations (MAD) ranging from 0.96 to 5.71 for *Ao* and from 0.00 to 1.57 for *fo*. Maximum HVSR values were predominantly observed at azimuths below 30° across most regions. These variations are likely related to differences in soft layer thickness and/or the presence of a suspected fault near the study area, both of which could influence seismic wave propagation. A statistically derived model of an 8.9-magnitude megathrust earthquake revealed no significant differences in Ground Shear Strain values, with the results remaining within the same Modified Mercalli Intensity (MMI) scale. Therefore, despite azimuthal variability, the assumption of isotropic ambient noise in Kota Baru remains valid. This study can contribute to earthquake mitigation planning in Kota Baru by providing a better understanding of how local geological characteristics influence seismic wave propagation.

Keywords: *amplifications, dominant frequency, fault, megathrust earthquake, soft layer*

Introduction

Kota Baru is situated in South Lampung Regency, Lampung Province, at the southern tip of Sumatra Island, bordering the Sunda Strait. This area is being prepared as the new capital of Lampung Province, replacing Bandar Lampung City, with the aim of decentralizing urban activities and promoting regional development [1]. However, the relocation does not necessarily ensure a lower earthquake hazard, as the region remains seismically vulnerable. Kota Baru is located near the Semangko Fault segment, a part of the Great Sumatran Fault system, which generated a 6.9–7.2 Mw earthquake in Liwa, Lampung, in 1994. Additionally, the region faces the potential threat of megathrust earthquakes along the southwestern coast of Sumatra and the Sunda Strait, which could reach magnitudes of up to 8.9 Mw [2].

The geological characteristics of Kota Baru further influence its seismic susceptibility. The area is underlain by the Plio-Pleistocene Lampung Formation (QTl) (**Figure 1**), which consists predominantly of rhyolite-dacite tuff and volcanoclastic tuff [3]. This formation is composed mainly of pumiceous tuff with poorly sorted grains, interbedded with tuffaceous sandstone. These lithological properties suggest that certain areas, particularly those with thick and soft layers, may experience seismic wave amplification, increasing the intensity of ground shaking. Moreover, the Lampung Formation unconformably overlies older rock units

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and inter-fingers with other formations, indicating potential fault interactions that could further influence seismic behavior.

Given these geological conditions, understanding site effects and seismic wave propagation in Kota Baru is crucial for assessing earthquake hazards. One widely used technique for site characterization is the Horizontal-to-Vertical Spectral Ratio (HVSR) method. HVSR provides insights into subsurface resonance frequencies and amplification effects by analyzing ambient seismic noise. By applying this method, it is possible to evaluate the variability of seismic response across different locations, helping to determine whether local geological factors contribute to directional variations in ground motion. Therefore, investigating azimuthal variations in HVSR parameters can offer a more comprehensive understanding of how subsurface conditions interact with seismic waves, ultimately aiding in seismic hazard assessment and mitigation efforts in the region [4]. Given these potential earthquake threats, several studies have been conducted as part of efforts to mitigate earthquake risks. One such method is the Horizontal-to-Vertical Spectral Ratio method, used to estimate seismic vulnerability indices [5-6], assess the thickness of soft layers that influence earthquake amplification [7], and estimate parameters such as peak ground acceleration (PGA) and ground shear strain (GSS) [8].

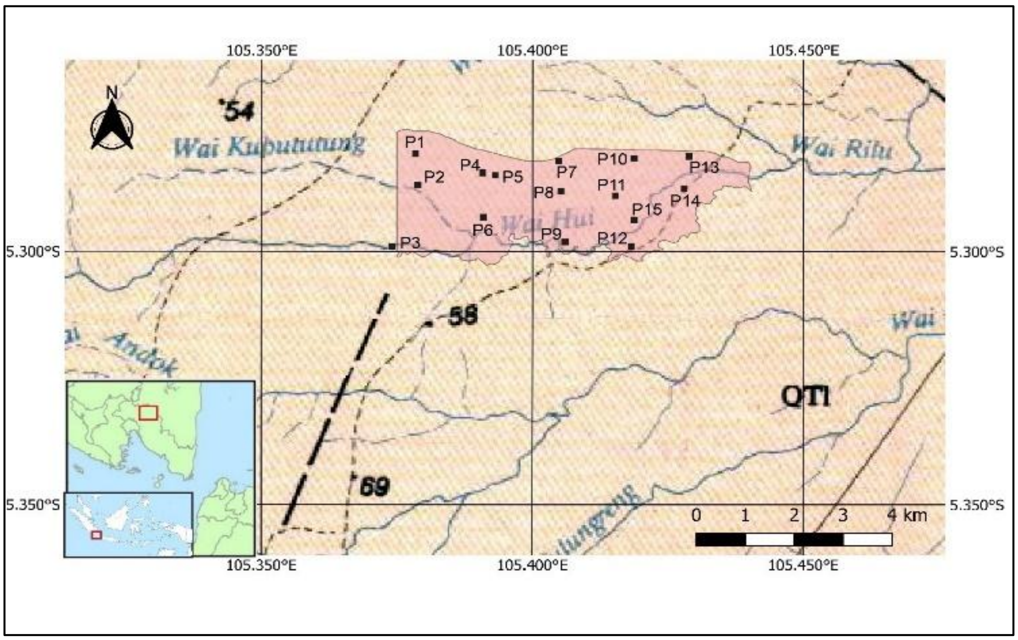

Figure 1. The administrative map of Kota Baru shows microtremor measurement points scattered throughout (solid black square). All research areas are located within the Lampung Formation (QTl), which is dominated by volcanic rocks of the tuff type. The dashed line in the southwest indicates the estimated location of a fault

Results from these studies suggest that, while Kota Baru is generally considered to have a low seismic hazard based on historical earthquake records and regional seismic activity [5, 8], the presence of thick soft layers could still amplify ground shaking during strong earthquakes[6-7].

The HVSR method, based on ambient noise measurements as known as microtremor, is a quick, practical, and non-invasive approach commonly used to estimate a site's dominant frequency (*fo*) and its peak amplitude or amplification factor (*Ao*) [9]. This method, originally introduced by Nogoshi & Igarashi [10], gained widespread recognition following Nakamura's work [11].

The HVSR method relies on two key assumptions: (i) that the ambient noise wavefield is isotropic in all directions, and (ii) that the site is one-dimensional, meaning the surface is flat and the subsurface consists of horizontally layered, homogeneous strata extending over large areas [9]. However, recent studies have challenged the isotropic noise assumption by rotating the measured horizontal components through various azimuths, revealing significant variability in some regions [12-13]. Conversely, other studies, such as those conducted at the Euroseistest site in Greece, found no significant azimuthal dependence in HVSR measurements [14]. These contrasting findings suggest that azimuthal effects may be site-specific and influenced by geological conditions.

In the case of Kota Baru, the presence of the Lampung Formation, which consists of rhyolite-dacite tuff and volcanoclastic tuff with potentially heterogeneous subsurface conditions, suggests that azimuthal variability in HVSR could be present. Additionally, the proximity of the study area to a suspected fault raises the possibility of directional effects in seismic wave propagation. Despite these geological complexities, previous HVSR studies in Kota Baru did not account for azimuthal variability, assuming isotropic ambient noise and laterally homogeneous subsurface conditions. However, neglecting this variability may limit the accuracy of site response assessments, as it overlooks potential anisotropic subsurface properties, such as lateral changes in sediment composition, fault-related deformations, or dipping layers. These factors can significantly influence seismic wave behavior and, consequently, local ground motion characteristics.

To address this gap, this study aims to evaluate azimuthal variability in HVSR calculations and investigate its underlying causes. By incorporating azimuthal analysis, we assess whether the isotropic noise assumption remains valid in Kota Baru or if directional effects must be considered in seismic hazard assessments. Furthermore, we apply this analysis to ground shear strain calculations under a potential megathrust earthquake scenario southwest of Sumatra to determine the significance of azimuthal variability in such an event. The findings of this study will contribute to a more reliable site characterization, essential for earthquake hazard assessment. Improved understanding of the directional dependence of HVSR can enhance the accuracy of seismic hazard maps and inform urban planning policies, particularly in selecting appropriate locations for critical infrastructure and developing effective earthquake mitigation strategies.

Methods

Research Area and Microtremor Recordings

The research area is located between 105.374° E and 105.4289° E, and 5.28064° S to 5.29936° S. Microtremor measurements were conducted at a total of 15 points, considering the standard criteria for site spacing and the total area of Kota Baru [15], as shown in **Figure 1**. A short-period seismometer with three components—up-down (U-D), north-south (N-S), and east-west (E-W)—was used for data acquisition. Each measurement was recorded for a duration of 35 minutes.

HVSR with azimuthal variation

Before conducting the core calculations, transient signals in the 35-minute microtremor data were manually trimmed, leaving smoother data with relatively uniform amplitudes. The data were then divided into smaller segments with a window length of 30 seconds and an overlap of 15 seconds (50%). This segmentation was applied to all three components: U–D, N–S, and E–W. Each 30-second segment was transformed into the frequency domain using the Fast Fourier Transform (FFT) method and smoothed using a convolution method with 20 data points. The spectrum of the horizontal components (N–S and E–W) was then divided by the vertical component (U–D):

$$HVSR = \frac{S_H}{S_V} = \frac{\sqrt{(S_{N-S})^2 + (S_{E-W})^2}}{S_{U-D}} \qquad (1)$$

Where S_H, S_V, S_{N-S}, S_{E-W}, and S_{U-D} are the smoothed spectra of the horizontal, vertical, N–S, E–W, and U–D components, respectively. The HVSR for each segment was then averaged to obtain the HVSR value for the measurement point.

To account for azimuthal variation, the S_H component was modified. In this step, S_H is the Fast Fourier Transform's result from combining the N–S and E–W microtremor data segments [9]:

$$D_H = D_{N-S} \cos\alpha + D_{E-W} \sin\alpha \qquad (2)$$

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$$S_{H*} = FFT(D_H) \quad (3)$$

$$HVSR^* = \frac{S_{H*}}{S_V} \quad (4)$$

Where D_H, D_{N-S}, and D_{E-W} represent the microtremor data segments for the horizontal components, N–S and E–W, respectively. α is the azimuth, which in this study was varied in 10° increments. S_{H*} and $HVSR^*$ are the horizontal spectrum and HVSR values considering azimuthal variation, respectively. The calculation of *fo* and *Ao* from the HVSR curve is shown in **Figure 2**.

Mean Absolute Deviation (MAD)

To quantify how azimuthal variability affects the $HVSR^*$ values relative to the standard HVSR values, we define the Mean Absolute Deviation (MAD) parameter as:

$$MAD = \frac{1}{n}\sum_i^n |x_i^* - x| \quad (5)$$

where n is the number of azimuth ranges, x_i^* is the parameter value at a specific azimuth, and x is the parameter without considering azimuthal variation.

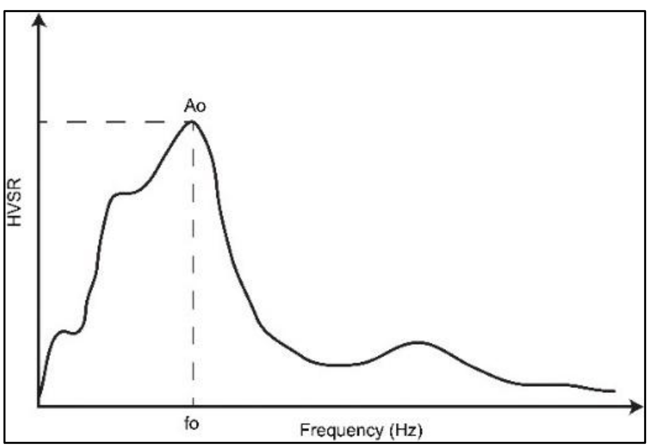

Figure 2. An illustration of the HVSR graph and the method for obtaining *Ao* and *fo*. The *Ao* parameter is derived from the highest peak of the HVSR graph, while *fo* is the frequency that corresponds to that peak

Results And Discussion

HVSR with azimuthal variation

The 3D plot of the HVSR curves at different azimuth angles (α) for each point in the study area is shown in **Figure 3**. The HVSR peak values at the same frequency change as the azimuth varies. For HVSR curves with a single dominant peak, such as at P3 (**Figure 3c**) and P9–P13 (**Figure 3i–m**), the range of HVSR value changes is generally less than 2 (dimensionless, as it's a ratio), except for P9 (**Figure 3i**), which ranges from 6.5 to 12.4. The change in HVSR peak values with azimuth does not follow a uniform pattern, as observed at P1 (**Figure 3a**), P4 (**Figure 3d**), P8 (**Figure 3h**), and P15 (**Figure 3o**). The 3D plots for these points show more than one dominant peak, with variations in the shape of the first peak differing from the second. Notably, P4 (**Figure 3d**) and P15 (**Figure 3o**) exhibit a shift in the dominant frequency from one peak to another.

To further illustrate the changes in dominant frequency in the HVSR curve with respect to azimuth, see **Figure 4**. Drastic changes in dominant frequency are also observed at P1 (**Figure 4a**) and P14 (**Figure 4n**), although the peaks at both points exhibit uniform HVSR peak variation patterns. The changes in maximum peak HVSR values with azimuth are shown in **Figure 5**. In general, there are four types of variation: increasing (P3 and P10 in **Figure 5c** and **5j**, respectively), convex (P11 and P12 in **Figure 5k** and **5l**, respectively), concave (P9, **Figure 5i**), and decreasing (the rest). Similarities in the maximum HVSR variation tend to cluster at the same location, particularly for the decreasing and convex shapes.

Mean Absolute Deviation (MAD), The magnitude of the changes in maximum peak HVSR with azimuth and dominant frequency can be assessed from the MAD values. HVSR variation with azimuth ranges from 0.96 to 5.71, while the variation in dominant frequency with azimuth ranges from 0.00 to 1.57. In general, the MAD values for maximum HVSR are less than 2.2, except for P9, which has a value of 5.7. Meanwhile, the MAD values for dominant frequency mostly remain below 0.75 Hz, with a maximum value of 1.57 Hz (see **Table 1**)

The changes in HVSR maximum peak values and dominant frequencies with variations in azimuth exhibit complex behavior. These changes are not uniform across each peak and can lead to shifts in the dominant frequency. The precise cause of azimuthal variability remains unknown and warrants further investigation [13]. Matsushima et al [12] suggested that azimuthal variations in HVSR data, amplitude, and period might be attributed to uneven subsurface topography and/or faulting. To investigate the influence of subsurface topography on the effects of azimuthal variation in Kota Baru, we can compare this study results with the results of previous studies [7]. Ipmawan et al [7] determined the thickness of soft layers by inverting HVSR curves, which indirectly reflect subsurface topography. The majority pattern of the effects of azimuthal variation is decreasing curve, P1–P8, P13–P15 (see **Figure 5a–5h**, **5m–5o**, respectively). Majority of these decreasing curve corelate with the location of thinner soft layer (32–57 m) [7]. Whereas the other patterns corelate with the location of thicker soft layer (58–102 m). These directional dependencies correlate with the geological characteristics of the Lampung Formation where the thickness of soft volcanic materials may influence seismic wave propagation and contribute to the observed azimuthal variability in HVSR measurements.

Table 1. Calculation of the Mean Absolute Deviation (MAD) for HVSR parameters at each point.

Location	HVSR parameter	MAD
P1	*Ao**	1.03
	*fo**	0.05
P2	*Ao**	1.29
	*fo**	0.05
P3	*Ao**	1.99
	*fo**	0.03
P4	*Ao**	1.16
	*fo**	1.01
P5	*Ao**	1.49
	*fo**	0.68
P6	*Ao**	1.28
	*fo**	0.04
P7	*Ao**	0.96
	*fo**	0.03
P8	*Ao**	1.35
	*fo**	0.07
P9	*Ao**	5.71
	*fo**	0.03
P10	*Ao**	2.05
	*fo**	0.06
P11	*Ao**	2.07
	*fo**	0.00
P12	*Ao**	2.08
	*fo**	0.00
P13	*Ao**	2.05
	*fo**	0.06
P14	*Ao**	1.62
	*fo**	1.57
P15	*Ao**	1.28
	*fo**	1.23

The majority pattern of the effects of azimuthal variation is decreasing curve, P1–P8, P13–P15 (see **Figure 5a–5h**, **5m–5o**, respectively), indicating that maximum HVSR values are higher at azimuths <90° and gradually or exponentially decrease. Matsushima et al [12] examined the correlation between the strike of the Obaku fault in Kyoto, Japan, and the variation in horizontal HVSR values at the angle where the difference between two horizontal components is greatest. They found that the largest difference ranged from 5–15°, while the strike of the Obaku fault was approximately 13°. To evaluate whether the presence of faults affects azimuthal variability in HVSR measurements, we investigated faults near Kota Baru. A suspected fault is located southwest of the study area (**Figure 1**), with a strike of 24°. This corresponds to an azimuth range of 0–30°, which aligns with the largest change in maximum HVSR values for most points. Therefore, the observed azimuthal variability in HVSR measurements likely corresponds with subsurface conditions and/or the presence of fault at Kota Baru.

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Table 2. Ground Shear Strain (GSS) calculations, both with and without considering azimuthal variation.

Loc	Long	Lat	*Ao*	*Ao** (α=70°)	*fo*	*fo** (α=70°)	R	PGA	GSS	GSS* (α=70°)
P1	105.3784	-5.2806	4.37	3.41	0.43	0.40	354.36	8.95×10^{3}	3.94×10^{7}	2.59×10^{7}
P2	105.3788	-5.2869	5.02	3.74	3.93	4.00	354.17	8.96×10^{3}	5.73×10^{8}	3.12×10^{8}
P3	105.3740	-5.2991	6.81	4.94	0.63	0.60	353.23	9.05×10^{3}	6.56×10^{7}	3.64×10^{7}
P4	105.3931	-5.2849	4.64	3.48	0.77	0.80	355.75	8.81×10^{3}	2.52×10^{7}	1.35×10^{7}
P5	105.3910	-5.2934	4.65	2.91	5.70	7.80	355.22	8.86×10^{3}	3.39×10^{8}	9.70×10^{9}
P6	105.3909	-5.2844	4.51	3.14	4.43	0.90	355.53	8.83×10^{3}	4.11×10^{8}	9.81×10^{8}
P7	105.4047	-5.2821	3.64	2.72	0.90	4.40	357.07	8.69×10^{3}	1.32×10^{7}	1.51×10^{8}
P8	105.4053	-5.2880	5.82	4.55	0.83	0.80	356.92	8.71×10^{3}	3.64×10^{7}	2.31×10^{7}
P9	105.4062	-5.2983	14.20	6.59	0.37	0.40	356.64	8.73×10^{3}	4.92×10^{6}	9.72×10^{7}
P10	105.4188	-5.2814	5.94	3.86	0.53	0.60	358.57	8.55×10^{3}	5.92×10^{7}	2.22×10^{7}
P11	105.4154	-5.2821	8.73	6.93	1.70	1.70	358.19	8.59×10^{3}	4.01×10^{7}	2.52×10^{7}
P12	105.4179	-5.2994	9.42	8.05	1.20	1.20	357.84	8.62×10^{3}	6.62×10^{7}	4.83×10^{7}
P13	105.4289	-5.2812	7.04	4.76	0.87	0.80	359.64	8.46×10^{3}	5.11×10^{7}	2.54×10^{7}
P14	105.4280	-5.2878	5.21	3.44	0.67	5.30	359.31	8.49×10^{3}	3.64×10^{7}	2.00×10^{8}
P15	105.4189	-5.2939	4.76	3.43	1.70	1.50	358.13	8.59×10^{3}	1.19×10^{7}	7.00×10^{8}

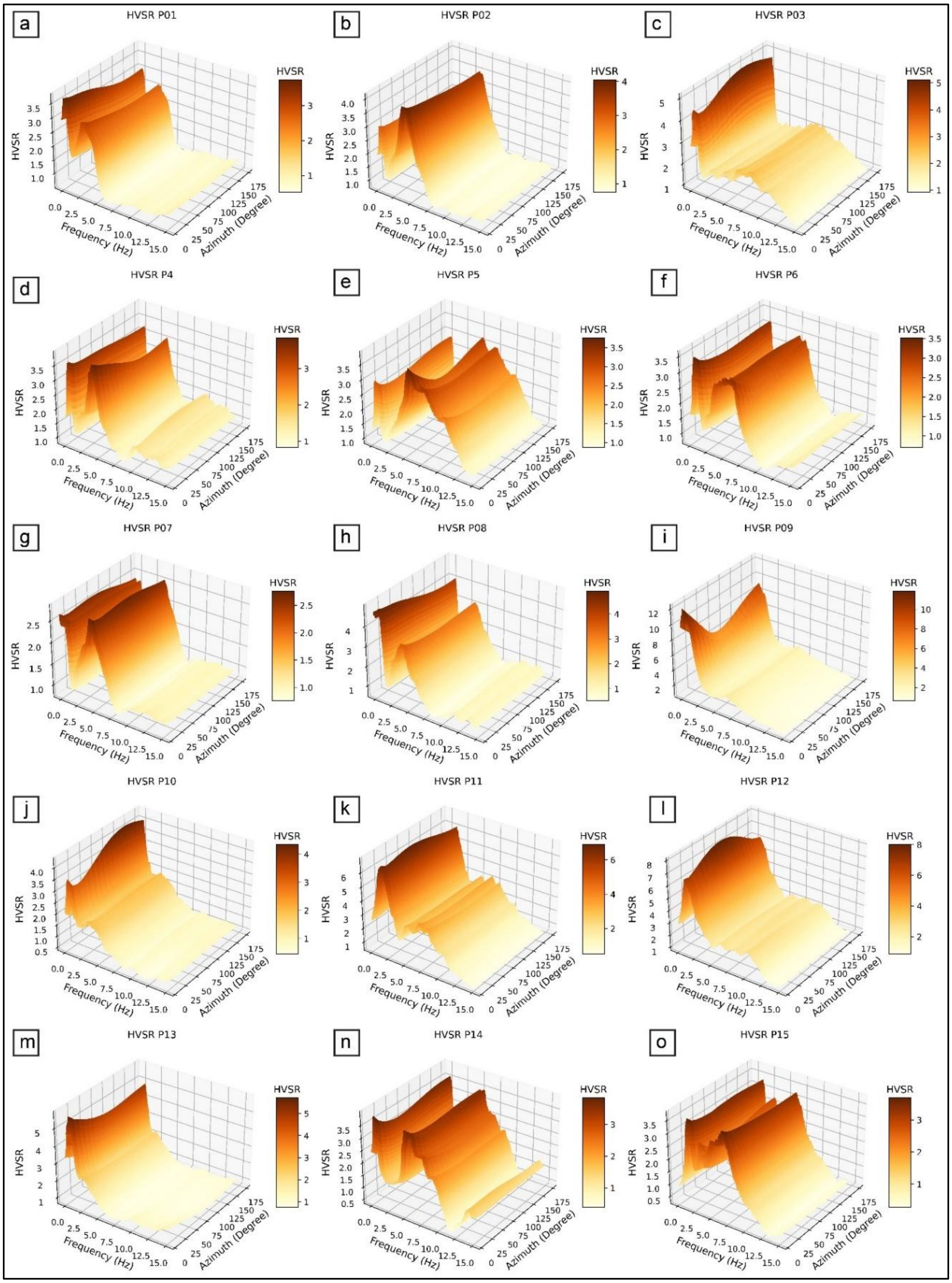

Figure 3. A 3D plot of the HVSR curve with the x-axis representing frequency (Hz), the y-axis representing azimuth (degrees), and the z-axis representing HVSR values (dimensionless, as it is a ratio). The redder the color, the higher the HVSR value; conversely, the more yellow, the lower the HVSR value.

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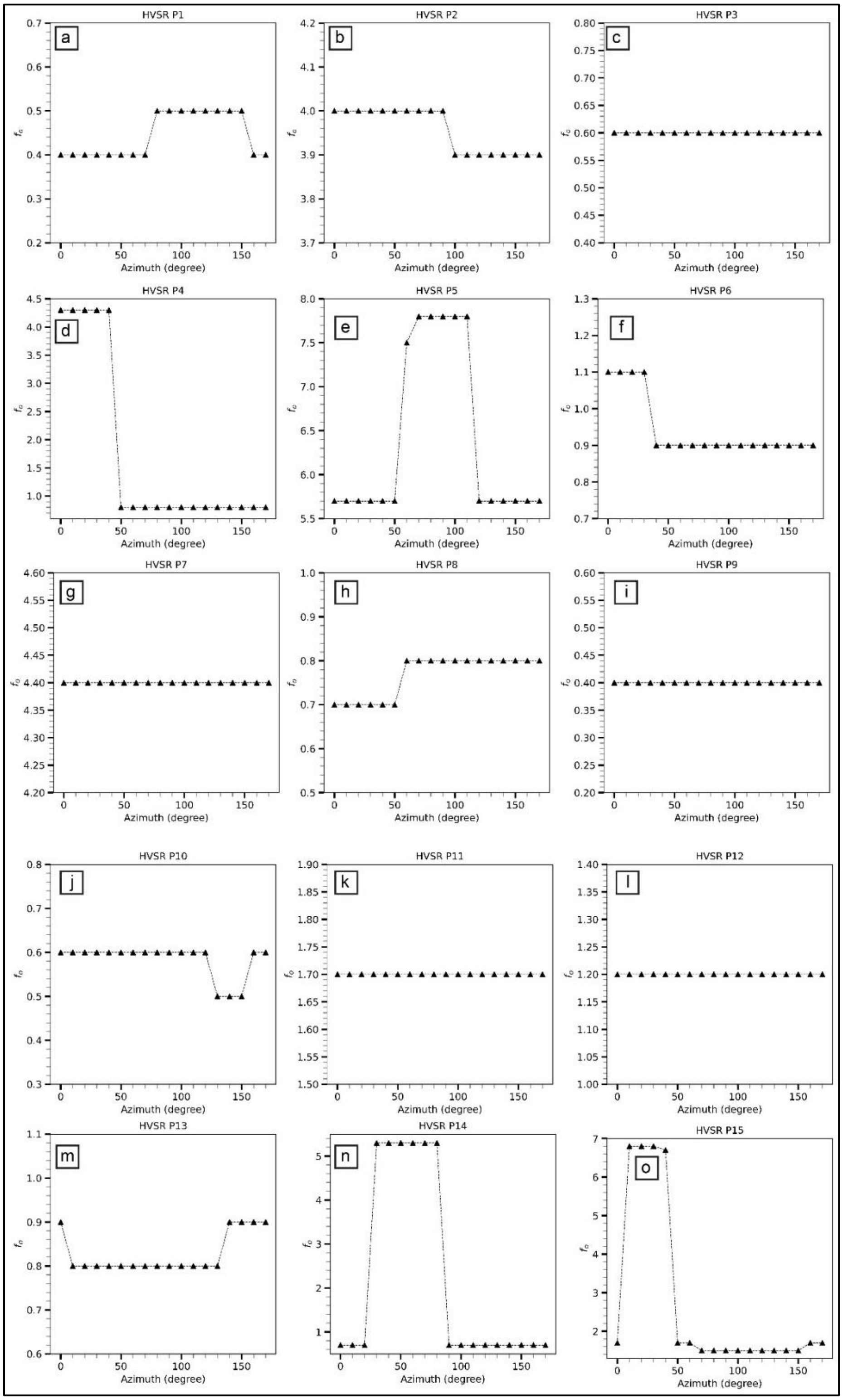

Figure 4. A plot of the changes in the dominant frequency (*fo*) against azimuth values for all measurement points.

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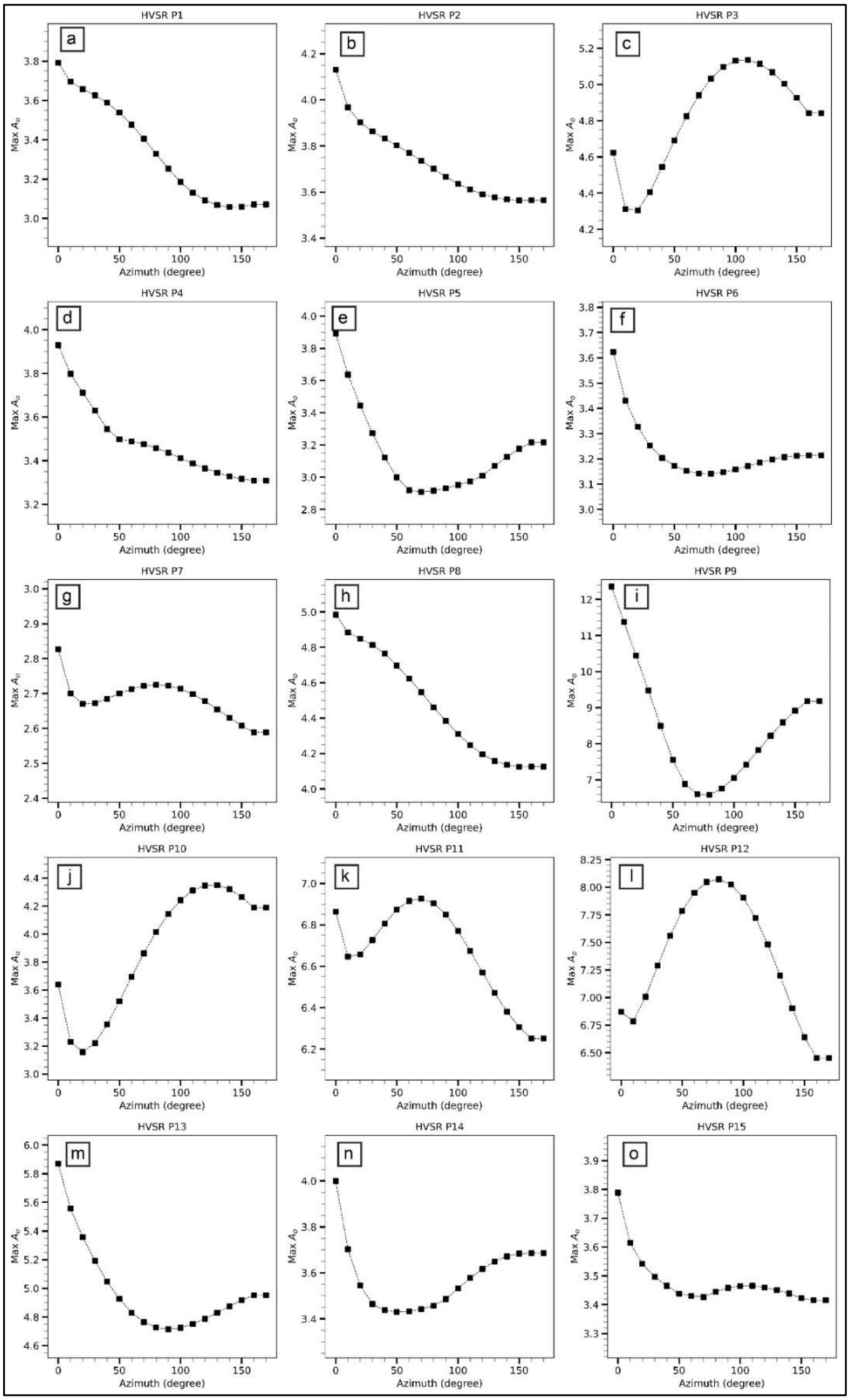

Figure 5. A plot of the changes in the maximum peak amplitude of HVSR (*Ao*) against azimuth values for all measurement points

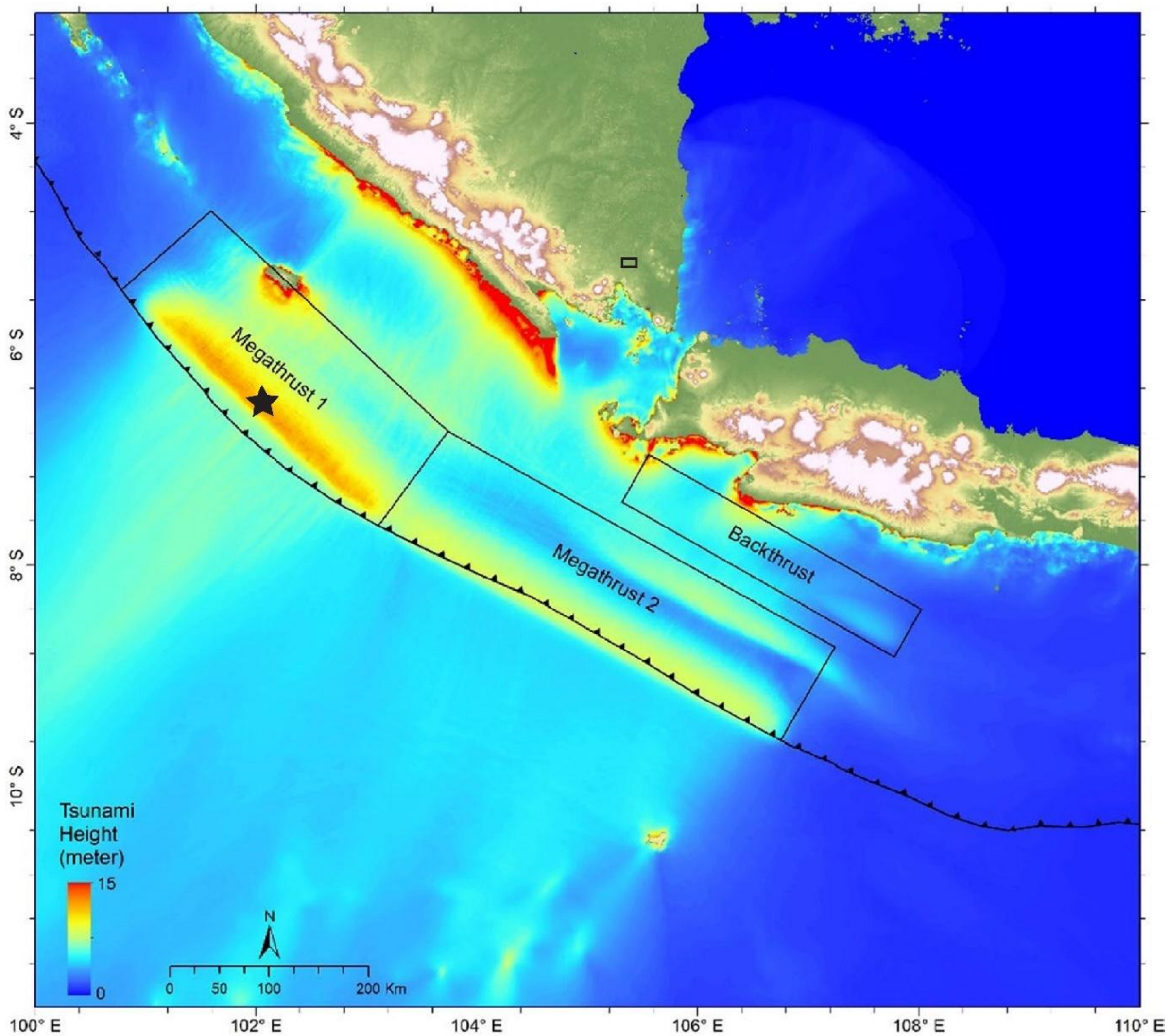

Figure 6. The location of the earthquake source model caused by megathrust activity to the southwest of Sumatra Island is marked by a solid black star. The research area is located within a hollow black rectangle (102.3655° E, 6.3264° S) This figure is a modified version from Supendi et al [2]

To assess the significance of azimuthal variability during an earthquake, we evaluated ground shear strain (GSS) values from HVSR analysis, assuming isotropy (no azimuthal variation) and non-isotropy (with azimuthal variation). A reference earthquake source was modeled from a megathrust earthquake located 370 km southwest of Sumatra, with an azimuth of approximately 250°. Due to the symmetry of azimuth, this corresponds to an azimuth of 70° (**Figure 6**). GSS values can be calculated using Nakamura's equation [16]:

$$GSS = \frac{A_o^2}{f_o} \times PGA \times 10^{-6} \qquad (6)$$

where PGA can be estimated using the equation from Fukushima & Tanaka [17]:

$$\log(PGA) = 0.41M + \log(0.32R \times 10^{0.42M}) - 0.0034R + 1.30 \qquad (7)$$

Here, M is the moment magnitude in Mw and R is the hypocenter distance in kilometers. The complete results of the calculations are shown in **Table 2**. The range of GSS values obtained without considering azimuth is 3.39×10^{-8} to 4.92×10^{-6} while the range considering azimuth is 9.70×10^{-9} to 9.72×10^{-7}. These GSS values are predicted to cause ground vibrations due to wave propagation, resulting in soil dynamics that remain elastic [18]. This interpretation aligns with the estimated PGA values, which range from 8.46×10^{-3} to 9.05×10^{-3} m/s². With this range of PGA values, the likely Modified Mercalli Intensity scale would be I–II, meaning the effects would be noticeable only to people in tall buildings, with items slightly swaying, but no structural damage occurring.

Conclusions

The HVSR calculations at 15 points in Kota Baru, South Lampung, demonstrate that HVSR values are influenced by azimuthal variation. The maximum HVSR variation with respect to azimuth and dominant frequency is reflected in the MAD values, with HVSR variation ranging from 0.96 to 5.71 and dominant frequency variation from 0.00 to 1.57. The pattern of azimuthal variation effects correlates with the distribution of soft volcanic material thickness, which may influence seismic wave propagation and contribute to the observed azimuthal variability in HVSR measurements. Additionally, the azimuthal variability in HVSR measurements at Kota Baru is plausibly associated with the presence of a fault, as indicated by the maximum HVSR value aligning with the strike of the suspected fault near the study area.

To assess the impact of azimuthal variation on GSS values, a megathrust earthquake with a magnitude of 8.9 km off the southwest coast of Sumatra was modeled. The results indicated no significant differences in GSS values, which remained within the same Modified Mercalli Intensity (MMI) scale. Therefore, while HVSR values are affected by azimuthal variation, the practical impact of this variation can be considered negligible. Consequently, the assumption that the ambient noise wavefield is isotropic in all directions remains valid for this case study in Kota Baru.

However, this study has certain limitations, particularly in the number and spatial distribution of measurement points. Future research could expand the dataset by incorporating a larger number of HVSR measurement sites with denser spatial coverage to further refine the understanding of azimuthal variability. Additionally, integrating other geophysical methods, such as seismic refraction or surface wave analysis, could provide complementary insights into subsurface anisotropy and fault structures.

From an application perspective, while the isotropic noise assumption appears valid for Kota Baru, its general applicability to other regions with different geological settings remains uncertain. Further studies are necessary to validate this assumption in areas with more complex subsurface conditions, such as those with pronounced lateral heterogeneity or extensive fault networks. Such research would not only strengthen the reliability of HVSR-based site characterization but also enhance its effectiveness in seismic hazard assessment and urban planning.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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