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Shear wave velocity model using HVSr inversion beneath Bandar Lampung City

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KEY POINTS:

- The study found stiff soil layers at depths of approximately 5 m with a value of $V_s < 330$ m/s, and bedrock layers with a velocity of over 1250 m/s were visible at a depth of 100 m.
- The city of Bandar Lampung is divided into two zones based on the V_s structure, with a trending NW-SE boundary.
- The north-central-eastern part has higher V_s values and is dominated by hard rock, whereas the south-central-western part has low-to-moderate V_s values and is a groundwater basin area with a thick sediment layer.
- Fault structures are clearly visible in both the lateral and vertical sections, indicating a complex fault structure throughout the city.

⁴ ABSTRACT

The horizontal-to-vertical spectral ratio (HVSr) method has been used to characterize site-effect parameters that are indispensable in seismic hazard and risk-reduction studies in urban areas and rapid land-use planning. This method is widely used because it is the cheapest and simplest

geophysical method for the acquisition and processing stages. In subsequent developments, the HVSR method has been widely used to determine elastic rock parameters, particularly shear wave velocity (V_s), through the HVSR curve inversion process. Furthermore, the V_s structural model can be used to delineate the presence of complex geological structures, particularly faults and sedimentary basins. Bandar Lampung is a city in Lampung Province with many fault structures and groundwater basins to the south. There are 83 HVSR measurement points around Bandar Lampung for delineating the presence of fault structures and groundwater basins. We produced the HVSR curve from the measurement results and then performed an inversion process using the particle swarm optimization algorithm to obtain V_s for the depth profile. Subsequently, from this profile, we produced a two-dimensional (2D) lateral and vertical model. The mean V_s value was calculated from all the measurement points, and we found stiff soil layers reaching depths of approximately 5 m, with a value of $V_s < 330$ m/s. A bedrock layer with a velocity exceeding 1250 m/s was visible at a depth of 100 m. Based on the 2D model, the V_s structure shows that the city of Bandar Lampung is divided into two zones, with a NW-SE boundary. The north-middle-eastern part of the city consists of harder rocks. This harder rock is characterized by extremely high V_s values, starting from a depth of 50 m. In contrast, the south-middle-west exhibits a low-moderate V_s anomaly associated with groundwater basins SW of the city. From the 2D V_s structural model, fault structures can be found along the city, characterized by a contrast of V_s values from low to medium and from medium to high.

Keywords: shear wave velocity, HVSR, fault structures, groundwater basin, Bandar Lampung City.

1. INTRODUCTION

Site characterization is a powerful tool that provides information on basic seismic risk and describes boundary zones vulnerable to the effects of local earthquakes. Information obtained from site characterization includes fundamental frequency (f_0), site amplification (A_0), and shear wave velocity (V_s). This information is essential for planning strategies for seismic risk mitigation by subdividing potentially earthquake-prone areas into zones based on the same geological and

geophysical properties. Thus, seismic responses can vary inside urban settlements owing to lateral and vertical heterogeneities in the geologic setting (Hartzell et al., 1997; Panzera et al., 2017; Toni et al., 2019). In areas with complex geologic settings, where manufactured structures interfere with the reconstruction of the subsoil geometry, a detailed geologic survey coupled with knowledge of shear wave velocity and fundamental frequency is important (Panzera et al., 2019). In addition, it is crucial to evaluate the quantitative seismic risk and estimate the site amplification factors precisely because the effect of site amplification is significant, particularly at sites with thick and soft sediments where most urban environments have been built (Kawase et al., 2019).

Local site conditions play a fundamental role in earthquake damage distribution and refer to the effects of the local geological surface and subsurface structure characteristics on seismic ground motion. The seismic ground response is related to the sediment depth (h) and shear wave velocity (V_s) (Aki and Richards, 2002; Stanko et al., 2017), expressed by the fundamental/natural frequency and site amplification of the sediment. A low fundamental frequency indicates thick sedimentary layers and an extremely soft material. For thin sedimentary layers, the fundamental frequency is high. Local site amplification refers to the amplitude increase in seismic wave propagation through surface geological structures. The peak amplitude (A_0) is related to the contrast impedance between the surface layer and underlying bedrock, lateral heterogeneities, material damping of the sediment, and characteristics of the incident wavefield.

Studies using ambient noise measurements (microtremors) have been widely conducted using the horizontal-to-vertical spectral ratio (HVSr) technique. It provides reasonable estimates for determining the natural frequency of soil (Mucciarelli and Gallipoli, 2001). The HVSr method can be applied to various scientific disciplines, including geology (Mantovani et al., 2017), seismology and site micro-zonation study (D'Amico et al., 2008; Gallipoli et al., 2004; Paolucci et al., 2015; Scherbaum et al., 2003), engineering (Gallipoli et al., 2018; Mucciarelli and Gallipoli, 2001), fault and subsoil investigations (Akkaya, 2015; Akkaya and Özvan, 2019; Harutoonian et al., 2013; Khalili and

Mirzakurdeh, 2019; Maresca et al., 2018; Setiawan et al., 2018; Zaenudin et al., 2022), and archaeology (Abu Zeid et al., 2016; 2017a; 2017b; Bignardi et al., 2017; Wilken et al., 2015).

HVSR applications in the geotechnical field have also been developed to obtain a one-dimensional (1D) layer model described in the shear wave velocity-to-depth profile (Raptakis and Makra, 2010). This shows that the HVSR is sufficient for obtaining the shear wave velocity structure model at a local site. However, if a priori information is known, such as the range of V_s and thickness of the layers around the research area, the accuracy of the HVSR curve inversion increases (Fäh et al., 2003). Several other geophysical methods have been used to determine the thickness and number of layers in the HVSR curve inversion process (Pilz et al., 2010; Maghgami, 2021; Rahman et al., 2016; Pamuk et al., 2017).

⁴³ in this study, the shear wave velocity structure in Bandar Lampung, located in Lampung Province (southern Sumatra Island), was investigated. Bandar Lampung has a relatively complex geological structure, with many fault structures crossing the city and various rock formations. Most of the fault structures are northwest-to-southeast (NW-SE) (Fig. 1). Therefore, this study focused on mapping the structure of V_s and estimating the presence of faults from the V_s cross sections. In addition, this study focused ² on the thickness of the sediment layer in Bandar Lampung. According to Zaenudin et al. (2020), gravity data show that the southwestern area toward Mount Betung contains a thick layer of sediment. In this area, the groundwater basins are located ⁹ at a depth of 800 m.

Microtremor data obtained using the HVSR method were used to determine the seismic site characteristics (dynamic properties) of subsurface soil layers, expressed by the fundamental/natural frequency (f_0). Then, we inverted the HVSR curve to obtain V_s for the depth profile around Bandar Lampung. In the inversion stage, we used the particle swarm optimization (PSO) inversion algorithm because this method converges quickly and is relatively stable (Farduwin and Yudistira 2021). Although there are many sophisticated and reliable inversion algorithms for HVSR curve inversion, the inversion method using the PSO algorithm is sufficient for identifying subsurface structures. Using

the PSO inversion algorithm, Zaenudin et al. (2022) determined the local fault structure based on the Vs structure obtained from the HVSR curve inversion. To increase the best model of the obtained inversion results, we correlated them with the natural frequency (f_0) as a reference to estimate the thickness of the sediment layer and depth of the bedrock, as suggested by Ibs-Von Seht and Wohlenberg (1999).

2. Geological Setting

The study area is located on the southern tip of Sumatra Island in the southern part of Lampung Province. Sumatra is one of the largest islands in Indonesia, with complex geological conditions. The structure of the island resulted from the subduction of the Indian Plate beneath the Eurasian Plate. This subduction has occurred since the Cenozoic Period, forming a subduction zone along the collisional boundary (McCaffrey, 2009) and causing a changing the position of Sumatra Island, which initially trended west-east to NW-SE (Hamilton, 1979). These conditions make Sumatra an area of high seismicity. The deformation process on Sumatra began during the Oligocene-Miocene. This led to the formation of the Sumatra Fault, which is a horizontal fault that remains active today and forms several fault segments (Barber et al., 2005). The Sumatra Fault extends from Aceh (northern tip of Sumatra) to Lampung (southern tip) and is a dextral strike-slip fault that moves obliquely to the northwest (Sieh and Natawidjaja, 2000).

Regionally, the study area lies within the Sumatra fault system segment, extending from the pull-apart basin zone in Suoh to the Semangka and Lampung Bay segments. The Semangka fault represents the Semangka Bay segment. It continues to the Sunda Strait, whereas the Lampung-Panjang and Tarahan faults represent the Lampung Bay segment and continue to the Rajabasa Mountains. Sinistral strike-slip faults dominate the fault segment around Lampung Bay. This fault movement is greatly influenced by the oblique subduction of the Eurasian Plate in the Sunda Arc.

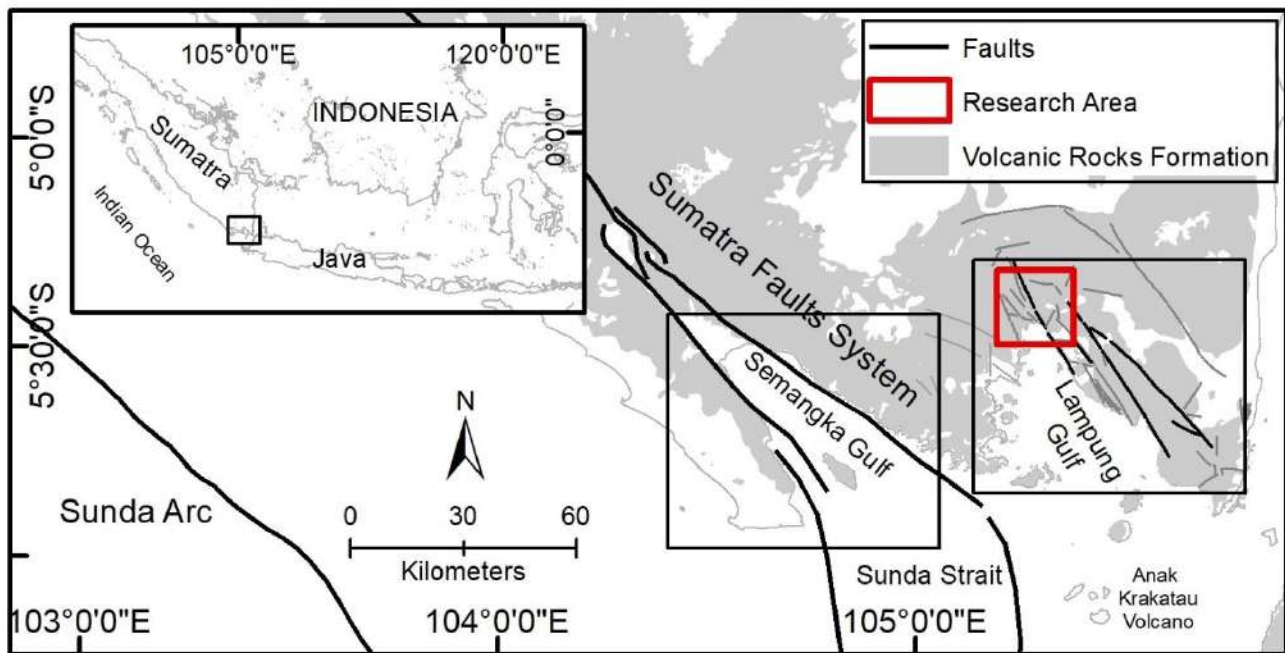


Figure 1. Regional geological structure of the Sumatra fault system along the Semangka and Lampung segment (Barber et al., 2005; Darmawan et al., 2021; Mangga et al., 1993). The red box indicates the research area located in Bandar Lampung City.

Bandar Lampung is located 80 km (western research area) from the Semangka Fault earthquake source line. The Lampung-Panjang and Tanjung–Karang faults are also located in this city with the same orientation and characteristics as the Semangko Fault. Based on the geological map of Tanjung Karang (Mangga et al., 1993), Bandar Lampung consists of three main strata (Fig. 2): The Pre-Tertiary consisting of the bedrock of metamorphic rock (basement of Bandar Lampung) is distributed in eastern and southeastern research area, and intrusive igneous rock is distributed in the eastern area; the Tertiary strata are composed of the magmatic intrusive igneous rock in the western part and sedimentary rock in the southeastern-northeastern and western-southwestern parts; and the Quaternary strata are composed by sedimentary rock, surface deposits (alluvium), and young volcanic deposits distributed in the part of central to the western research area.

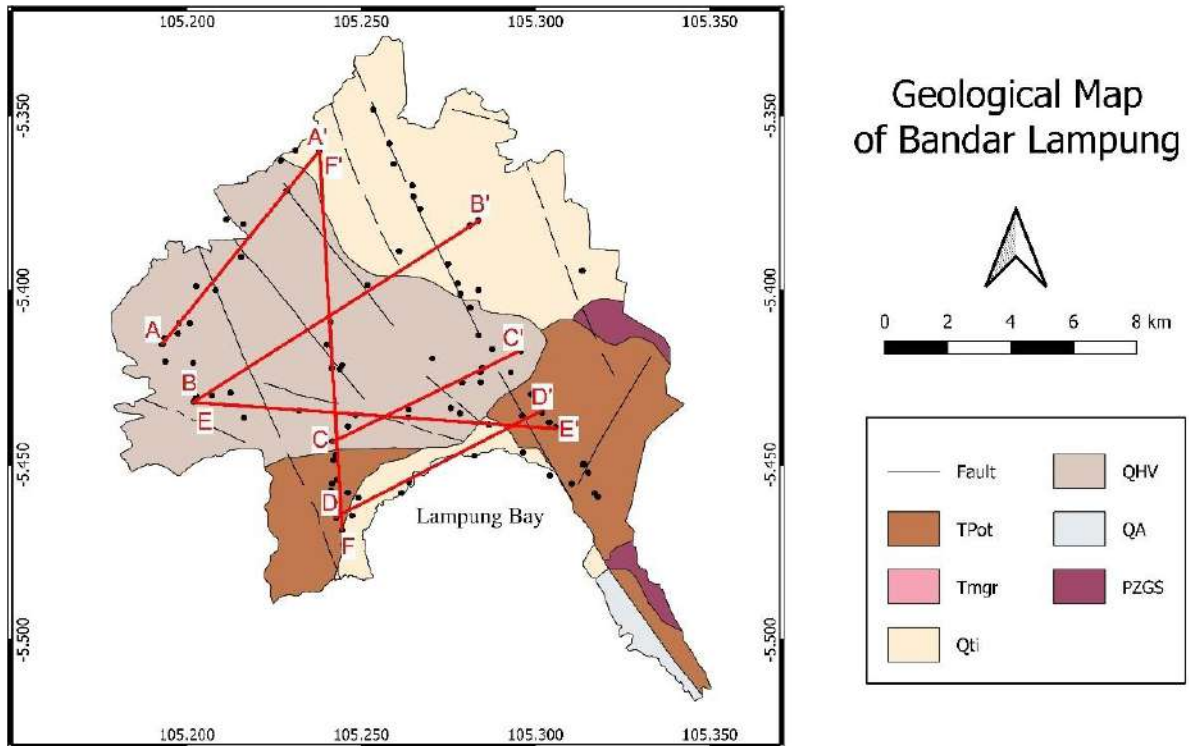


Figure 2. Geological map of Bandar Lampung consisting of surficial deposits (QA: cobble, pebble, sand, clay, and peats), volcanic rock (QHV: andesite-basalt lava, breccia, and tuff; Qti: pumiceous tuff, rhyolitic tuff, welded tuff, tuffaceous claystone, and tuffaceous sandstone), sedimentary rock (TPot: welded tuff and breccia with intercalations of chert), metamorphic rock (PZGS: green amphibole-schist and dioritic orthogneiss amphibolites), and intrusive rock (Tmgr: granite and granodiorite). The red lines indicate the trajectory of cross sections A to F and the black dots are HVSr acquisition points (modified from Mangga et al., 1993).

Bandar Lampung contains four geomorphological units: structural, volcanic, denudational, and fluvial (Mulyasari et al., 2019). The structural unit is associated with the Lampung-Panjang and Tanjung–Karang faults, which played a role in the changing geomorphology. The volcanic unit was controlled by recent volcanic activity (Betung Volcano) and magnetism. Denudational units were controlled by erosion and are characterized by a lithology or rock formation on a hill morphology that differs from the surrounding lithology. Fluvial units are the products of recent geological processes.

They are characterized as unlithified and sedimentary materials distributed in a plain or flat relief (Rustadi, Setiawan, et al., 2022).

3. HVSR theory

HVSR is a method based on ambient seismic noise measurements. Ambient noise, commonly called microtremors, can appear anywhere on the surface of the Earth and is related to atmospheric phenomena and anthropogenic activities (Asten, 1978; Gutenberg, 1958). A ¹ microtremor is characterized by tiny wave oscillation (10^{-4} to 10^{-2} mm) with highly attenuated spectral components and can be measured by passive recording techniques. During ¹ propagation from source to receiver, elastic waves encounter attenuation—generally caused by geometric factors (increased wavefront dimensions)—and are inelastic because not all rocks are perfectly elastic, particularly sediments.

The HVSR method is simple and reliable, estimating natural/dominant frequency values by measuring the three components of microtremors (NS, EW, and vertical). Owing to its simplicity in measurement and processing, this method has developed rapidly. It has been widely applied in many areas to determine site effects and microzonation maps, particularly in densely populated areas (urban settlements). This method was first proposed by Nogoshi and Igarashi (1970, 1971), then developed by Nakamura (1989), and is commonly referred to as the Nakamura Technique. ²⁵ In 1989, Nakamura stated that the peak amplitude of the HVSR was the result of multiple body-wave reflections. Nevertheless, in 2000, Nakamura revealed a theory stating that there is a combination of surface and body waves that affects the shape of the HVSR curve and depends on the viscoelastic parameters of the layers, distance, and distribution of sources (Bonney-Claudet et al., 2006).

The HVSR processing stage obtains an HVSR curve at a single point ¹ in the measurement location. The three recorded seismic components are divided into several windows based on the desired window length. Then, on each of these windows, a Fourier transform is performed for all components, smoothing the curves, and ²⁹ calculating the ratio between the horizontal and vertical components. ³ The

Fourier spectral ratio between the horizontal and vertical (H/V) components of the microtremors can be expressed as

$$H / V(\omega) = \{[S^2(\omega)_{NS} + S^2(\omega)_{EW}] / 2S^2(\omega)_V\}^{1/2} \quad (1)$$

where $[S(\omega)_{NS}$ and $S(\omega)_{EW}]$ are the spectra of two horizontal components, $[S(\omega)_V]$ is the spectrum of the vertical component (V), and ω is the angular frequency. The average value was calculated from all curves to obtain the HVSR curve as a function of frequency. The HVSR curve consists of one or more peaks describing the subsurface layer as several layers of sediment above the bedrock layer. In general, we assume that there is more than one peak amplitude in the HVSR curve. In this case, the peak with the lowest frequency is called the resonant fundamental frequency (f_0).

There are two types of parameters at the peak of the curve: the peak amplitude and frequency. The peak frequency, where the peak amplitude occurs, is referred to as the natural or fundamental frequency (f_0). In contrast, the peak amplitude (A_0) is directly related to the speed contrast, i.e., a sharp speed contrast produces a large H/V peak amplitude and vice versa. The peak amplitude in the HVSR curve is also caused by the difference between the top layer of the sediment and the rock layer below it (SESAME, 2004). The HVSR method is suitable for areas with low-to-moderate seismic activity (Kyaw et al., 2015).

4. Methodology

Microtremor measurements were conducted in Bandar Lampung City using a three-component seismometer at 83 measurement point locations (Fig. 2) for 25–30 min with a sampling time of 0.01 s. Determining the measurement parameters was necessary to reduce the disturbance at the measurement location. We used a Butterworth filter of order two with a cutoff frequency of approximately 0.3 Hz to reduce the effect of wind around the measurement location and drift caused by the tool (Mihaylov et al., 2019, 2016). During processing, we used *Geopsy* and *Octave software* concerning the standard HVSR processing procedure to obtain a reliable curve (Nakamura 1989; SESAME, 2004). The processing parameters include a frequency filter range of 0.5–20 Hz and window length of 30 s with

25% overlap. (Maghami, 2021). We then applied an antitrigger algorithm to eliminate transient or very low amplitude signals (short-term average (STA)=1 s; long-term average (LTA)=30 s) with STA/LTA of 1.0–3.5. We used a filter with a smoothing coefficient of 20 to remove the effects of modulation and spikes with extreme values on the HVSR curve (Konno and Ohmachi, 1998). The following equation is used to calculate the HVSR curve for each window:

$$HVSR = \frac{H(f)}{V(f)}$$

$$H(f) = \sqrt{E(f)^2 + N(f)^2} \quad (2)$$

where: $H(f)$ = amplitude spectra of the horizontal component;

$V(f)$ = amplitude spectra of the vertical component;

$E(f)$ = amplitude spectra of EW component;

$N(f)$ = amplitude spectra of NS component;

The spectral ratio between the horizontal and vertical components of ambient noise shows a peak value at a certain frequency, which is related to the resonant frequency (f_0) of the soil layer thickness at a site (Ibs-von Seht and Wohlenberg, 1999):

$$h = af_0^b \quad (3)$$

where h is the depth of the sediment layer (Quaternary), and a and b are the correlation coefficients related to the geometry and geotechnical properties of a site. From Eq. 3, it is difficult to determine the suitability of the correlation coefficient for the geometry of the dynamic properties of the soil layers. Therefore, the HVSR curve inversion was used to determine the thickness of each layer at each site.

In the HVSR curve inversion stage, we applied the PSO algorithm to estimate the value of the shear wave velocity (V_s) against depth (H). This algorithm has advantages in terms of geophysical data inversion because it converges quickly and is relatively stable (Farduwin and Yudistira, 2021; Farduwin et al., 2021). Zaenudin et al. (2022) compared the PSO and GA algorithms using synthetic

modelling and found that PSO is faster, provides the best solution, and is more stable. PSO is an inversion technique that imitates the social behavior of bird swarms (particles or individuals) to find food (Kennedy and Eberhart, 1995). Flocking behavior and individual intelligence affect the behavior of each particle in finding food or a target. When an individual finds the closest target, all others head toward it.

There are five stages in the PSO algorithm. First, we determine the number of individuals to generate the search space of the model parameter (X where $X_{min} \leq X \leq X_{max}$). The second stage generates an initial population of X using random numbers in the model parameter search space determined in the first stage. We then obtain the initial populations $X_1^0, X_2^0, X_3^0, \dots, X_j^0$; where $i =$ iteration, $j = n$ -th individual, and $n =$ number of individuals. For the HVSR inversion, the model parameters consisted of h and V_s . The velocity (V) of each individual was set to zero in the initial iteration ($V_1^0 = V_2^0 = V_3^0 = \dots = V_i^0 = 0$). The third stage involves calculating the objective functions $f[X_1^0]; f[X_2^0]; f[X_3^0]; \dots; f[X_j^0]$. In this study, we used norm-2 ($\|e\|^2$) to calculate the objective function. In the next stage, we determine parameters l and g , where l is the best position of the individual in the given iteration. Thus, g is the best position that a particle can reach within a group. The best positions l and g , are determined from the smallest objective function (f_{min}). In the final stage, we update the V and X values for each iteration with the following equation:

$$v_i(k+1) = \omega v_i(k) + \phi_1(g(k) - x_i(k)) + \phi_2(l_i(k) - x_i(k)),$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (4)$$

where

$$\phi_1 = r_1 a_g, \phi_2 = r_2 a_l, r_1, r_2 \rightarrow U(0,1) \omega, a_l, a_g \in \mathbb{R} \quad (5)$$

ω is the inertia moment, ϕ_1 and ϕ_2 are the global and local acceleration, and a_l and a_g are global and local acceleration constants. Using regressive discretization (RR-PSO) on V and a in the time function

(Fernández-Martínez & García-Gonzalo, 2012), we obtain a discrete model using the following equation:

$$x'(t) \simeq \frac{x(t) - x(t - \Delta t)}{\Delta t};$$

$$x''(t) \simeq \frac{x(t) - 2x(t - \Delta t) + x(t - 2\Delta t)}{\Delta t^2} = \frac{x'(t) - x'(t - \Delta t)}{\Delta t} \quad (6)$$

Then, we apply the following relationship,

$$x(t) = (x(t - \Delta t) + v(t)\Delta t),$$

$$\frac{v(t) - v(t - \Delta t)}{\Delta t} + (1 - \omega)v(t) + \phi(x(t - \Delta t) + v(t)\Delta t) = \phi_1 g(t - t_0) + \phi_2 l(t - t_0),$$

$$v(t) = \frac{v(t - \Delta t) + \phi_1 \Delta t (g(t - t_0) - x(t - \Delta t))}{1 + (1 - \omega)\Delta t + \phi \Delta t^2} + \frac{\phi_2 \Delta t (l(t - t_0) - x(t - \Delta t))}{1 + (1 - \omega)\Delta t + \phi \Delta t^2} \quad (7)$$

Then, the equation for RR-PSO can be written as follows:

$$v(t - \Delta t) = \frac{v(t) + \phi_1 \Delta t (g(t) - x(t)) + \phi_2 \Delta t (l(t) - x(t))}{1 + (1 - \omega)\Delta t + \phi \Delta t^2}$$

$$x(t + \Delta t) = x(t) + v(t + \Delta t)\Delta t; \quad t, \Delta t \in \mathbb{R}$$

$$x(0) = x_0; \quad v(0) = v_0; \quad \phi = \phi_1 + \phi_2 \quad (8)$$

In the inversion stage, five-to seven-layer models were used. Seven layers were used at points located on the boundaries of the three rock formations, and there are many fault structures in the area. This method is expected to image a more detailed subsurface model because of its complex structure. We limited the search space for the V_s model in layer 1 to 100–800 m/s, 2–4 to 500–1500 m/s, and 5–7 to 800–2500 m/s. This search space refers to the EC8 soil classification (EN 1998-1) where soil deposits with loose-to-medium cohesion values or soft-to-hard soil layers have $V_{s30} < 180$ m/s. We assumed that the V_s value had the same range as that V_{s30} ; therefore, we limited the search space to a minimum of 100 m/s. The maximum value was set to 800 m/s because dense sand, gravel, or clay

deposits do not exceed 800 m/s. Furthermore, we set a larger value for the downward layer assuming that the velocity increases with depth. Therefore, we set the velocity to 2500 m/s for the last layer.

In search space model h , we created several schemas. For this model, the search space for layers 1–3 ranged from 1 to 20 m and that for layers 4–7 ranged from 5 to 50 m. We developed this scheme to detect thin layers associated with near-surface sediment layers. Then, we assigned each layer fixed q_p and q_s values of 30 and 10, respectively. We estimated the P-wave velocity (V_p) and density (ρ) values using the following equation (Brocher, 2005):

$$V_p = 0,9409 + 2,0947V_s - 0,8206V_s^2 + 0,2683V_s^3 + 0,0251V_s^4 \quad (4)$$

$$\rho = 1,6612V_p - 0,4721V_p^2 + 0,0671V_p^3 - 0,0043V_p^4 + 0,000106V_p^5 \quad (5)$$

where V_p is in km/s and density is in g/cm³. Eq. 4 is valid for V_s values of 0–4.5 km/s. The uncertainty information was calculated using the standard deviation of all models produced during the inversion process. The forward function used in this inversion stage is from Herak (2008), who assumes that the 1D model of the HVSr curve depends only on the ground response (amplification spectra) owing to the vertical propagation of body waves. Although several researchers have used the surface wave approach—particularly Rayleigh wave ellipticity—and more complex modeling using Rayleigh and Love waves and the full wavefield approach, both comprehensive approaches used full wavefields or body waves to produce similar (but not identical) curves (Albarelo et al., 2023). The only difference was in amplitude (H/V).

5. Results and Discussion

5.1. Dominant frequency (f_0)

The dominant frequency value was selected automatically using *Geopsy software*, which was selected at the peak of the HVSr curve. Figure 3 shows the dominant frequency values, ranging from 0.9 to 7 Hz. Based on the figure, the Bandar Lampung area is regionally dominated by relatively moderate-to-high f_0 values ($f_0 > 2$ Hz), where high f_0 anomalies appear at the northern, southern, and western ends and in the central part to the east of Bandar Lampung City. The high f_0 anomaly in the

city center correlates with ² young volcanic deposits (QHV) consisting of andesite-basalt lava, breccia, and tuff. This young volcanic deposit originated from Mount Betung to the west. In addition, a low f_0 anomaly was observed in several parts of the city center, including the SW-central region, several parts above the NE, and the NW-central-SE direction. These low f_0 anomalies were primarily correlated with sedimentary deposits (TPOT and QTI) with tuff-dominated lithology. Areas with low f_0 values indicate that the area is composed of soft soil and has a thick layer of sediment. Thus, the sediment layers at the northern, western, and southern ends and central-to-east have a thin layer of sediment compared to other areas. In other words, the dominant frequency value in an area can be correlated with ¹⁰ the thickness of the sediment layer. This is consistent with the V_s distribution map shown in Fig. 7, in which areas with high frequencies have low V_s values at approximately 30 m depth. The rest, at approximately 100 m, showed relatively high V_s values, which spread from north to east and southeast.

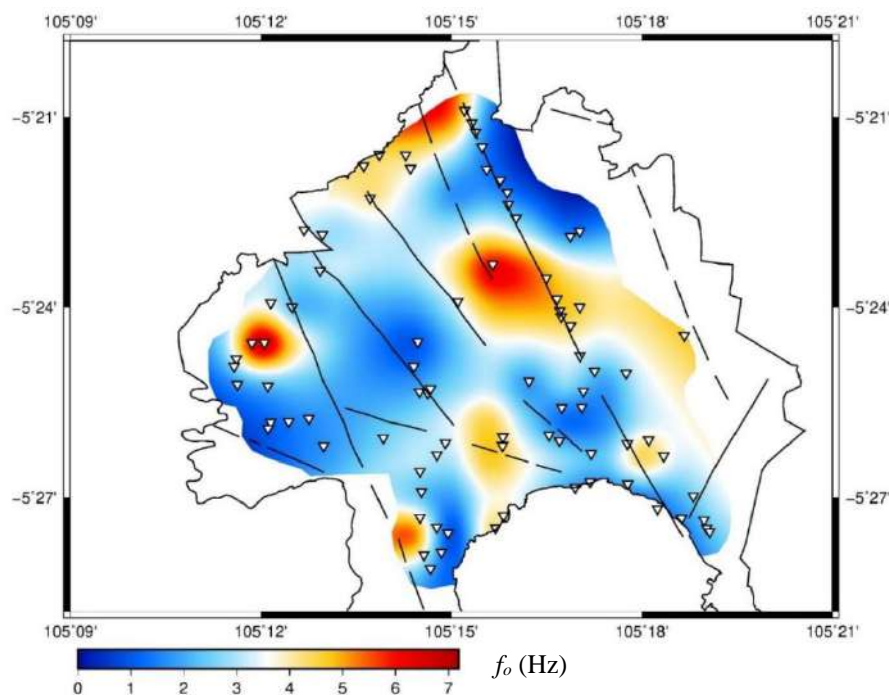


Figure 3. Map of dominant frequency (f_0) around Bandar Lampung City.

5.2. 1D model of V_s structure from PSO inversion result

In this study, the V_s -to-depth profile was obtained from the PSO inversion algorithm using the Herak (2008) code for the HVSR forward model based on body waves, where the approach using body

waves is better than that using surface waves (Dal Moro, 2008; Lunedei and Albarello, 2010). The PSO algorithm was selected because of its quick convergence, stability, and ease of implementation (Ding et al., 2019; Fernández Martínez et al., 2010; Pallero et al., 2017). We then used the inversion results to create a Vs distribution map at a certain depth and produced a cross-sectional map that crosses the measurement points in the Bandar Lampung area. A subsurface-layer model with five to seven layers was used for the inversion process. Models with more than five layers were used in areas with complex structures. This was performed to obtain a detailed model describing the fault structure in the Bandar Lampung area.

Figure 4 shows the HVSR curves obtained at several measurement sites and the one resulting from inversion using the PSO algorithm. The inversion results show a relatively matched HVSR curve between the observed and calculated values. The curve in Bandar Lampung was dominated by wide peak curves, which indicated the possibility of complex variations in the sedimentary and bedrock structures. This is consistent with the geological conditions of Bandar Lampung, where many faults cross in the NW-SE direction. The PJ13 and PJ18 curves showed more than one peak, indicating an impedance contrast at different depths. This is because of the geological conditions at that point, in the form of non-compact sediments on the surface, which are composed of compacted sediments below and extremely compact bedrock layers at the bottom.

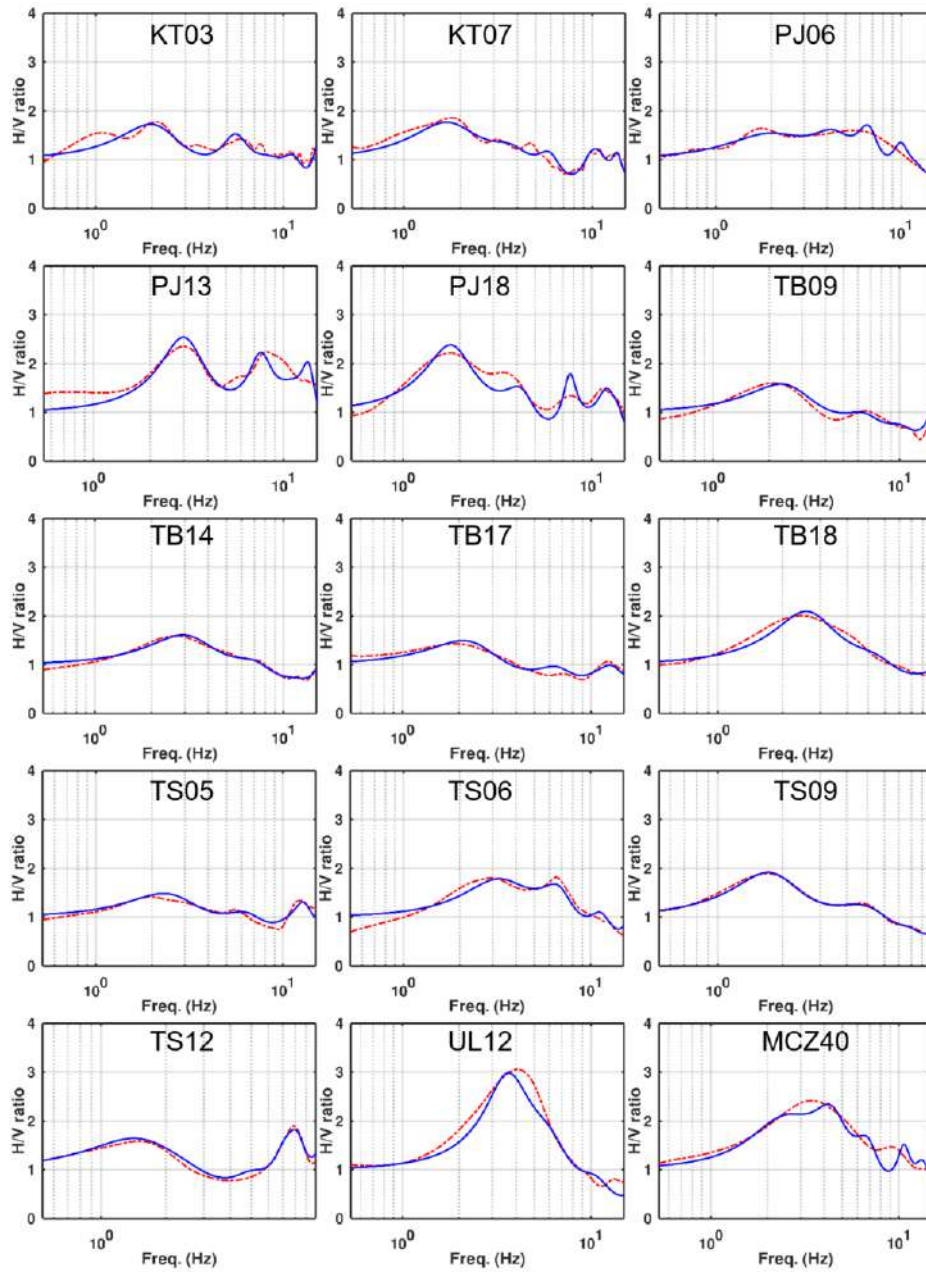
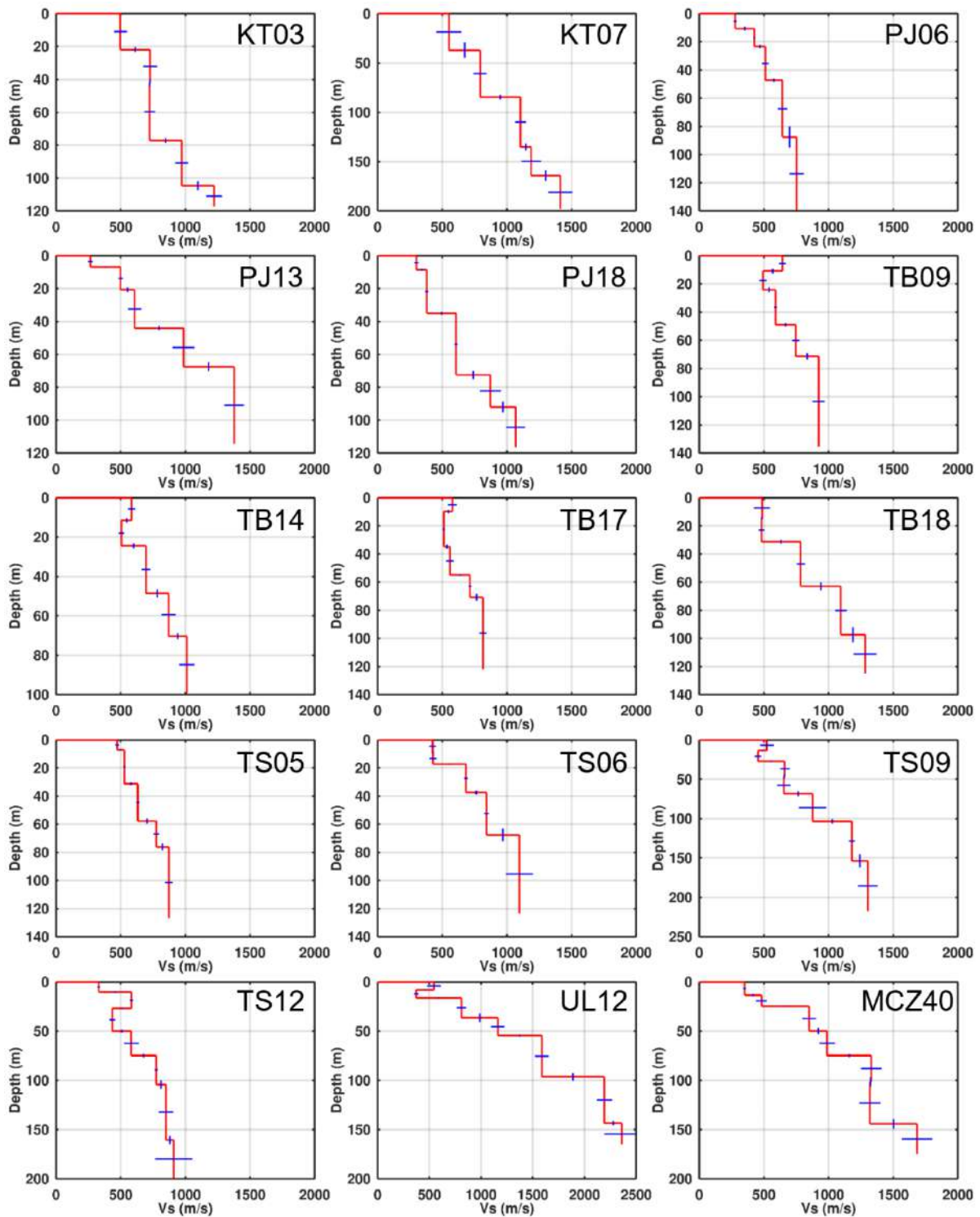


Figure 4. HVSR curve obtained for several observation sites (dashed red line), and the best HVSR curve obtained from the inversion process (blue line).



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 Figure 5. Vs profile obtained from the inversion process using the PSO algorithm. The blue line shows the uncertainty of each layer.

Figure 5 shows the subsurface layering model based on the Vs value profile against depth. The results of this inversion model were obtained to 250 m, with an average depth of 150 m. The minimum depth of the inversion results was 100 m. As shown in Fig. 5, the distribution of Vs increased with

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increasing depth. This can also be seen in Fig. 6, which shows that velocity V_s increases to a depth of 150 m. V_s increased significantly at depths of 5, 15, 45, and 100 m. At a depth of 0–5 m, the soil was dominated by layers with $V_s < 330$ m/s, making it a stiff soil. Then, at a depth of 15 m, it started to increase to 430 m/s and continued to increase until its speed reached 800 m/s at a depth of 45 m. At a depth of 100 m, the value of V_s appeared to increase significantly until the speed reached 1250 m/s, indicating a harder rock layer. The speed increased to 1350 m/s at a depth of 150 m.

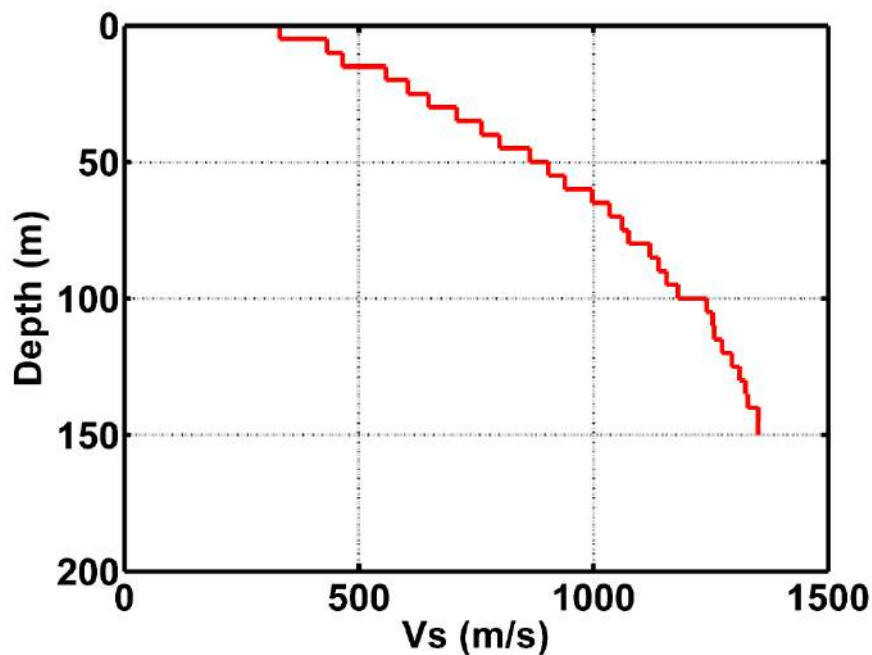


Figure 6. Mean V_s profile around Bandar Lampung City.

5.3. V_s structure

The V_s distribution map in the subsurface layer of the city of Bandar Lampung shows a clear structural trend. Laterally, V_s showed a relatively significant change and was marked in areas with faults. This indicates that the fault became the boundary of the changes in V_s , starting from low-to-medium or medium-to-high. V_s can be used to estimate sediment thickness using the well-known quarter-wavelength approximation (Ryanto et al., 2020) or the relationship between the average shear wave velocity and the fundamental resonant frequency. The sediment thickness was not calculated in this study. However, we examined at the distribution of V_s . Figure 7 shows the distribution of V_s at 0, 30, 50, and 100 m. At a depth of 0 m, Bandar Lampung City was dominated by low-to-moderate

⁴⁶ V_s . Low velocity dominates in most areas, particularly in the north, which has a very low-velocity anomaly. Conversely, there is a moderate velocity at the west end toward Betung Mountain and parts of the city center to the east. At a depth of 30 m, the distribution of V_s exhibits a relatively sharp change in the north-central-east direction, where a moderate anomaly (1000 m/s) appears and is relatively higher than in other areas. This trend continued to 100 m depth. Based on Fig. 6b–d, Bandar Lampung City is divided into two parts, where the north-central–eastern part has a higher anomaly. In contrast, the south-central-west region exhibited a relatively moderate anomaly.

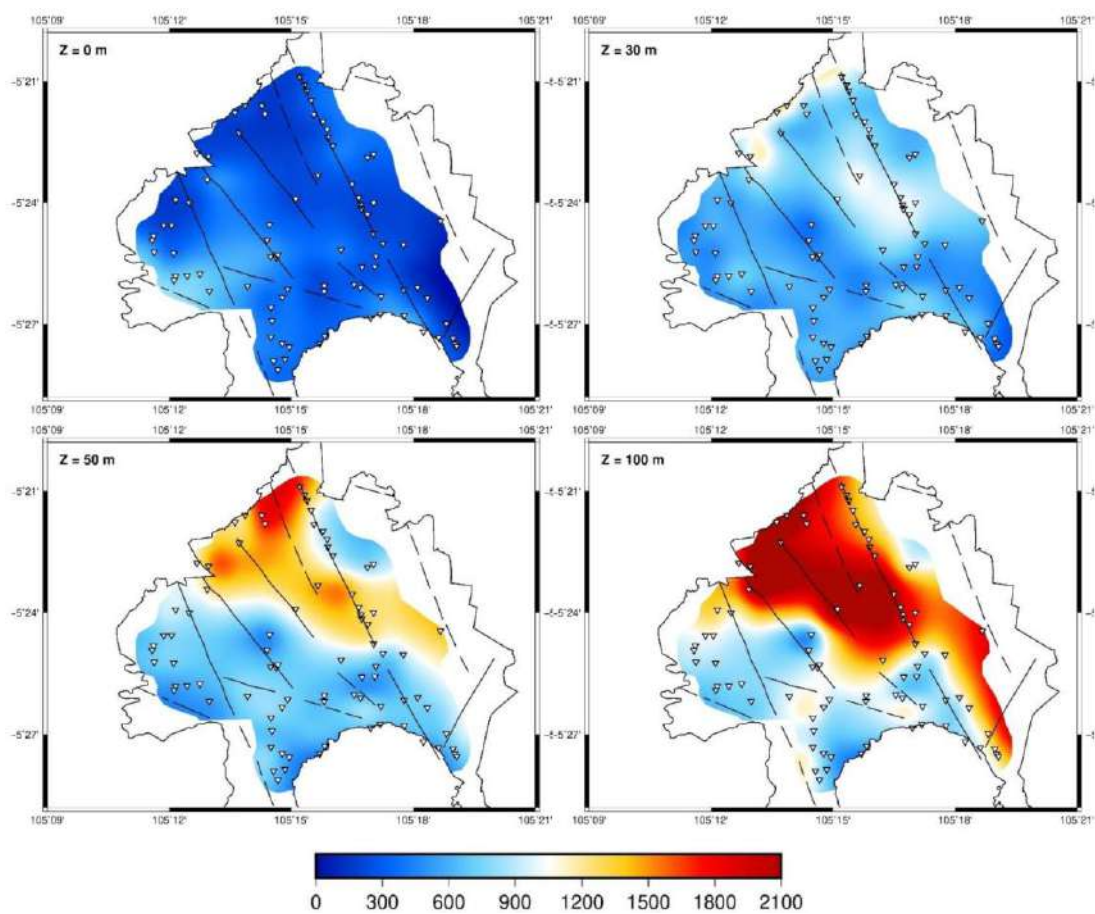


Figure 7. V_s structure of Bandar Lampung city obtained from HVSr inversion at 0 m (a); 30 m (b); 50 m (c); and 100 m (d). The black lines on the map indicate geologically confirmed faults based on the regional geological map.

The north-central-east area represents a higher anomaly where V_s reaches 2000 m/s. This high anomaly indicates a rock layer that is harder than those in other areas. This corresponds to the f_0 distribution map (Fig. 3), which shows that the north-central-east area has a high f_0 anomaly, indicating that the area has a thin sediment layer. The thickness of the soft sediment layer in this area was estimated to be no greater than 30 m. The west-central-south area shows a relatively low-moderate anomaly ($V_s < 1000$ m/s), indicating a relatively thick layer of sediment. This is consistent with the results of Zaenudin et al. (2020), who used the gravity method to identify groundwater basins. The results show that the south-central-west regions have low-to-moderate V_s . These values correlate with the presence of groundwater basins, corresponding to a low residual Bouguer anomaly from a previous study. The zero-value contour of the residual SVD Bouguer anomaly indicates the groundwater basin boundary. From this correlation, it is clear that the low V_s in the area is related to the presence of fluids filling the soil layers; in this case, it is related to the groundwater in the basin.

5.4. V_s Cross section

The data processing results showed patterns of V_s that could be interpreted as potential fault-plane boundaries. Three potential fault plane boundaries were successfully interpreted in cross sections A–A' and B–B' (Fig. 8). These fault planes were estimated to be part of the sinistral strike-slip fault of the Lampung-Panjang segment. There is potential for vertical displacement based on the pattern of shear wave velocities greater than 1000 m/s. Whether this indication can be interpreted as oblique movement accompanying a strike-slip fault requires further comparative data. However, this approach is expected to provide preliminary indications that support previous research on structural alignments based on gravity anomalies and second-vertical derivative residual anomalies in Bandar Lampung (Zaenudin et al., 2020).

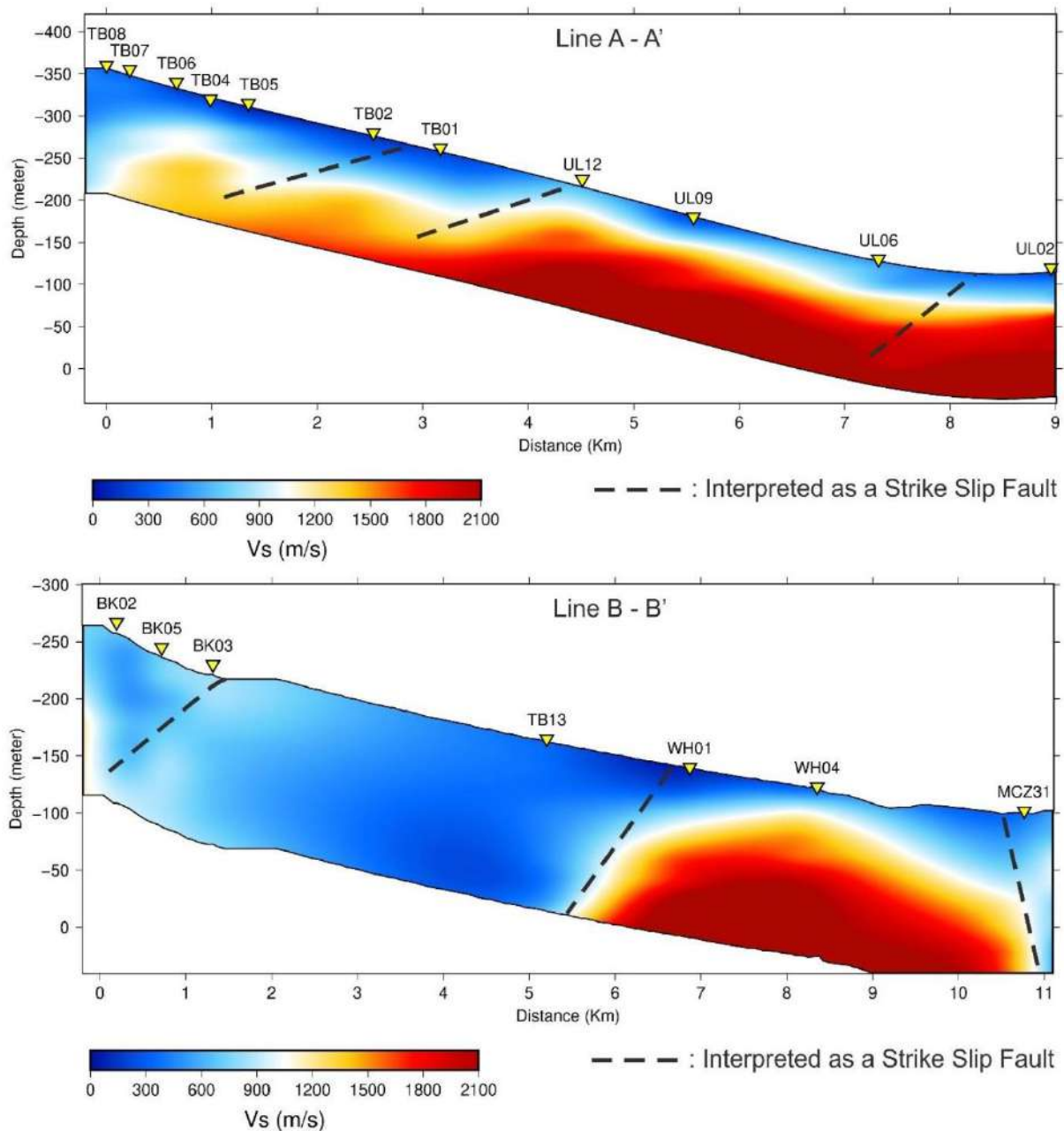


Figure 8. Inverse modeling of cross sections A-A' and B-B', indicating the potential for strike-slip fault structures.

Interesting results were also obtained from cross-sectional models C-C' and D-D', which indicate the potential for strike-slip fault planes, particularly near Lampung Bay. Geologically, this area is a depression located near Paleozoic schist bedrock. Outcrops of this bedrock are influenced by a sinistral strike-slip fault known as the Tarahan fault. The V_s distribution pattern was dominated by velocities of less than 1000 m/s, identified as Lampung Bay surface deposits.

The bedrock is located in deeper areas, with a pattern returning to the surface in the Tarahan area, as shown in cross section C-C' of Fig. 9. The interpretation of the downward movement of the fault zone also supports the geomorphological conditions of the Tarahan area in Lampung Bay. In addition, the results of the gravity measurements indicate a low-anomaly area in this region that can potentially be a groundwater basin zone (Rustadi, et al., 2022; Zaenudin et al., 2020).

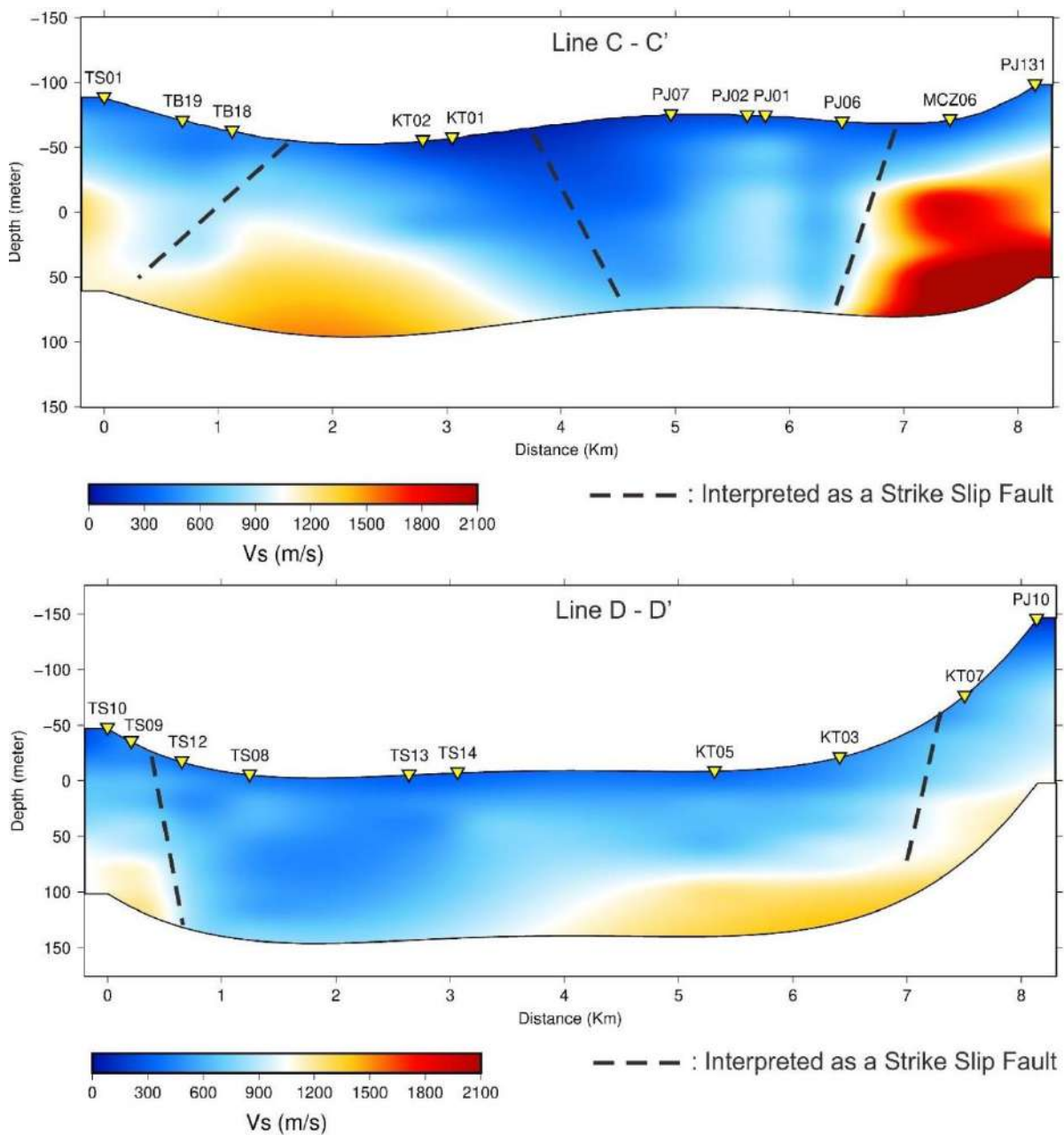


Figure 9. Inverse modeling of cross sections C-C' and D-D', indicating the potential for strike-slip fault structures.

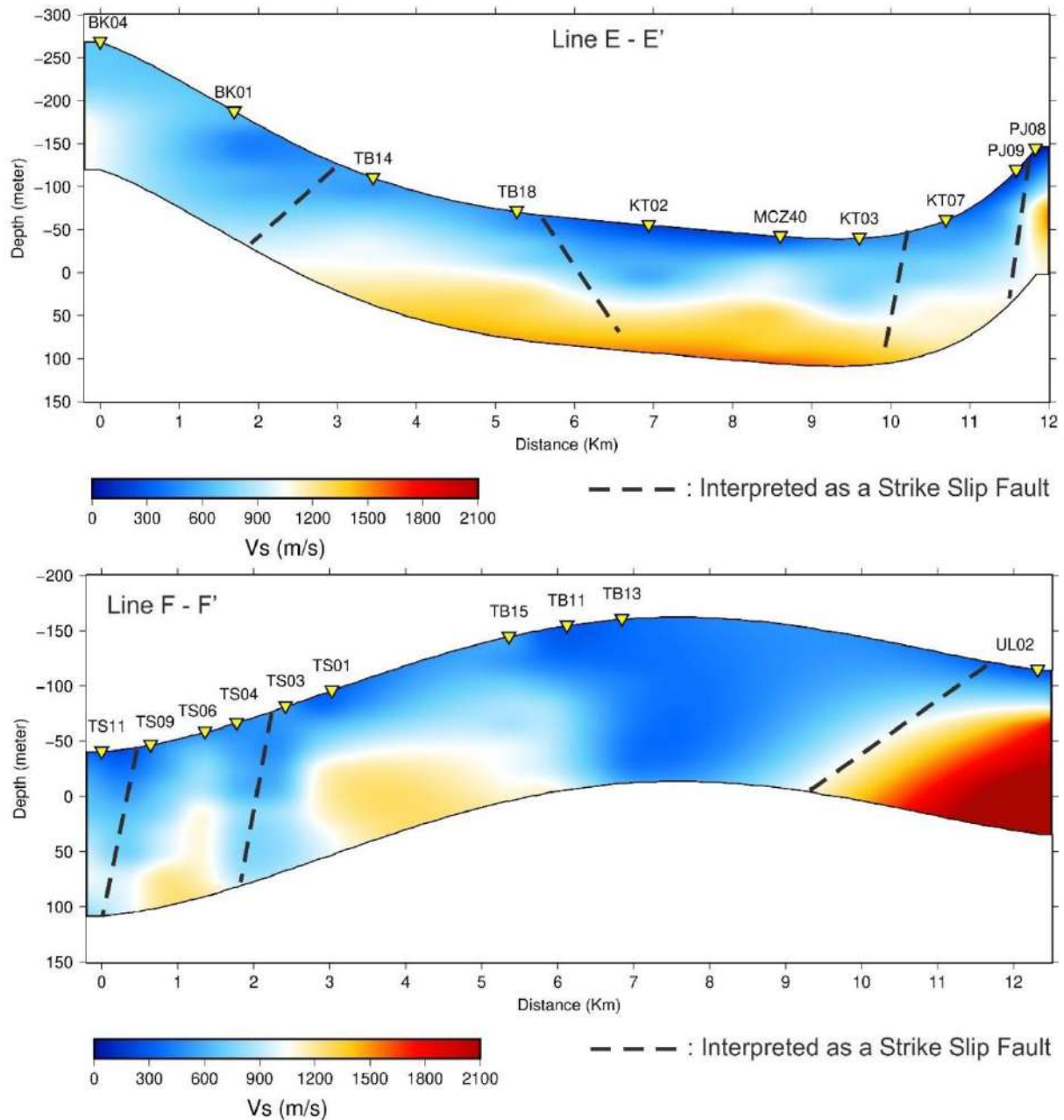


Figure 10. Inverse modeling of cross sections in the northwest-southeast (Line E-E') and south-north directions (Line F-F').

The next modeling was conducted on cross sections E-E' and F-F', intersecting the previous cross sections in the northwest-southeast and south-north directions, respectively (Fig. 10). The shear wave velocity distribution pattern shown in cross section E-E' was consistent with those of cross sections C-C' and D-D'. The potential for strike-slip fault structures was not clearly visible. However, this can still be seen from the pattern shown by velocities above 1000 m/s.

In addition, a potential strike-slip fault pattern indicating vertical movement in the Tarahan fault area was identified at the right end of cross section E-E'. These velocity patterns were also confirmed from cross sections C-C' and D-D'. Moreover, the shear wave velocity model in cross sections F-F' showed a pattern that was consistent with cross sections A-A' and B-B'. The consistency between the shear wave velocity model and previous gravity research results strengthens the interpretation of fault structures. These fault structures limit the potential groundwater basin area in Bandar Lampung (Zaenudin et al., 2020).

6. Conclusions

In this study, the V_s structure in Bandar Lampung City was estimated using microtremor data (natural seismic noise) and the HVSR technique. A total of 83 measurement points were used to detect geological structures and groundwater basins in the southern city, Bandar Lampung. The inversion method used in this study was PSO. This algorithm was selected because it is a global approach that avoids being trapped in a minimum local solution and is relatively fast and stable. In this regard, the V_s structures obtained from the inversion of the HVSR curve are displayed in the two-dimensional (2D) model both laterally and vertically (cross section). Based on the inversion result that has been conducted, the profile of the average V_s curve, with respect to depth, shows the value of V_s , which increases with increasing depth. At shallow depths (0–5 m), it had an extremely low velocity of less than 330 m/s, indicating that it was composed of soft layers (weathered layers). Hard rock layers ($V_s > 1250$ m/s) were visible at depths of > 100 m. Based on the lateral 2D model, Bandar Lampung City was divided into two rocky zones in the direction of the boundary trending NW-SE. The north-central-eastern part has a higher V_s anomaly, ranging from 30 to 100 m deep. The V_s velocity reached more than 2000 m/s, indicating that the area was dominated by hard rock and thin layers of soft sediment. This is suitable for the dominant frequency anomaly map, which shows that the

north-central-eastern region has a high dominant frequency anomaly. This high dominant frequency indicated that the area had a thin layer of sediment. On the south-central-west side, it had a ¹⁰ low dominant frequency, which indicates the presence of a thick layer of sediment. Based on the V_s structure map, this area also has low-to-moderate V_s values. Thus, the south-central-west region is a groundwater basin with a sediment layer thickness > 100 m. These results agree with those of previous studies of groundwater basins at a depth of 800 m. In addition, the V_s structure map shows clear fault structures both laterally and vertically. This was indicated by the difference in contrast between anomalies, both from low-to-moderate and from moderate-to-high anomalies. This fault structure is more clearly observed in the vertical section, where the Bandar Lampung area has a complex fault structure, and many faults are scattered throughout the city. This study provides a clear model description for delineating fault structures, groundwater basin structures, the thickness of weathered layers near the surface, and the characterization of ³ site dynamic parameters, which are needed in seismic hazard and risk reduction studies in urban areas ³ and rapid land use planning. However, more intensive measurements are recommended to obtain better seismic microzonation results.

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