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SITE EFFECTS IDENTIFICATION USING HVSR METHOD IN CISARUA HOT SPRING AREA, NATAR, SOUTH LAMPUNG

IDENTIFIKASI EFEK TAPAK MENGGUNAKAN METODE HVSR DI KAWASAN PEMANDIAN AIR PANAS CISARUA, NATAR, LAMPUNG SELATAN

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Abstract. Cisarua, which contains a geothermal hot spring, is an intriguing area to investigate due to its location far from any known heat source or volcanic activity. Using the HVSR technique, this study aims to characterize the local site effects based on key parameters: natural frequency (fo), amplification factor (Ao), and average shear-wave velocity down to 30 meters depth (Vs30). Microtremor measurements were conducted at 25 locations across the Cisarua hot spring area, with an average spacing of 300 meters. Each site was recorded for 40–50 minutes, and the data were processed using Geopsy software to extract the HVSR curves, along with the fo and Ao values. The HVSR curves were then inverted using the Particle Swarm Optimization (PSO) algorithm to derive Vs30 values. The results show that fo values range from 0.6 to 1.1 Hz, and Vs30 values are generally below 175 m/s. These two parameters exhibit minimal spatial variation, indicating the presence of thick, soft, and relatively homogeneous sedimentary layers across most of the study area. The Ao values range from 2 to 5, with values below 3 dominating near the geothermal manifestation zone. The spatial distribution of fo and Ao reveals a northwest–southeast trend, which is strongly correlated with the presence of the Lampung–Panjang Fault that likely controls sediment accumulation and layer thickness in the area. Around point T13, Vs30 drops to 125–150 m/s, suggesting localized softening of the soil due to hydrothermal alteration processes. These findings emphasize the interplay between site effects, regional geological structures, and geothermal activity in shaping the dynamic properties of the subsurface in this area.

Abstrak. *Cisarua, yang berisi mata air panas bumi, adalah daerah yang menarik untuk diselidiki karena lokasinya jauh dari sumber panas atau aktivitas vulkanik yang diketahui. Dengan menggunakan teknik HVSR, penelitian ini bertujuan untuk mengkarakterisasi efek lokasi lokal* *berdasarkan parameter utama: frekuensi alami (fo), faktor amplifikasi (Ao), dan kecepatan gelombang geser rata-rata hingga kedalaman 30 meter (Vs30). Pengukuran mikrotremor dilakukan di 25 lokasi di seluruh area mata air panas Cisarua, dengan jarak rata-rata 300 meter. Setiap lokasi direkam selama 40–50 menit, dan data diproses menggunakan perangkat lunak Geopsy untuk mengekstrak kurva HVSR, beserta nilai fo dan Ao. Kurva HVSR kemudian dibalik menggunakan algoritma Particle Swarm Optimization (PSO) untuk mendapatkan nilai Vs30. Hasilnya menunjukkan bahwa nilai fo berkisar antara 0,6 hingga 1,1 Hz, dan nilai Vs30 umumnya di bawah 175 m/s. Kedua parameter ini menunjukkan variasi spasial minimal, yang menunjukkan keberadaan lapisan sedimen tebal, lunak, dan relatif homogen di sebagian besar wilayah studi. Nilai Ao berkisar antara 2 hingga 5, dengan nilai di bawah 3 mendominasi di dekat zona manifestasi panas bumi. Distribusi spasial fo dan Ao menunjukkan tren barat laut-tenggara, yang sangat berkorelasi dengan keberadaan Sesar Lampung-Panjang yang kemungkinan mengendalikan akumulasi sedimen dan ketebalan lapisan di wilayah tersebut. Di sekitar titik T13, Vs30 turun menjadi 125–150 m/s, yang menunjukkan pelunakan tanah lokal akibat proses alterasi hidrotermal. Temuan ini menekankan interaksi antara efek tapak, struktur geologi regional, dan aktivitas panas bumi dalam membentuk sifat dinamis bawah permukaan di wilayah ini.*

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1. INTRODUCTION

Site effects are defined as local modifications of seismic wave characteristics caused by near-surface geological conditions, particularly the contrast in seismic impedance between soil layers and bedrock. These effects play a critical role in seismic hazard assessment, as they can significantly amplify ground motion during an earthquake. As such, understanding site effects is essential in studies related to local seismic response, especially in areas with complex subsurface conditions.

Lampung province possesses significant geothermal potential, supported by its complex geological systems, including numerous faults and a volcanic arc that forms part of the Mediterranean Circum-Pacific Belt. One of the major faults in this province is the Lampung-Panjang Fault, which extends through the provincial capital in a northwest–southeast direction. This fault is classified as a normal fault and plays a roe in the formation of the Tertiary sedimentary basin, with movements dominated by vertical displacement (Suharno et al., 2012). According to the study conducted by Juliarka and Iqbal (2020), the Cisarua hot spring in Natar is of particular interest due to its speculative geothermal potential of 25 MWe. This condition highlights the need for geophysical investigations to better understand the geothermal systems in the region.

The hot spring phenomenon in Cisarua, Natar, South Lampung, is notable because of its location far from active volcanic zones. The presence of hot springs in this non-volcanic area raises questions about the geological conditions and subsurface characteristics that facilitate geothermal activity. Therefore, understanding the subsurface structure and soil properties is crucial for identifying the mechanisms of heat transport and the hidden geothermal resource potential. A relevant geophysical approach to obtaining such information is the analysis of site effects—local ground response to seismic waves—which can provide insights into the dynamic properties of the subsurface in this area.

In this study, site effects are estimated using the Horizontal to Vertical Spectral Ratio (HVSR) method based on microtremor data. This method is a passive seismic technique that has been widely developed for studying soil characteristics, particularly for identifying site effects through the analysis of natural frequency (f_0), amplification (A_0), seismic vulnerability index (Kg), and shear-wave velocity (Vs) modeling (Ariyanto et al., 2024; Pinem et al., 2024; Rubaiyn et al., 2023). Moreover, by applying inversion techniques to the HVSR curves, subsurface shear wave velocity (Vs) models can be obtained (Maghami et al., 2021; Nelson & McBride, 2019; Trichandi et al., 2023; Zaenudin et al., 2022, 2024). The HVSR method was selected due to several advantages, such as ease of implementation, relatively short measurement time, low cost, and its non-destructive nature. These benefits make HVSR particularly suitable for application in hard-to-reach areas or where invasive geophysical surveys are not feasible. HVSR has proven effective in identifying natural frequency, amplification, and estimating average shear wave velocity to a depth of 30 meters (Vs_{30}), which is a key parameter in geotechnical and local seismic studies (Barber & Crow, 2005; Zaenudin et al., 2024).

A previous study by Karyanto et al. (2024) demonstrated that microtremor data processed using the HVSR technique could be employed to characterize near-surface geological features in the Way Ratai geothermal area. This illustrates the potential of HVSR for producing representative subsurface velocity models under various geological conditions. To obtain an accurate shear wave velocity profile, a reliable inversion technique is required. One such inversion method that has been developed uses the Particle Swarm Optimization (PSO) algorithm, as proposed by Zaenudin et al. (2022). This algorithm offers several advantages, including fast convergence, ease of application across various geophysical methods, robustness against noise, and a global search approach that avoids getting trapped in local minima (Farduwin & Yudistira, 2021; Laby et al., 2016; Putri et al., 2023; Zaenudin et al., 2022). Based on the aforementioned background, this study aims to estimate site effects in the Cisarua hot spring area using the HVSR method, and to determine key parameters such as natural frequency, amplification, and Vs_{30} as preliminary indicators of the dynamic characteristics of the soil. However, these parameters require further validation through independent geophysical or geotechnical methods to ensure their accuracy and reliability.

2. LITERATURE REVIEW

2.1. Regional Geology

Regionally, the study area is located in southern Sumatra, specifically in Natar District, South Lampung Regency. According to the Geological Map of the Tanjungkarang Sheet (Mangga et al., 1993), this region lies within an active tectonic zone influenced by the dynamics of the Great Sumatran Fault (GSF). The GSF is a major strike-slip fault system extending from the northern to the southern end of Sumatra Island, trending northwest–southeast. In the southern part of the island, the GSF branches into several local fault segments, including the Lampung–Panjang Fault, which is believed to play a significant role in controlling the geothermal system around Natar and its surroundings. The lithological units in this region range from older to younger formations, including:

a. Trimulyo Marble (Pzgm), a metamorphic basement unit of Paleozoic age.
b. Branti Granodiorite (Kgdb), a Cretaceous-aged intrusive body.
c. Lampung Formation (QTl), a pyroclastic and volcaniclastic sequence that is widely distributed and acts as the primary host rock of the geothermal system.
d. Young Volcanic Deposits (Qhpv) derived from Quaternary volcanic activity of Mount Betung.

In the context of geothermal systems, the Lampung Formation (**Figure 1**) is particularly important due to its composition of tuff, tuffaceous sandstone, and pumice-rich tuff, which are permeable and may act as conduits for hydrothermal fluid flow.

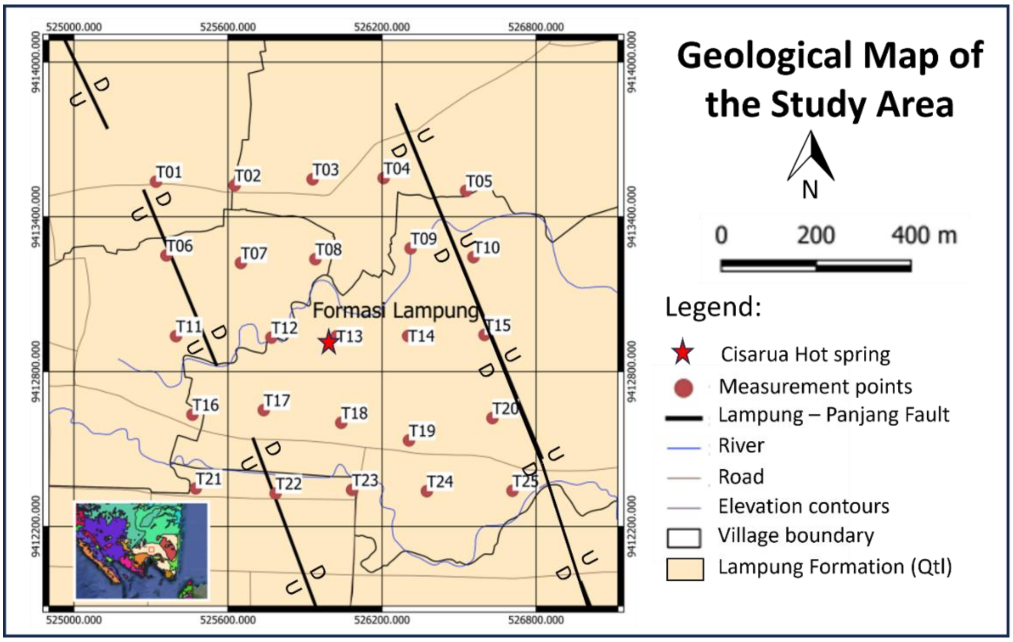

Figure 1. Geological map of the study area (modified from Mangga et al., 1993), showing HVSR measurement points (red dots), the Lampung–Panjang Fault (black lines), and the Cisarua hot spring (red star). The base map includes rivers (blue), roads (thin black lines), elevation contours (brown), and the Lampung Formation (Qtl) in beige.

The geophysical modeling results from Juliarka and Iqbal (2020) support this regional geological interpretation. Their gravity survey identified several normal faults trending northwest–southeast and north–south, consistent with the orientation of the GSF. These structures form a horst and graben system, which serves as a preferential pathway for geothermal fluid migration from the reservoir to the surface. Gravity anomaly analysis revealed a low-density depression in the vicinity of the hot spring manifestation, interpreted as a graben structure. This area is characterized by a shallow zone with low rock density (ρ = 1.9 g/cm^3) associated with the Lampung Formation, underlain by higher-density basement rocks such as granodiorite and metamorphic units with densities of 2.54 and 2.76 g/cm^3, respectively. The correlation between Bouguer anomaly patterns, fault geometry, and the location of geothermal manifestations confirms that the geothermal system in the Natar area—including the Cisarua hot spring—is structurally controlled by an active extensional tectonic regime. These fault structures are directly related to the regional fault network and serve as major conduits for upward migration of geothermal fluids from depth.

2.2. Natural frequency (fo)

The natural frequency of the soil, denoted as f_0, is the frequency at which seismic waves experience maximum resonance due to reflections between soft sedimentary layers and the underlying bedrock. This phenomenon occurs when waves interfere constructively, producing a sharp peak in the HVSR spectrum. This peak reflects local seismic conditions and is commonly used as an indicator of the depth to the sediment–bedrock interface (Lachet & Bard, 1994). The relationship between f_0 and the thickness of the sediment layer (h) can be approximated by the following empirical formula:

$$f_0 \approx \frac{V_s}{4h} \quad (1)$$

where Vs is the shear wave velocity of the soil layer. Therefore, the value of f_0 strongly depends on the thickness and stiffness of the surface soil. A low f_0 typically indicates the presence of thick or soft sediments, while a high f_0 suggests thin sediments or stiffer materials. Measuring f_0 is crucial as it can be used to detect subsurface structures such as buried tectonic valleys, calderas, or fault zones, and to assess the potential for resonance with building structures (Nakamura, 1989; Konno & Ohmachi, 1998).

2.3. Amplification (A_o)

Amplification in the context of site effects refers to the increase in seismic wave amplitude when waves propagate through soft surface soils compared to the underlying bedrock. This increase occurs due to strong impedance contrast, causing seismic energy to accumulate in the upper layers, leading to higher ground acceleration (Field & Jacob, 1995). In an HVSR curve, amplification is shown by the height of the spectral peak at the dominant frequency. The spectral ratio of horizontal to vertical components at f_0 often serves as a direct indicator of amplification level. Typically, HVSR values greater than 2 suggest significant amplification, which can be hazardous for buildings whose natural frequencies are close to the soil's f_0. This amplification is part of the broader site effect phenomenon, a major factor causing varying damage intensities in adjacent areas during earthquakes. Therefore, mapping zones with high amplification potential is vital for urban planning and seismic risk mitigation (SESAME, 2004; Kawase et al., 2018).

2.4. Velocity of Vs_{30}

Vs_{30} refers to the average shear wave velocity within the uppermost 30 meters of the subsurface. This parameter has become a global standard for soil classification and seismic site response analysis. It is used in classification systems such as NEHRP (National Earthquake Hazards Reduction Program) and Eurocode 8 (European Commitee for Standardization, 2004) and plays a key role in determining seismic design spectra for buildings. Mathematically, Vs_{30} is calculated using the following equation:

$$Vs_{30} = \frac{30}{\sum_{i=1}^{n} \frac{h_i}{Vs_i}} \quad (2)$$

where h_i and Vs_i are the thickness and shear wave velocity of the *i*-th layer, respectively, up to a total depth of 30 meters. Vs_{30} can be estimated from HVSR data by inverting the spectral curve. This approach has been widely applied in microzonation studies to provide quantitative input for local seismic hazard models (Herak, 2008; Ashayeri et al., 2022).

3. RESEARCH METHODS

This study employed the microtremor method to investigate subsurface conditions based on HVSR curve analysis. Data acquisition was conducted at 25 measurement points across the study area, with an average spacing of 300 meters to adequately capture local geological variations. Each site was recorded for 40–50 minutes with a sampling frequency of 100 Hz, which is considered sufficient to cover the dominant soil frequency range of approximately 0.5 to 20 Hz, typical for microzonation applications.

The acquisition instrument used was the Raspberry Shake 3D Outdoor, a three-component geophone-based seismometer. This instrument was provided by the Geophysics Engineering Laboratory, Sumatera Institute of Technology. To minimize recording disturbances, careful site selection was conducted to avoid anthropogenic noise sources such as vehicle activity, heavy traffic, industrial operations, as well as natural sources such as strong winds or localized vibrations. Measurement points were chosen in relatively quiet areas, far from main roads or zones with intense human activity. Recordings were also carried out during periods expected to have minimal disturbances, such as early mornings.

The data processing stage was performed using Geopsy, a software package specifically designed for passive seismic and HVSR analysis. Raw data from each measurement point underwent a pre-processing phase to ensure signal quality before calculating the HVSR curve. The initial data conditioning steps included:

a. Detrend: This process removes linear trends (slopes) from the signal caused by instrument drift or unstable environmental conditions during recording. It is essential to maintain the stationarity of the signal.
b. Demean: This step removes the mean (average) of the signal to centre it around zero, preventing spectral bias during Fourier transformation.

c. Bandpass Filter (0.5 – 20 Hz): This filter is applied to retain frequency components relevant for microzonation analysis, while removing low-frequency (<0.5 Hz) and high-frequency (>20 Hz) noise that do not carry meaningful site response information but are prone to contamination.

After data conditioning, the HVSR curve was computed for each measurement point. The resulting curve provides key information, including f_0 and A_0. in this process, the spectral analysis of ambient noise data was segmented using a time window of 60 seconds with 50% overlap to ensure statistical robustness while preserving temporal resolution. To suppress transient events and low-amplitude non-stationary signals that could distort the spectral estimate, an anti-trigger algorithm based on the Short-Term Average over Long-Term Average (STA/LTA) method was applied, with STA and LTA set at 1 second and 30 seconds respectively, and an STA/LTA threshold range of 0.5 to 2.5. Following signal conditioning, the HVSR curves were subjected to logarithmic smoothing using the Konno and Ohmachi (1998) filter with a smoothing coefficient of 40. This procedure aims to attenuate high-frequency fluctuations and reduce the influence of spurious peaks and modulations, thereby producing more stable and interpretable spectral ratio curves that accurately represent the site's fundamental resonance characteristics.

In the final stage, after the H/V spectral curves were obtained, an inversion process was carried out using the Particle Swarm Optimization (PSO) algorithm to estimate subsurface model parameters, including shear wave velocity (*Vs*) and layer thickness (*H*) for each layer. The PSO algorithm has been widely applied in geophysical inversion problems and has demonstrated rapid convergence and solution stability. The inversion parameters used in this study follow the configuration proposed by (Farduwin et al., 2021; Farduwin & Yudistira, 2021; Laby et al., 2016; Zaenudin et al., 2022) including the inertia (*w*) and acceleration constants (*cp* and *cq*), which govern particle movement during the optimization process. A five-layer subsurface model was adopted, following previous studies conducted in similar geological settings (Zaenudin et al., 2024). Subsequently, once the shear wave velocity (*Vs*) and layer thickness (*H*) values are obtained, the average shear wave velocity in the upper 30 meters (Vs_{30}) can be calculated using Equation 2.

4. RESULTS AND DISCUSSION

The interpretation of HVSR curves allows for the identification of natural frequency values, which are indicative of sediment thickness and impedance contrasts. Such information is essential for assessing site effects and understanding subsurface conditions. **Figure 2** presents the HVSR curves derived from microtremor measurements at six observation points: T08, T12, T13, T14, T18, and T23. The red curve represents the average H/V spectral ratio, while the two black dashed curves indicate the lower and upper bounds of the standard deviation, reflecting the level of uncertainty associated with the H/V values at each frequency. Spatially, point T13 corresponds to the location of the Cisarua hot spring manifestation, which serves as the central reference point for the measurements. Points T12 and T14 are located approximately 300 meters to the west and east of T13, respectively, while T08 and T18 are positioned at similar distances to the north and south. Point T23 is situated about 600 meters to the south of the hot spring manifestation.

Analysis of the HVSR curves reveals that most of the measurement points exhibit spectral peaks at relatively low natural frequencies (f_0), typically less than 1 Hz (f_0 < 1 Hz), with amplification values (A_0) generally exceeding 2. These low natural frequency values suggest the presence of thick sedimentary layers beneath the surface. As stated in Equation 1, the natural frequency (f_0) is inversely proportional to the thickness of the subsurface layer (*h*).

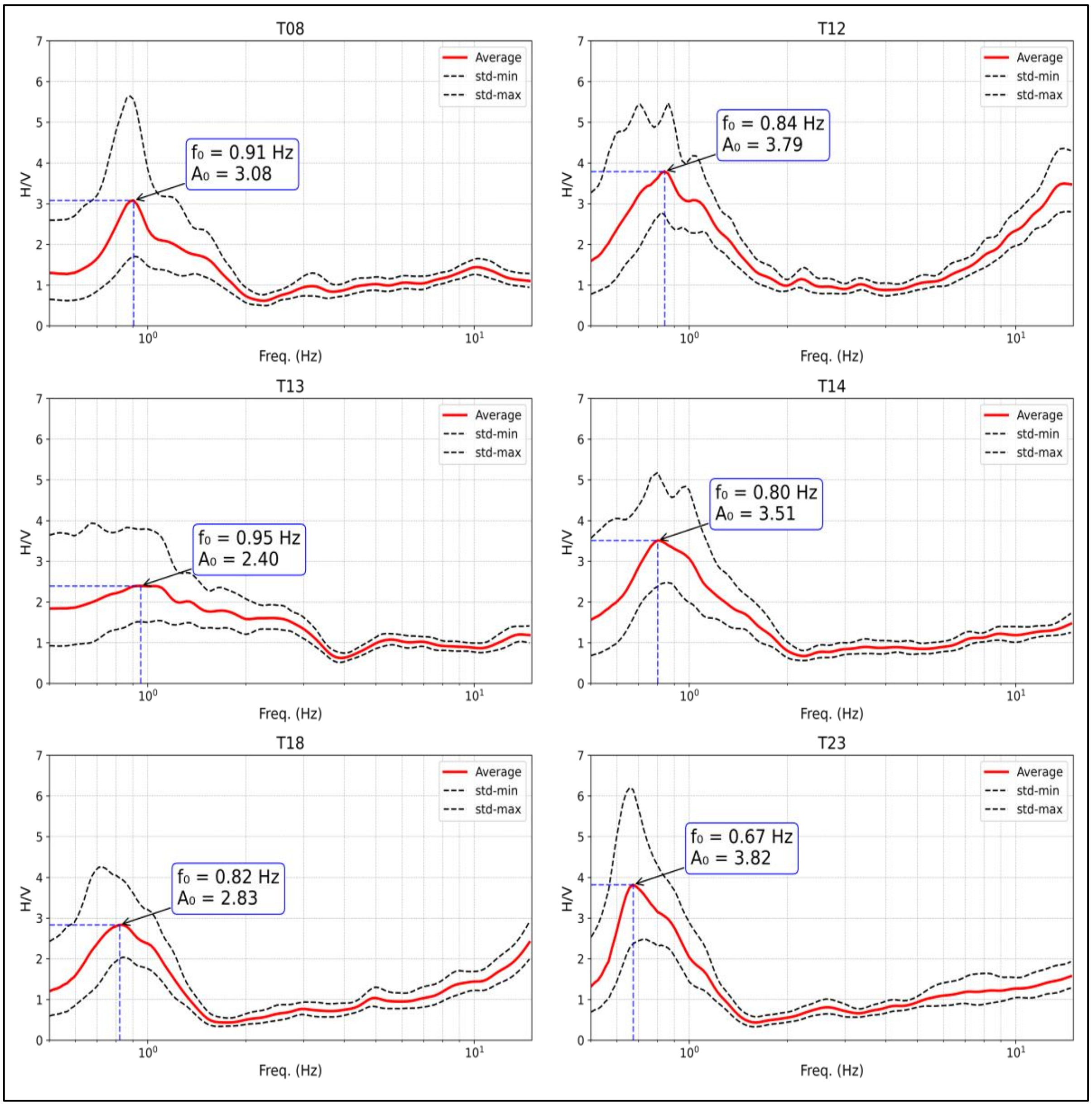

Figure 2. HVSR curves at six measurement points (T08, T12, T13, T14, T18, and T23) showing the average H/V (red) and standard deviation range (black dashed).

Therefore, lower f_0 values imply greater sediment thickness. This pattern is most evident at point T13, which lies directly above the hot spring manifestation zone. The HVSR characteristics at this location exhibit low frequency and moderate amplification, which may reflect a significant impedance contrast between the sedimentary layer and the underlying bedrock. It may also indicate the presence of geological structures such as faults or fractures that could act as conduits for geothermal fluid migration. Comparisons with nearby points, particularly T12 and T14, suggest lateral variations in sediment thickness and possible orientations of subsurface structures that influence the hydrothermal system in the area.

Following the HVSR curve analysis, the distribution of natural frequency (f_o) across the measurement sites was visualized to highlight spatial patterns and potential geological transitions. **Figure 3** describes the distribution of natural frequency (f_o) values in the vicinity of the Cisarua hot spring area. Based on the mapping results, f_o values in this region generally range from 0.6 to 1.1 Hz, reflecting the presence of sedimentary layers with soft mechanical properties and considerable thickness. Spatially, there is a noticeable increase in f_o values in the northern part of the area, particularly around the geothermal manifestation point (T13), suggesting variations in the thickness or stiffness of the sedimentary layers in that zone. Conversely, the southern, western, and eastern parts tend to exhibit lower f_o values. Nevertheless, the overall variation in f_o across the study area is not substantial, indicating that the region is predominantly composed of relatively homogeneous geological units.

Generally, the study area can be spatially divided into two main zones: a high f_0 zone and a low f_0 zone, forming an elongated pattern oriented in a northwest–southeast direction. This pattern reflects significant variations in subsurface geological conditions, particularly in terms of sediment layer thickness and stiffness. Several measurement points, such as T01, T07, T12, and T18, appear to act as transitional boundaries between the high and low-frequency zones, suggesting the presence of local geological contrasts—possibly due to changes in lithology or the existence of geological structures such as faults, which influence the distribution of sediment layers.

The low *fo* values (< 1.1 Hz) imply that the subsurface structure in the Cisarua area is dominated by thick and soft sedimentary layers. These layers are most likely the result of intense hydrothermal alteration processes associated with geothermal activity, which reduce the shear modulus and density of the rock formations. This is consistent with the presence of surface hot spring manifestations, which indicate the existence of an active hydrothermal system beneath the surface.

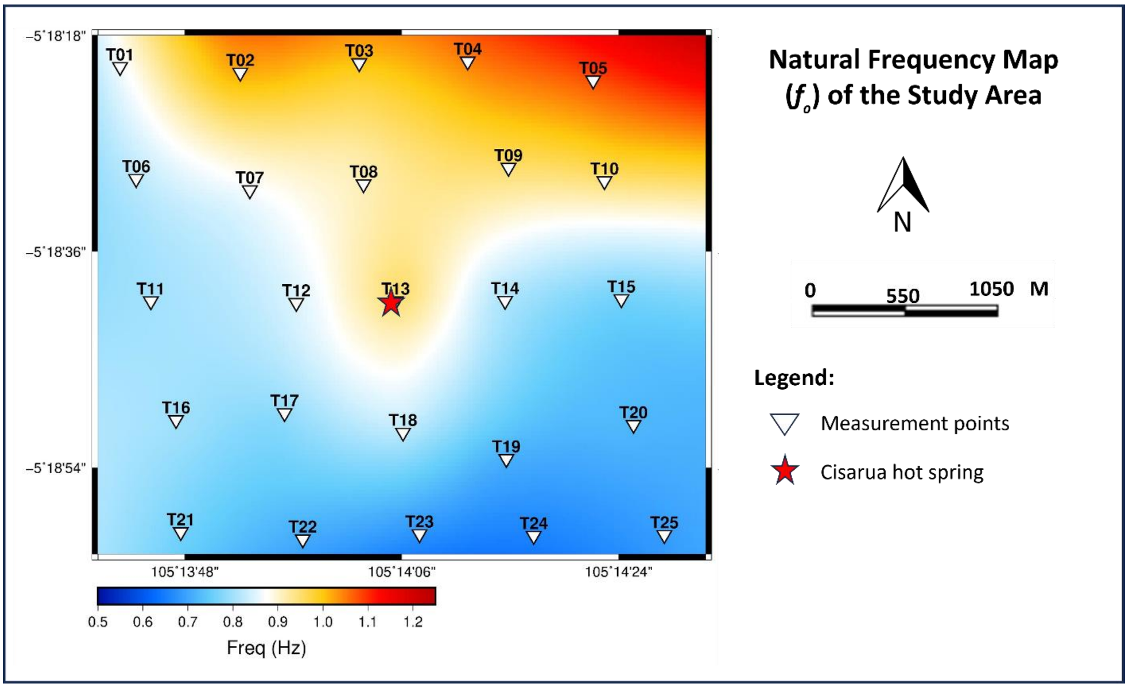

Figure 3. Distribution map of natural frequency (*fo*) in the Cisarua hot spring area. Lower *fo* values generally indicate thicker, soft sediment layers, while higher values suggest shallower bedrock or stiffer subsurface materials.

As part of the HVSR-based microtremor analysis, the peak amplification factor (A_0) was mapped to evaluate the impact of subsurface conditions on local ground motion behavior. **Figure 4** illustrates the spatial distribution of the peak amplification values (A_0) obtained from the HVSR analysis across the study area. In general, A_0 values range from 2 to 5, with the majority of the Cisarua region dominated by values below 3. The A_0 parameter reflects the level of seismic wave amplification due to local site effects, which are directly influenced by the seismic impedance contrast between the soft surface sediments and the underlying bedrock. Overall, the study area can be categorized as having moderate to high A_0 values.

Relatively high A_0 values, particularly in the southeastern and northwestern parts of the study area (A_0 > 3), indicate significant impedance contrasts, typically caused by soft sediment layers with low density and low shear wave velocity (*Vs*) overlying stiffer bedrock. This condition increases the potential for seismic wave amplification, which could significantly impact the vulnerability of surface structures. Conversely, lower A_0 values (A_0 < 3) are observed in the eastern part of the study area and around the geothermal manifestation point in Cisarua, where A_0 reaches approximately 2.4, suggesting that seismic amplification in these areas is relatively low.

Furthermore, the spatial distribution of A_0 values reveals a northwest–southeast trending pattern for both high and low amplification zones. This trend is suspected to be influenced by the regional geological structure, particularly the presence of the Lampung–Panjang Fault, which shares a similar orientation. This fault structure may serve as a controlling pathway for sediment accumulation and variations in sediment layer thickness, ultimately affecting local amplification levels. The correlation between A_0 trends and geological structure supports the interpretation that subsurface geological conditions play a key role in modifying the local seismic response in this region.

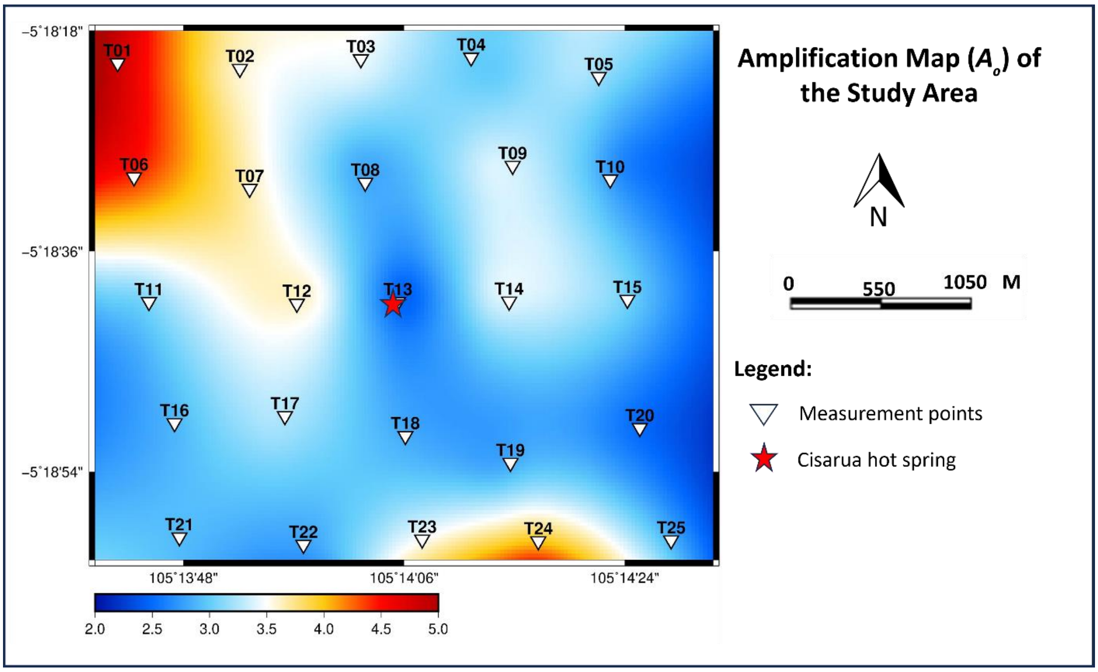

Figure 4. Map showing the distribution of amplification values (Ao) around the Cisarua hot spring area, based on HVSR peak amplitude analysis.

To assess the seismic site conditions more comprehensively, the average shear-wave velocity in the upper 30 meters (Vs_{30}) was calculated and spatially mapped across the study area. **Figure 5** presents the distribution of average shear-wave velocity in the top 30 meters of the ground surface (Vs_{30}) across the study area. The analysis shows that most of the region is dominated by Vs30 values below 175 m/s, indicating soft soil characteristics according to the NEHRP classification. This condition reflects the presence of thick sedimentary layers with low stiffness, which may significantly amplify seismic waves during an earthquake.

In general, the spatial variation of Vs_{30} across the study area is relatively uniform, showing no significant changes. This pattern is consistent with the distribution of natural frequency (f_0) values, which are also relatively homogeneous and low. These observations support the interpretation that the region is predominantly composed of soft and thick sedimentary deposits with similar seismic characteristics throughout most measurement points.

However, a local anomaly is observed near point T13, which corresponds to the location of a hot spring manifestation. Within a radius of approximately 300 meters from this point, Vs_{30} values further decrease to a range of 125–150 m/s. This suggests the presence of a zone with very low soil stiffness, likely resulting from hydrothermal alteration processes, which modifies mineral composition and reduces the mechanical strength of soils and rocks. This finding is particularly important in the context of seismic microzonation, as areas with very low Vs_{30} values exhibit high seismic vulnerability, especially to local resonance and surface wave amplification.

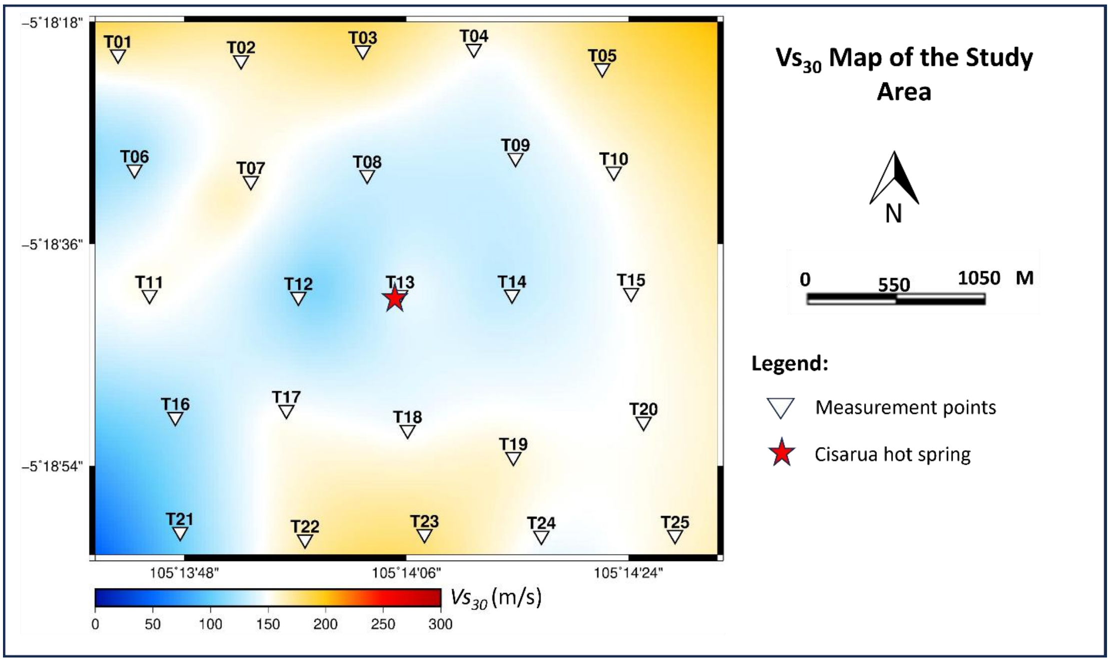

Figure 5. Vs_{30} distribution map around the Cisarua hot spring area, illustrating the variability of near-surface shear-wave velocity down to 30 meters depth.

5. CONCLUSION

The site effect analysis, including the distribution of natural frequency (f_0), amplification (A_0), and average shear-wave velocity (Vs30), demonstrates a strong consistency in reflecting the subsurface geological characteristics of the study area. Low f_0 values (< 1.2 Hz) and Vs30 values generally below 175 m/s indicate the presence of thick, soft sedimentary layers with low seismic impedance across most parts of the area. This interpretation is further supported by A_0 values that are moderate to high (ranging from 2 to 5), confirming the potential for seismic amplification due to local site effects.

The spatial distribution of f_0 and A_0 reveals a pattern trending northwest–southeast, which is suspected to be closely associated with the presence of regional geological structures such as the Lampung–Panjang Fault. This fault system may influence the sediment accumulation by creating accommodation space and controlling the subsurface topography, which affects both the thickness and lateral distribution of the sediments. Consequently, it also influences the stiffness of the overlying soil layers. Measurement points such as T01, T07, T12, and T18 appear to represent transition zones between seismically contrasting areas, suggesting the possible presence of subsurface geological boundaries or fractures.

A new insight emerging from this study is that the zone surrounding the geothermal manifestation (T13) exhibits a significant reduction in Vs30 values (125–150 m/s) and relatively low A_0 values (≈ 2.3), which may be attributed to hydrothermal activity. Such processes are believed to cause mineral alteration and degradation of the elastic properties of the soil and rocks, thereby locally modifying the seismic response. This finding highlights that geothermal manifestations not only serve as indicators of geothermal potential but may also affect specific dynamic soil properties such as shear-wave velocity (Vs30) and amplification potential (A_0), which are key parameters in microzonation studies and seismic risk mitigation. These changes are likely due to mineral alteration and reduced stiffness caused by hydrothermal processes.

Overall, the HVSR-based approach applied in this study has proven effective in identifying zones of high seismic vulnerability and provides valuable insights into the interrelationship between geological conditions, soil dynamics, and seismic amplification potential in areas with complex structural settings and geothermal activity.

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