Microtremor HVSR Inversion for Delineating Weathered Granite Layers: A Case Study from Granit Indah, Lampung

Ahmad Zaenudin[1*], Yayan M. Husni[1], Rustadi[1], Rahmat C. Wibowo[1], Alhada Farduwin[2]

[1]*Geophysical Engineering, University of Lampung, Jl. Sumatri Brojonegoro No. 1, Bandar Lampung 35145 Lampung, Indonesia*
[2] *Geophysical Engineering, Sumatera Institut of Technology, Jl. Terusan Ryacudu, Lampung Selatan 35365 Lampung, Indonesia*

Received: 21 October 2025

Accepted: 9 December 2025

***Correspondent Email:**
ahmad.zaenudin@eng.unila.ac.id

Abstract: The Horizontal-to-Vertical Spectral Ratio (HVSR) method is an efficient and non-invasive approach for estimating subsurface layer thickness and delineating near-surface geological structures. This study employs HVSRPy, an open-source Python-based tool, to characterize the subsurface stratigraphy of the Granit Indah area in Lampung. Microtremor data were collected at 24 stations using three-component sensors with 30-minute acquisition durations. Processing involved window selection, Fourier transformation, and HVSR curve computation. Dominant frequencies ranging from 0.2 to 5.3 Hz indicate the presence of thick near-surface deposits. Inversion using Dinver resolves three principal layers—topsoil, weathered saprolite, and unweathered granite—with shear-wave velocities of 200–600 m/s. The subsurface model shows strong agreement with Wenner–Alpha resistivity measurements, supporting its reliability. The results demonstrate that HVSRPy provides a robust, time-efficient, and cost-effective workflow for subsurface characterization in regions with limited geophysical data.

Keywords: *HVSR; Microtremor; HVSRPy; Shear-Wave Velocity; Inversion*

1. INTRODUCTION

The Horizontal to Vertical Spectral Ratio (HVSR) method is widely regarded as a rapid and reliable technique for estimating the natural frequency of a site (f_0). Numerous studies have demonstrated that, in the presence of strong impedance contrasts, the HVSR peak frequency (f_0, HVSR) shows a strong correlation with the site's fundamental resonance frequency (f_0, site) (Lachet & Bard, 1994; Lermo & Chávez-García, 1993; Zaenudin et.al, 2024; Zaenudin et.al, 2025). The HVSR approach was first introduced by Nogoshi and Igarashi (1971) and later popularized by Nakamura (1989). Its extensive application in site effect and subsurface investigations is largely attributed to its operational simplicity, both in field data acquisition and signal processing.

Field data acquisition was conducted by deploying a three-component sensor (Raspberry seismograph) directly on the ground to record ambient vibrations generated from subsurface sources over a fixed duration of 30 minutes per station.

The data processing workflow began with segmenting the continuous recordings into shorter time windows to suppress noise and isolate stable microtremor signals. The window length was set between 15 and 50 s, the longer windows were applied at sites with lower fundamental frequencies (f_0, site), as recommended by SESAME (2004). For each window, the two horizontal components were combined into a single resultant horizontal component prior to spectral analysis. All three components were then transformed from the time domain to the frequency domain using the Fourier transform. The HVSR curve was subsequently generated by computing the spectral amplitude ratio between the horizontal and vertical components. The entire processing was implemented using Python based coding through the open source package HVSRPy (Vantassel, 2025).

This study utilizes the HVSRPy package to perform Horizontal to Vertical Spectral Ratio analysis for determining the fundamental frequency (f_0) and peak amplitude (A_0) of the HVSR curve. The resulting HVSR curves are subsequently used as input for shear-wave velocity (V_s) inversion to model the subsurface velocity structure and delineate stratigraphic layering within the study area.

2. MATERIALS AND METHODS

2.1. HVSR Curves

The dataset used in this study was collected through direct field measurements at 24 observation points located in the Granit Indah area, Bandar Lampung City, Lampung Province. Each station recorded ambient vibrations continuously for 30 minutes using a three-component sensor, capturing ground motion in the vertical (Z) direction and two orthogonal horizontal directions, North–South (NS) and East–West (EW).

Data processing was performed using Python-based source code implemented in the HVSRPy software, with the analysis performed over a frequency range of 0.2–20 Hz and window lengths varying between 10 and 50 s. Following the SESAME (2004) recommendations, the window length should not be shorter than ten times the fundamental period $\frac{1}{f_0}$. To ensure statistical reliability in f_0 estimation, the total recording duration should cover at least 40–60 times the selected window length. The continuous signals were segmented using a Tukey window taper to minimize spectral leakage and suppress noise-induced artifacts at the measurement sites. Subsequently, a bandpass Butterworth filter was applied, with adjustable lower and upper cutoff frequencies, to remove unwanted frequency components and enhance signal quality to HVSR computation.

Butterworth bandpass filtering is not mandatory when the acquired microtremor signals exhibit high signal to noise ratios and stable spectral characteristics. High quality recordings with minimal transient disturbances, cultural noise, or instrumental interference typically preserve their spectral integrity, allowing HVSR computation to be performed without additional frequency filtering. However, in practical field measurements, low-frequency noise from wind, traffic, or anthropogenic activities, as well as high frequency artifacts from sensor coupling or electrical interference, may be present. In such cases, the application of a bandpass filter helps to suppress unwanted frequency components while retaining the primary spectral content required for accurate HVSR analysis. Therefore, the decision to apply filtering was determined through preliminary data quality inspection to ensure that the processing steps enhanced signal clarity without distorting the fundamental resonance peaks.

The number of windows retained for analysis depended on the stability criteria. The resulting HVSR curves were then visualized based on all selected windows. Although individual HVSR curves may exhibit considerable variability across different window lengths, the median HVSR curve and its confidence interval remain relatively stable and show no significant deviation (Cox et al., 2020). This indicates that, despite variations at the single-window level, the median H/V spectrum provides a robust and reliable representation of the site's dominant resonance behavior.

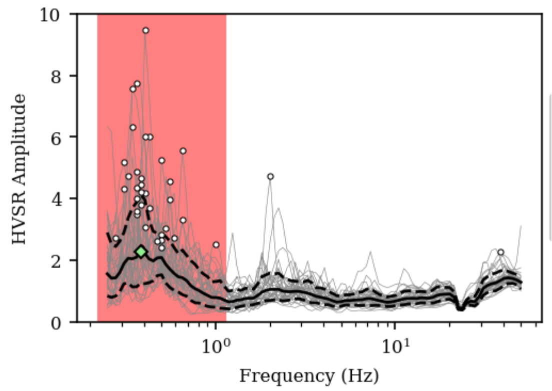

Figure 1. H/V curves generated from HVSRPy processing

The HVSR results were considered reliable when the derived H/V curves satisfied the assessment criteria defined in the SESAME (2004) guidelines. These criteria ensure that the analysis is based on stable and trustworthy spectral peaks, enabling the outcomes to be confidently used in subsequent interpretation and modeling stages. The reliability conditions applied in this study are outlined as follows:

$$f_0 > {}^{10}/_{l_w} \quad (1)$$

$$n_c(f_0) > 200 \quad (2)$$

$$\sigma_A(f) < 2, for\ 0.5f_0 < f < 2f_0, if\ f_0 < 0.5\ Hz \quad (3)$$

$$\sigma_A(f) > 2, for\ 0.5f_0 < f < 2f_0, if\ f_0 < 0.5\ Hz \quad (4)$$

where f_0 is the peak frequency of the H/V curve, l_w is the window length, $n_c = l_w \times n_w \times f_0$ represents the number of significant cycles, n_w is the number of selected windows, and σ_A is the standard deviation.

According to SESAME (2004), HVSR curve patterns can theoretically be classified into three main types. The first type is a single peak HVSR curve, which indicates a clear impedance contrast at a certain depth, resulting in significant wave amplification. The second type is a double-peak HVSR curve, commonly associated with layered geological conditions, where unconsolidated sediments occur near the surface, underlain by more compact sediment layers, and further bounded by a significantly stiffer bedrock. The third type is a broad peak HVSR curve, which is typically linked to basin effects or sloping bedrock topography.

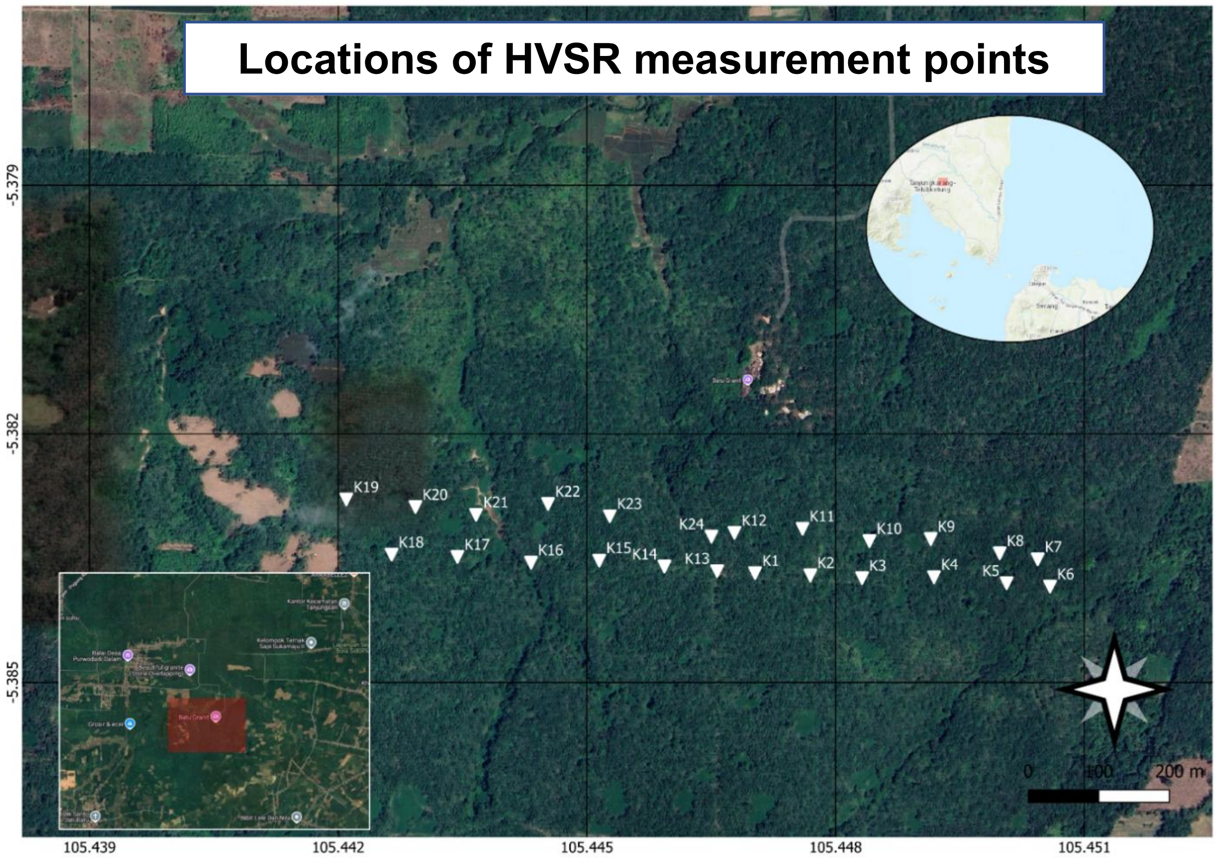

Figure 2. Map of Measurement Locations (Inverted white triangles indicate the coordinates of the HVSR measurement points

2.2 HVSR Curves Inversion

Characterizing local geological conditions using the Horizontal to Vertical Spectral Ratio method requires an understanding of the subsurface parameters that control the dominant frequency and amplification behavior at a site. The HVSR curves obtained from the earlier processing using the HVSRPy source code were subsequently inverted with the Dinver software to derive the shear-wave velocity (V_s) structure of the subsurface.

Dinver operates on the assumption of a homogeneous viscoelastic medium. The HVSR curve is influenced by six key parameters V_s, V_p, Q_s, Q_p, layer thickness (h), and density (ρ). Among these, V_s is recognized as the most significant parameter affecting the shape of the HVSR curve (Sungkowo, 2008) Dinver functions by comparing theoretical HVSR curves with field measured HVSR curves (observed HVSR). Adjusting the aforementioned parameters results in corresponding variations in the theoretical curve. Through iterative optimization, Dinver identifies the theoretical HVSR curve that best matches the observed data, characterized by the minimum misfit between both curves.

3. Results and Discussions

3.1 Analysis of Dominant Frequency

Dominant frequency is an important parameter closely associated with the local geological conditions of a site. This parameter reflects the characteristics of the subsurface layering, where lower dominant frequency values indicate a thicker subsurface profile, while higher dominant frequency values correspond to thinner near-surface layers (Kanai, 1983)

Based on the processed field data, the dominant frequencies obtained at each measurement point are relatively low, ranging from 0.2 to 5.3 Hz (Figure 5). This limited variation is likely due to the close spacing between stations, resulting in minimal differences in dominant frequency values across the survey area. Low dominant frequencies are typically associated with a relatively thick subsurface layer underlying the measurement sites.

These dominant frequency characteristics provide an initial indication of the subsurface conditions across the study area. To gain a more comprehensive understanding of the site response and stratigraphic configuration, further analysis was conducted by examining the amplification behavior of the HVSR curves and interpreting the spatial distribution of both f_0 values and their corresponding peak amplitudes. This integrated approach helps refine the assessment of subsurface layering and supports the subsequent inversion and geological interpretation stages.

3.2 Analysis of Dominant Amplitude

Based on theoretical considerations, dominant amplitude values are associated with local amplification effects resulting from impedance contrasts between sediment layers and the underlying bedrock. A higher A_0 value indicates stronger amplification and, consequently, greater seismic vulnerability. The processed data show a range of dominant amplitude values, classified into five categories: 2.1–4.1, 4.1–6.1, 6.1–8.1, 8.1–10.1, and 10.1–12.1 (Figure 5), with most measurement points exhibiting A_0 values greater than 4. This suggests significant amplification, indicating the presence of soft surface soil and a relatively thick subsurface sedimentary sequence.

These amplitude characteristics, when interpreted together with the dominant frequency results, provide a clearer understanding of the local site response and the underlying geological structure. The consistent presence of high A_0 values across the study area reinforces the indication of soft near surface materials and considerable sediment thickness. To further validate these observations, the spatial distribution of A_0 and f_0 was compared with the subsurface velocity profiles derived from HVSR inversion. This integrated analysis enables a more robust interpretation of the stratigraphic layering and offers insights into the mechanical behavior of the subsurface materials, particularly their potential influence on seismic wave amplification.

3.3 Inversion of HVSR Curves

The HVSR curves obtained from the previous processing using the HVSRPy source code were subsequently used for shear wave velocity (V_s) modeling through inversion with the Dinver software. The analysis was performed by matching the observed HVSR curves with theoretical HVSR curves computed from an initial shear-wave velocity model. This iterative procedure aims to identify the model that provides the best fit between the observed and theoretical responses.

The comparison between the theoretical curves generated from the initial V_s model and the observed HVSR curves is then visualized to assess the degree of agreement between them. This measure of agreement, commonly referred to as the misfit, indicates how closely the theoretical response replicates the observed data.

A lower misfit value reflects a better correspondence between the theoretical and observed curves, indicating that the proposed subsurface velocity structure closely represents the actual geological conditions. During the inversion process, multiple models are evaluated, and the one with the smallest misfit is considered the most reliable representation of the site's shear wave velocity profile. This optimal model is then used to infer the subsurface layering, including the identification of contrasts between soft sediments, weathered materials, and bedrock.

The shear-wave velocity (V_s) profiles derived from the HVSR curve inversion provide insight into the subsurface stratigraphic structure at the measurement locations. These profiles reveal variations in material properties with depth and allow for the identification of distinct geological layers underlying the study area.

Based on the inversion results of the HVSR curves using a three-layer initial model, three subsurface layers were identified, each exhibiting varying shear wave velocity (V_s) values. Overall, the velocity ranges from approximately 200 m/s to 600 m/s across the different layers.

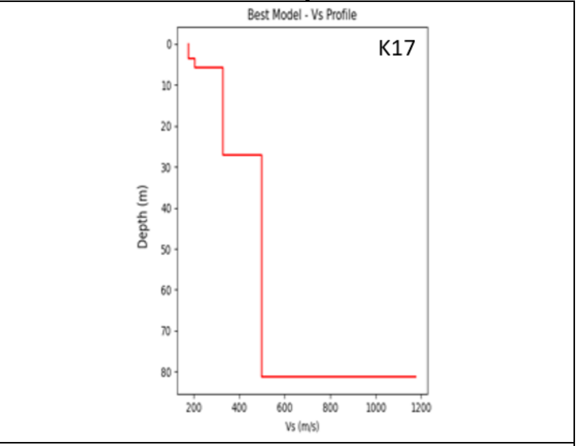

Figure 3. Shear-wave velocity profile for station K17

Interpretation of the inverted V_s profiles suggests that the first layer, characterized by low shear wave velocities, corresponds to the near-surface soil composed of relatively soft, unconsolidated materials. The second layer exhibits moderate V_s values, indicating the presence of saprolite, a partially weathered material that retains the structural fabric of the parent rock. The third layer, which shows significantly higher V_s values, represents the unweathered granite bedrock underlying the study area. This three-layer configuration is consistent with the regional geological setting and supports the interpretation of a thick sedimentary cover overlying competent crystalline basement rock.

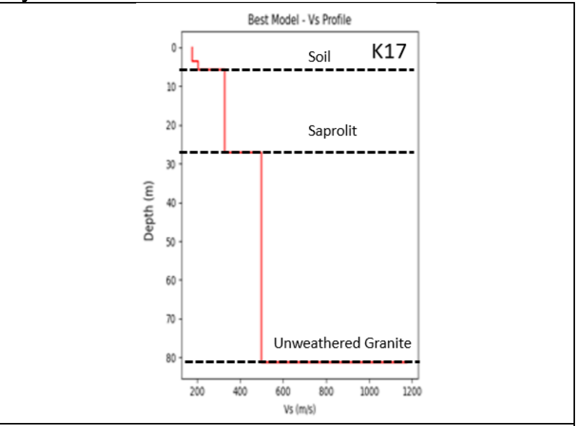

Figure 4. Interpretation of subsurface layers from the V_s profile at station K17

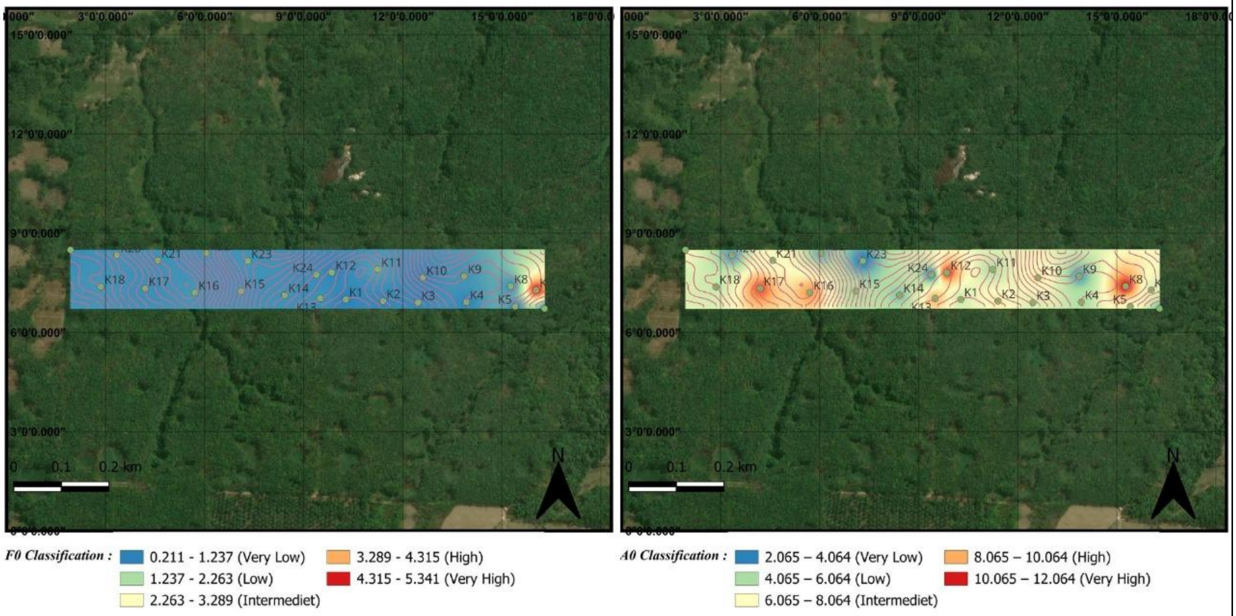

Figure 5. a Map of amplification factor values (A0) and dominant frequency (f0)

In addition, the shear-wave velocity (V_s) inversion results at certain locations indicate the presence of a two layer subsurface structure.

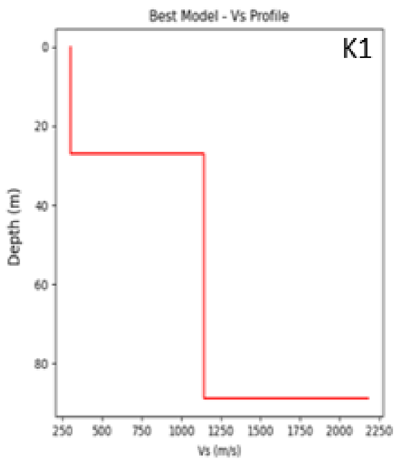

Figure 6. Shear-wave velocity profile for station K1

Interpretation of the two-layer V_s profiles indicates that the first layer corresponds to saprolite, representing an advanced weathering product of the granite bedrock. This layer is characterized by moderate shear-wave velocities and retains partial structural features of the parent rock. The second layer is interpreted as unweathered granite, a competent crystalline bedrock unit that has not undergone significant weathering. This lower layer exhibits substantially higher V_s values, ranging from approximately 1000 to 1250 m/s, reflecting its dense and intact geological nature. The presence of this simplified two-layer configuration suggests that in certain locations the weathered zone is relatively thin, enabling the inversion process to clearly delineate the boundary between the saprolite and the underlying unweathered granite.

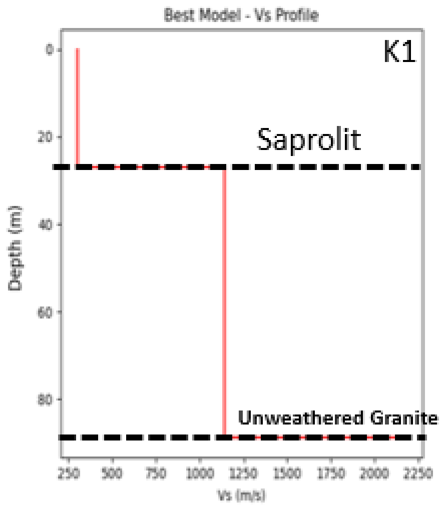

Figure 7. Interpretation of subsurface layers from the V_s profile at station K1

These results are consistent with the findings from the electrical resistivity data processed using the Wenner–Alpha configuration in the same area as the HVSR measurement locations.

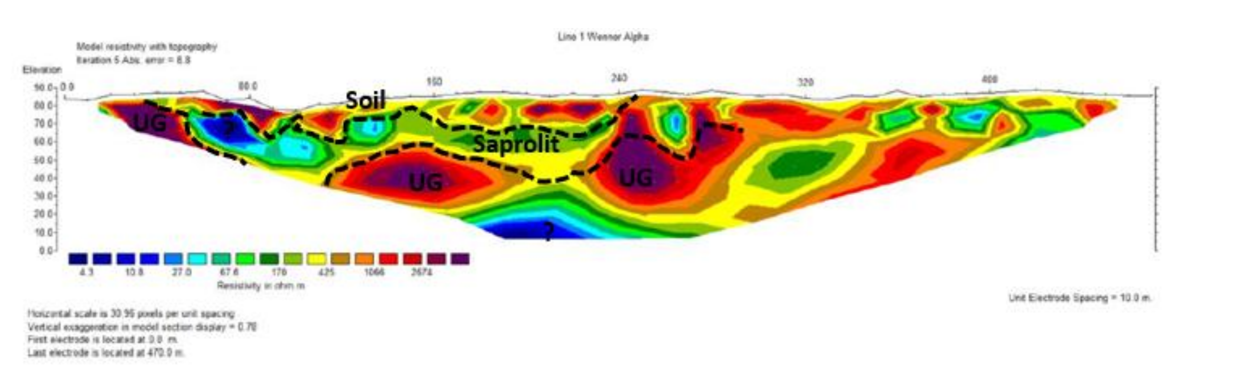

Figure 8. Vertical resistivity section for the area corresponding to the HVSR measurement sites

The electrical resistivity results support the HVSR-based interpretation by revealing subsurface layers with resistivity values ranging from 27.0 Ωm to 2674 Ωm, forming two and three-layer configurations that closely correspond to the V_s profiles. These resistivity variations delineate a near surface soil layer characterized by low resistivity, an intermediate saprolite layer with moderate resistivity, and a highly resistive unweathered granite (UG) bedrock. The strong correspondence between the resistivity structure and the shear-wave velocity model reinforces the reliability of the interpreted stratigraphy. This agreement across independent geophysical methods HVSR and electrical resistivity demonstrates robust identification of soft soil, weathered material, and crystalline bedrock, thereby enhancing confidence in the geological and site-response characterization of the area.

4. CONCLUSIONS

The Horizontal to Vertical Spectral Ratio (HVSR) method, implemented using the HVSRPy source code, proved effective for generating H/V spectral ratio curves, which were subsequently inverted using the Dinver software.

The HVSR curves reveal relatively low dominant frequency values at all measurement points, ranging from 0.2 to 5.3 Hz, with most values falling below 0.5 Hz. Such low dominant frequencies indicate the presence of thick subsurface layers beneath the measurement sites. The inversion of these HVSR curves produced a three-layer subsurface model consisting of soil, saprolite, and unweathered granite (UG). These results show strong agreement with the Wenner Alpha electrical resistivity data acquired from the same measurement locations.

Overall, the HVSR method, when implemented using the HVSRPy source code, demonstrates a reliable capability for estimating subsurface layer thickness and delineating near surface geological structures.

ACKNOWLEDGMENTS

This research was supported by LPPM University of Lampung, with Contract Number: 2052/UN26.21/PN/2025.

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