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Seismic Site Characterization Using Horizontal-to-Vertical Spectral Ratio (HVSR) Analysis of Ambient Noise at Sukasari Village, Sumedang, West Java

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ABSTRACT

Local geological conditions can significantly influence seismic wave amplification during earthquakes, particularly in regions composed of unconsolidated volcanic deposits. This study aims to characterize the seismic site conditions of Sukasari Village, Sumedang Regency, West Java, using the Horizontal-to-Vertical Spectral Ratio (HVSR) method based on ambient seismic noise measurements. A total of 72 microtremor measurement points were distributed across the study area to capture spatial variations in near-surface geological conditions. HVSR analysis was conducted to determine key parameters, including dominant frequency (F_0), amplification factor (A_0), dominant period (T_0), and the seismic vulnerability index (K_g). The results show that F_0 values range from 1.1 to 19.1 Hz, T_0 ranges from 0.058 to 1.788 s, A_0 ranges from 1.4 to 7.3, and K_g ranges from 1.0 to 22.8, indicating significant variations in sediment thickness and subsurface stiffness across the study area. Areas characterized by low F_0 values and high A_0 and K_g are associated with thick unconsolidated sediments that have a higher potential for seismic wave amplification, whereas areas with high F_0 and low Kg correspond to compact volcanic formations with relatively stable ground conditions. These findings demonstrate that the HVSR method effectively identifies spatial variations in local site response and provides important information for seismic microzonation and earthquake-resilient land-use planning in Sukasari Village.

1. INTRODUCTION

West Java lies within a geologically active region formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. Much of the province, including the Sumedang area, is underlain by Quaternary volcanic deposits produced by relatively young volcanic activity z. These unconsolidated materials, such as volcanic ash, lapilli, and pyroclastic deposits (Saputra et al., 2018), are generally soft and highly weathered, making the region susceptible to ground motion amplification during earthquakes (Pereira et al., 2024).

The geomorphology of West Java ranges from alluvial plains to hilly terrains, producing significant spatial variations in sediment thickness and subsurface stiffness (Warnana et al., 2011). These variations strongly influence local ground response and shaking intensity during seismic events (Kramer, 1996). Therefore, understanding near-surface geological conditions is essential for evaluating local site amplification and assessing seismic hazards in heterogeneous volcanic environments.

One widely used technique for investigating local site response is the Horizontal-to-Vertical Spectral Ratio (HVSR) method based on ambient seismic noise. The HVSR method, originally proposed by Nakamura (1989), estimates the resonance characteristics of near-surface layers by comparing the spectral amplitudes of horizontal and vertical ground motion components. Because the method is non-invasive, cost-effective, and relatively simple to apply, HVSR analysis has been widely used in seismic microzonation studies and site characterization investigations in many tectonically active regions.

Within this geological context, Sukasari Village in Sumedang Regency represents a volcanic environment influenced by regional tectonics and local geological structures, and is situated within an active fault zone associated with the continuation of the Lembang Fault system, indicating significant seismic hazard potential (Aruan et al., 2024). This tectonic setting suggests that the area is susceptible to seismic ground motion, which may contribute to geohazards such as slope instability and variations in local site response. The area exhibits diverse topography ranging from alluvial plains to volcanic hills, suggesting variations in sediment thickness and subsurface stiffness that may influence local seismic response. However, detailed investigations of local site response in Sukasari Village using the HVSR approach remain limited. Therefore, this study aims to characterize the seismic site conditions of Sukasari Village using HVSR analysis based on ambient noise measurements. The results are expected to provide valuable information for understanding spatial variations in site response and to support seismic microzonation and earthquake risk mitigation in the Sumedang region.

2. METHODS

2.1 Study Area

This study was conducted in Sukasari Village, Sukasari District, Sumedang Regency, West Java Province. According to the Central Bureau of Statistics of Sumedang Regency (BPS Kabupaten Sumedang, 2024) , Sukasari Village covers about 2.6 km^2 with a population of 5,433. Geographically, it lies in central Sumedang and borders several other villages within the Sukasari District, forming a varied topography that influences local geological and seismic characteristics.

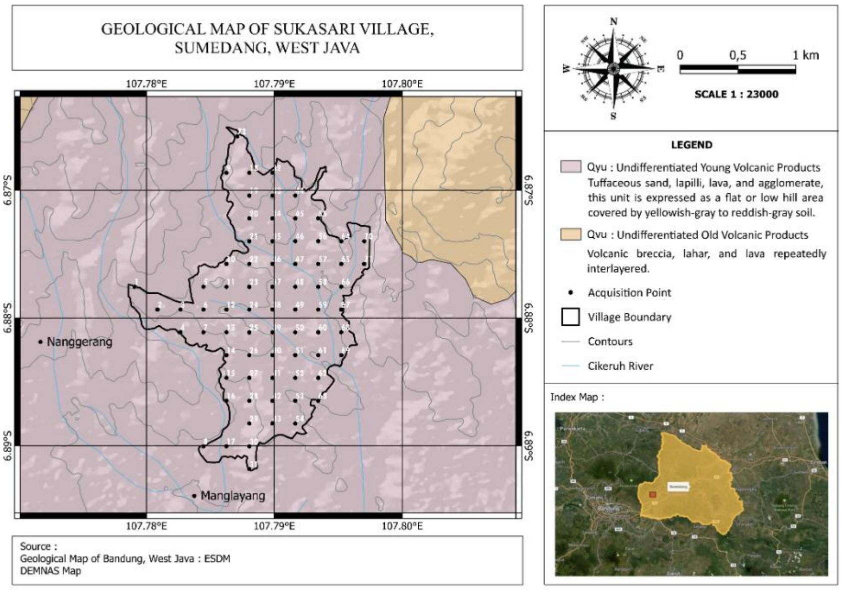

Figure 1. Regional Geological Map of the Research Location

Figure 1 shows the geological map of the study area compiled from the Geological Map of the Bandung Sheet published by the Ministry of Energy and Mineral Resources (ESDM) and DEMNAS data. Sukasari Village is predominantly underlain by undifferentiated young volcanic deposits (Qyu) consisting of tuffaceous sand, lapilli, lava, and agglomerate. These deposits form gently undulating terrain characterized by flat to moderately sloping hills with yellowish-gray to reddish-gray soil cover. In the northeastern part of the study area, older volcanic deposits (Qvu) are locally exposed and consist mainly of breccia, lahar, and lava units that are interlayered. The contour pattern indicates generally gentle to moderate topographic relief across the area, becoming steeper toward the northeastern sector.

The geological setting is dominated by Quaternary volcanic materials derived mainly from Mount Tangkuban Perahu, with minor contributions from Mount Tampomas (Aruan et al., 2024). Alluvial deposits occupy valley areas, while older Miocene sedimentary units were subsequently modified by Pliocene volcanic activity and tectonic deformation associated with the Java geanticline. In addition, local geological structures such as the Sukasari anticline may influence subsurface configuration and stratigraphic variability within the study area (Silitonga, 2003).

2.2 Data Acquisition Procedure

Ambient seismic noise measurements were collected from 72 points across Sukasari Village to capture spatial variations in near-surface conditions. Measurement points were distributed in a grid pattern with an average spacing of approximately 250 m, ensuring representative coverage of different geological and geomorphological units within study area.

Data acquisition was performed using a three-component passive seismic recorder equipped with 4.5 Hz geophones with a sensitivity of 28 V/m/s, operating in a 16-bit, three-channel configuration. At each location, ambient noise was recorded for a duration of 15-30 minutes following the SESAME guidelines Acerra et al. (2004) to ensure stable and reliable measurements. Sensors were installed on stable ground surfaces, and sites affected by excessive anthropogenic noise were avoided to minimize data contamination. All recordings were stored in miniSEED format for subsequent processing and HVSR analysis.

The acquired microtremor data were stored in miniSEED format and processed using Geopsy software to generated HVSR curves. From these curves, the dominant frequency (F_0) and amplification factor (A_0) were determined. Finally, interpolation in QGIS was used to generate spatial distribution maps of F_0, A_0, K_g , with each HVSR curve visually inspected to ensure the reliability of the resonance peak before interpretation (Gosar, 2010).

2.3 HVSR Processing and Analysis

Ambient seismic noise data were processed using Geopsy software to compute the HVSR following standard procedures. The HVSR method was applied to estimate site resonance characteristics based on the ratio between the horizontal and vertical components of ambient vibrations (Nakamura, 1989). The HVSR function is expressed as:

$$HVSR(\omega) = \frac{\sqrt{H_{EW}(\omega) \times H_{NS}(\omega)}}{V(\omega)} \qquad (1)$$

where $H_{EW}(\omega)$ and $H_{NS}(\omega)$are the Fourier amplitude spectra of the horizontal north–south and east–west components, respectively, and $V(\omega)$is the vertical component. The dominant frequency corresponds to the frequency at which $HVSR(\omega)$ reaches its maximum peak.

Signal processing included Fourier transformation, removal of unstable time windows, and to refine the spectral curve, the Konno-Ohmachi filter was applied with a bandwidth coefficient of 40 and a smoothing width of 5% (Konno and Ohmachi, 1998). Non-overlapping time windows of 25 s were selected following stability criteria to ensure reliable spectral estimates. Each HVSR curve was visually inspected to confirm the clarity and stability of the resonance peak prior to interpretation.

Final output of the HVSR analysis is presented as H/V spectral ratio curves, where frequency is plotted on the x-axis and H/V ratio on the y-axis, as shown in Figure 2. From these curves, the dominant frequency (F_0) is identified as the peak frequency, while the corresponding peak amplitude represents the amplification factor (A_0). These parameters were subsequently used to calculate T_0 and K_g. The dominant period (T_0) of the soil was calculated as,

$$T_0 = \frac{1}{F_0} \tag{2}$$

Furthermore, the seismic vulnerability index (K_g) was calculated as,

$$K_g = \frac{A_0^2}{F_0} \tag{3}$$

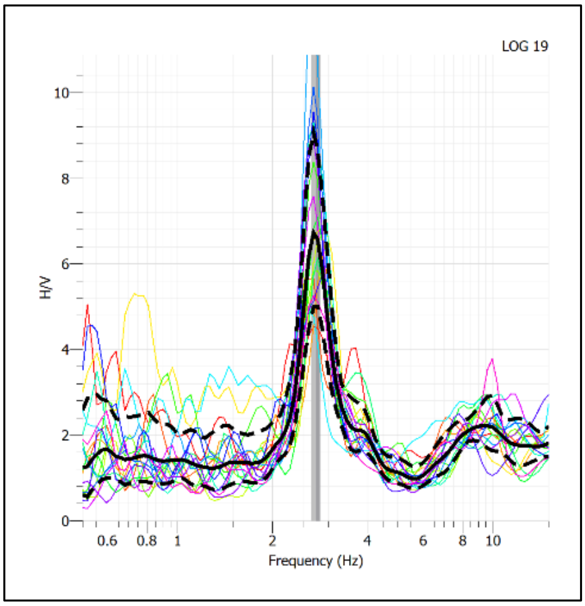

Figure 2. Representative HVSR curve showing the H/V spectral ratio

Spatial interpolation and mapping of F_0, A_0, T_0, and K_g were performed using QGIS to generate distribution maps that represent the spatial variation of local site response across the study area. The overall research workflow is summarized in the flowchart shown in Figure 3.

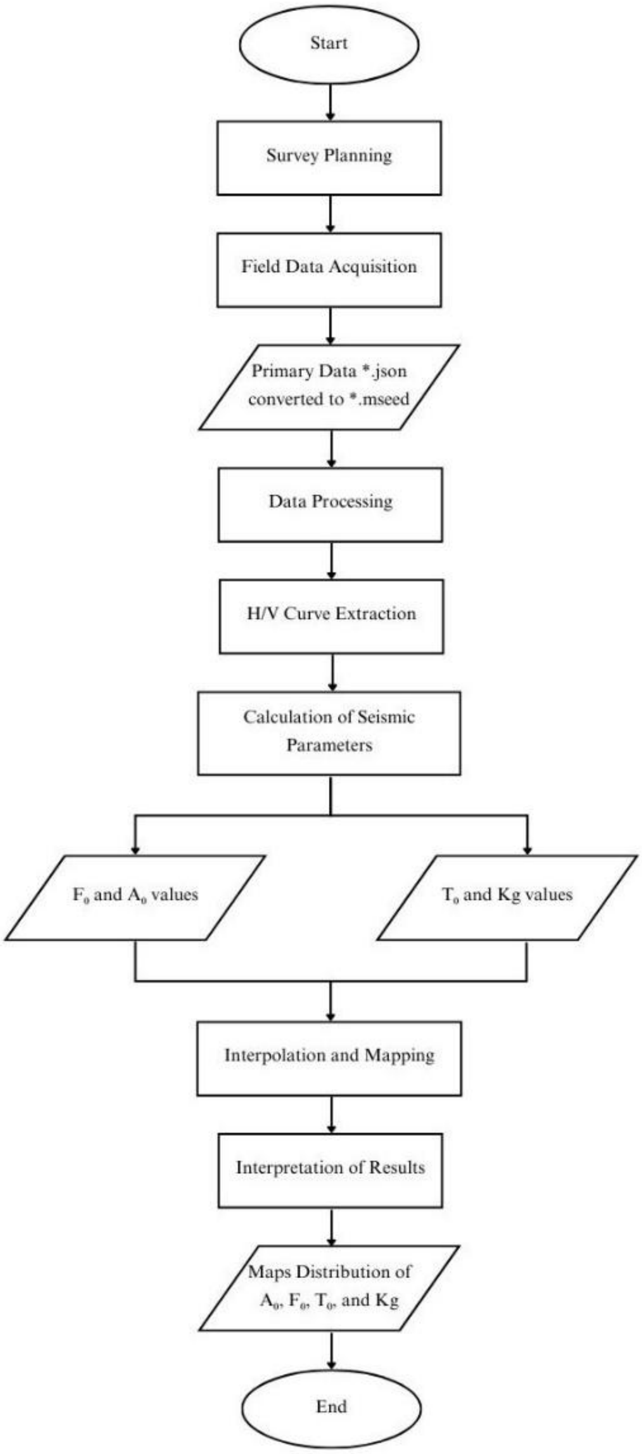

Figure 3. Research Flowchart

For site characterization, the derived dominant frequency (F_0) and dominant period (T_0) were interpreted by referring to the classification scheme proposed by Kanai (1983), which relates these parameters to subsurface conditions such as sediment thickness and stiffness. Lower F_0 values (or longer T_0) generally indicate thicker and softer sediments, whereas higher F_0 values (or shorter T_0) correspond to thinner and more compact materials. The classification schemes used in this study are presented in Table 1 and Table 2. It should be noted that the classification order differs between frequency and period representations due to their inverse physical relationship.

Table 1. Soil Classification Based on Dominant Frequency Referring to Kanai's Classification

Soil Classification	F_0 (Hz)	Kanai Classification	Description
Type I	< 2.5	Dominated by unconsolidated alluvial deposits such as clay, mud, and organic soils formed in depositional environments.	Very soft ground with very thick sedimentary layers
Type II	2.5 - 4.0	Composed of alluvial materials including sandy gravel, clay, and loam with relatively low stiffness.	Soft ground with thick sediment deposits
Type III	4.0 - 10	Characterized by moderately compacted sediments such as sandy clay and gravel.	Medium stiffness with moderate sediment thickness
Type IV	10 - 20	Consists of older geological formations such as compact sand, gravel, and hard rock materials.	Hard ground with thin surface sediments

Table 2. Soil Classification Based on Dominant Period Referring to Kanai's Classification

Soil Classification	T_0 (s)	Description	Characteristics
Type I	0.05 - 0.15	Dominated by older geological formations such as tertiary rocks with high consolidation levels, consisting mainly of compact sandy gravel and other hard materials.	Hard
Type II	0.15 - 0.25	Composed of relatively shallow alluvial deposits, typically around several meters thick, including sandy gravel, clay, and loam with moderate compaction.	Medium
Type III	0.25 - 0.40	Characterized by thicker alluvial sediments compared to Type II, with lower stiffness and the possible presence of slope or transitional depositional features.	Soft
Type IV	> 0.40	Consists of thick unconsolidated alluvial materials such as clay, silt, and organic-rich soils formed in depositional environments, indicating very low stiffness and high compressibility.	Very Soft

3. RESULT AND DISCUSSION

The results begin with an overview of the spatial framework established for microtremor data acquisition across Sukasari Village. This framework ensures that the subsequent HVSR analysis accurately represents the geological and geomorphological variability of the study area. Through this spatial context, the interpretation of amplification values and site response can be directly linked to local subsurface conditions, thereby enhancing the reliability of the results. Based on this framework, the following sections present the analysis of F_0, A_0, T_0, and K_g to evaluate local site characteristics.

3.1 Amplification Factor (A_0) and Dominant Frequency (F_0) Distribution

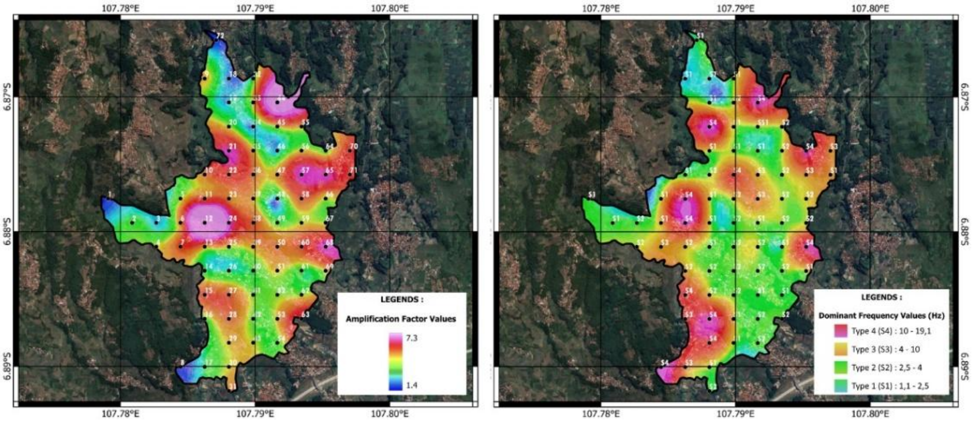

Figure 4. (a) Map Distribution of A_0 Value and (b) Map Distribution of F_0 Value in Sukasari Village

The amplification factor (A_0) derived from HVSR analysis, quantifies the degree of seismic wave amplification at the dominant frequency (Araque-Perez, 2024). In Sukasari Village as shown in Figure 4, A_0 values range from 1.4 (blue) to 7.3 (pink), indicating clear spatial variability in seismic response. High values (> 5) are predominantly found in the central to southeastern sectors at stations 12, 44, 57, and 68. Although these locations are mapped within the same Qyu volcanic formation, the high amplification may be associated with locally weathered, unconsolidated to weakly consolidated volcanic deposits, which can exhibit low stiffness and significant impedance contrast. In addition, possible contributions from near-surface alluvial materials in valley areas may further enhance seismic wave amplification. This interpretation is consistent with the HVSR concept, which relates amplification effects to impedance contrasts between near-surface layers and underlying materials, with softer or less consolidated layers generally producing higher amplification (Acerra et al., 2004). In contrast, lower A_0 values (< 3) such as at stations 34, 46, and 48 are observed in the northern and southwestern zones, where compact volcanic rocks such as breccia, lava, and andesitic intrusions effectively damp seismic energy.

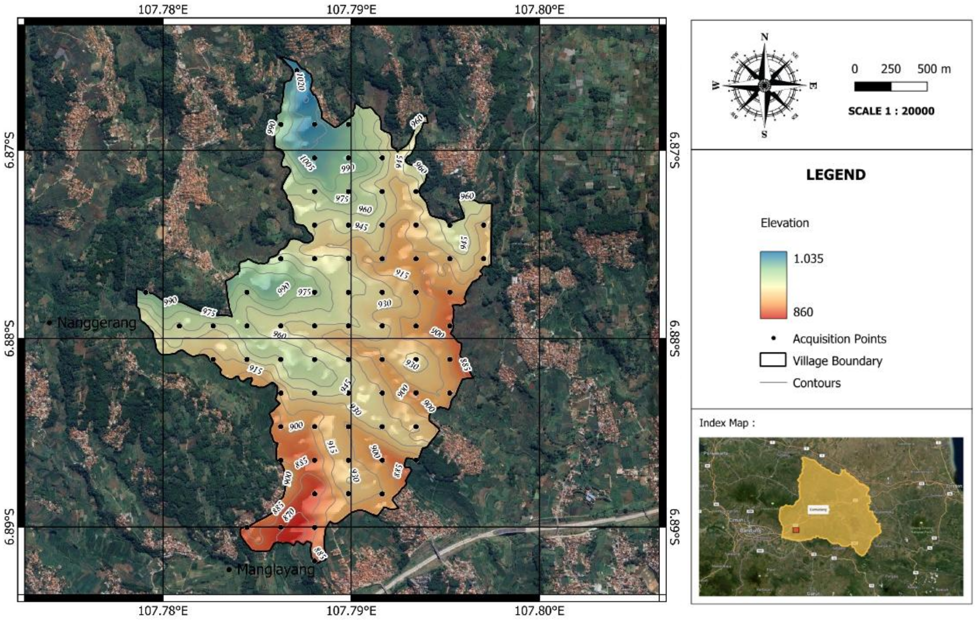

Figure 5. Topographic Map of Sukasari Village

The dominant frequency (F_0) varies between 1 Hz and 19.1 Hz, reflecting differences in sediment thickness and subsurface rigidity across the study area. High F_0 values (> 10 Hz) occur in the northern and southwestern regions, which correspond to shallow volcanic formations with hilly morphology as indicated by the topographic map in Figure 5, characterized by rigid breccia and tuff deposits. Conversely, at low F_0 values (< 4 Hz) are concentrated in the central and southeastern areas, where thick sedimentary layers produce lower resonance frequencies associated with soft soil behavior. These variations indicate that F_0 can serve as an indicator of subsurface stiffness and sediment thickness, providing essential information for assessing local site response. This distribution highlights a clear contrast between shallow volcanic bedrock and deep sedimentary basins, serving as an essential parameter for seismic microzonation.

Dominant frequency represents the natural resonance of local soils, where ground motion amplification occurs when incoming seismic waves match this frequency. Resonance causes a significant increase in shaking intensity, making F_0 a critical parameter for site characterization. The value of F_0 is primarily influenced by sediment thickness and stiffness, with higher values indicating thinner and stiffer deposits, while lower values reflect thicker and softer sediments. Based on this relationship, the classified distribution of HVSR-derived F_0 values for Sukasari Village is presented in Table 3.

Tabel 3. Distribution of F_0 in Sukasari Based on HVSR Analysis

Acquisition Point	F_0 (Hz)	Soil Classification	Description
S1	1.1 - 2.5	Type I	Very soft ground characterized by thick unconsolidated sediment layers.
S2	2.5 - 4.0	Type II	Soft ground with relatively thick alluvial deposits.
S3	4.0 - 10	Type III	Moderately compacted sediments with intermediate stiffness.
S4	10 - 19.1	Type IV	Hard ground dominated by compact materials or rock.

According to this classification, high-frequency zones (> 10 Hz) in Sukasari correspond to Type IV soils, characterized by thin and stiff deposits with sediment thickness generally less than 5 m. Intermediate frequencies (4 -10 Hz) indicate Type III soils with moderate stiffness and sediment thickness ranging between 5 and 10 m. Zones with lower frequencies (2.5 - 4 Hz) represent Type II soils, consisting of thicker unconsolidated sediments with depths of approximately 10 - 30 m. The lowest frequencies (< 2.5 Hz) correspond to Type I soils, which are associated with very thick and soft sedimentary layers exceeding 30 m in thickness and exhibiting the highest amplification potential. These findings confirm that the F_0 distribution is consistent with the geological and geomorphological setting of Sukasari.

Based on the topographic characteristics, a total of 42 measurement points are located in hilly areas, predominantly classified as Type III - IV, indicating thin and relatively stiff subsurface conditions. In contrast, approximately 30 points are situated in valley regions, mainly falling under Type I - II, which correspond to thicker and softer sedimentary deposits. This spatial relationship highlights the strong control of topography on subsurface conditions and seismic response, emphasizing the effectiveness of HVSR analysis for local site characterization and seismic microzonation in tectonically active areas.

The correlation between A_0 and F_0 indicates that zones characterized by low dominant frequencies generally exhibit higher amplification, suggesting increased seismic susceptibility. This pattern reflects the combined influence of lithological and structural controls, including volcanic deposits associated with Mount Tangkuban Parahu and Mount Tampomas, as well as tectonic features such as the Lembang Fault and the Sukasari anticline. The integration of these parameters allows for a more robust delineation of areas prone to strong ground motion, which is essential for seismic microzonation and risk mitigation (Azifah et al., 2025).

In Sukasari, this relationship is particularly evident in the central to southeastern regions, where low F_0 values coincide with elevated amplification levels. These conditions are indicative of thick, unconsolidated subsurface materials that promote resonance and enhance seismic wave amplification. This inverse relationship between A_0 and F_0 has been widely documented in previous studies. (Lermo and Chávez-García, 1993) demonstrated that soft soil layers generate low dominant frequencies accompanied by strong amplification due to resonance effects. Similarly, Stolte et al. (2022) demonstrated that HVSR-derived amplification patterns in sedimentary basins are strongly controlled by multiple impedance contrasts within the subsurface layers. In the Indonesian context, Pranata et al. (2018) observed that volcaniclastic and alluvial deposits in the Bandung Basin exhibit analogous behavior, supporting the interpretation of the Sukasari results.

However, local deviations are observed within the same volcanic formation, where relatively high amplification occurs despite moderate frequency values. This suggests that factors beyond sediment thickness such as weathering, fracturing, and the degree of consolidation also significantly influence site response. Similar observations were reported by Lunedei and Malischewsky (2015), who noted that weathered volcanic materials can exhibit mechanical behavior comparable to soft sediments.

From a mechanistic perspective, this relationship can be explained by resonance phenomena in layered media. Dominant frequency is inversely proportional to sediment thickness and controlled by shear-wave velocity. Under such conditions, thicker and softer layers tend to trap seismic energy, while strong impedance contrasts between surface deposits and underlying bedrock further amplify ground motion (Ibs-von Seht and Wohlenberg, 1999). Overall, the consistency between the Sukasari results and previous studies suggests that the observed A_0 and F_0 relationship represents a fundamental site response mechanism rather than a purely local effect. This agreement suggests that the observed pattern is consistent with site response characteristics commonly reported in volcanic sedimentary environments, including those in West Java.

3.2 Dominant Period (T_0) and Seismic Vulnerability Index (K_g) Distribution

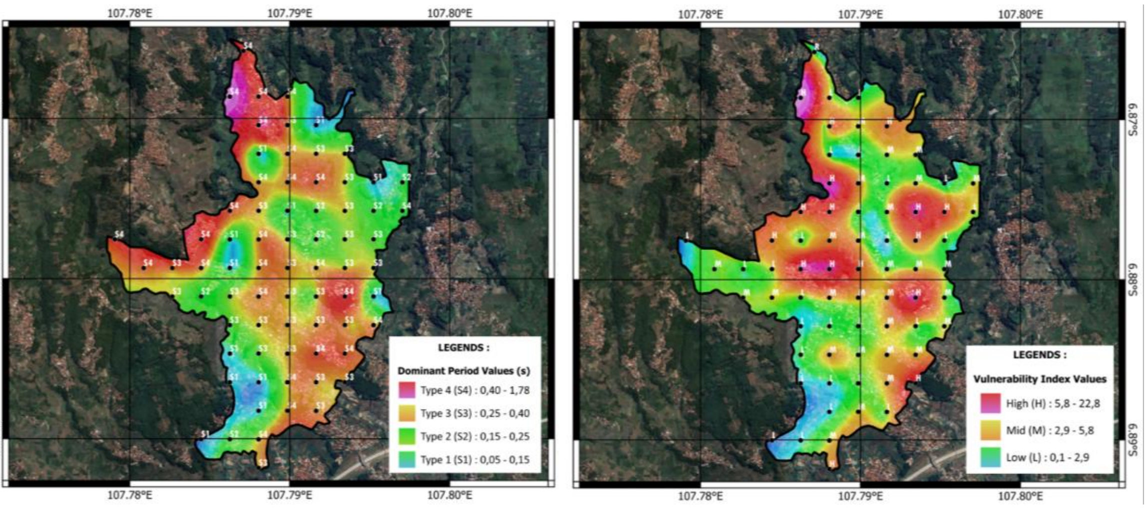

Figure 6. (a) Map Distribution of T_0 Value and (b) Map Distribution K_g Value in Sukasari Village

The dominant period (T_0) represents the time required for seismic waves to travel through near-surface layers, reflect at impedance contrasts, and return to the surface. It serves as a key indicator of local resonance and subsurface stiffness, being inversely proportional to the dominant frequency (F_0). Variations in T_0 reflect differences in subsurface conditions, where longer periods indicate thicker and softer sediments, while shorter periods correspond to thinner and more compact materials. The classified distribution this values for Sukasari Village is presented in Table 4.

Tabel 4. Distribution of T_0 in Sukasari Based on HVSR Analysis

Acquisition Point	T_0 (s)	Soil Classification	Characteristics
S1	0.05 - 0.15	Type I	Hard
S2	0.15 - 0.25	Type II	Medium
S3	0.25 – 0.40	Type III	Soft
S4	0.40 - 1.78	Type IV	Very Soft

The spatial distribution of T_0 in Sukasari Village ranges from 0.058 to 1.788 seconds, as illustrated in Figure 6 based on 72 HVSR measurement points. Low T_0 values (0.05 - 0.25 s) dominate the southwestern and southern zones, underlain by hard volcanic rocks such as breccia, lava, and tuff, representing soil types I - II. Intermediate periods (0.25 - 0.40 s) occur in the central and eastern sectors with moderately consolidated sediments (Type III). Meanwhile, the northern and southeastern lowlands exhibit the high T_0 (> 0.40 s), associated with thick Quaternary alluvial deposits of clay, silt, humus, and mud, corresponding to soil type IV (very soft soil). Areas with highest T_0 (> 0.6 s) are of particular engineering concern, as their resonance periods may overlap with those of multi-story buildings, potentially amplifying structural response during earthquakes. Overall, the T_0 distribution delineates distinct seismic risk zones where thick sedimentary layers coincide with higher resonance potential, providing a basis for microzonation and urban planning.

The spatial distribution of K_g in Sukasari Village reveals considerable variability, ranging from 1.0 (dark blue) to 22.8 (bright pink). Zones with high K_g values (> 6.0), predominantly found in the central and northern sectors, indicate zones of elevated seismic vulnerability. These areas, dominated by loose or weathered sediments, are more prone to deformation and damage under seismic loading, making them priority zones in hazard assessment. Similar behavior has been widely documented in recent studies. For example, Vessia et al. (2021) demonstrated that unconsolidated sediments with low shear-wave velocity can significantly amplify seismic waves. In a related context, Susanti et al. (2026) demonstrated that high K_g values are closely associated with zones of low shear-wave velocity and thick unconsolidated sediments, which significantly enhance ground motion amplification.

In Sukasari Village, the concentration of high K_g values within lowland areas reflects a similar mechanism, where sediment thickness and impedance contrast control the level of ground amplification. Comparable conditions have also been identified in the Bandung Basin, where thick Quaternary deposits generate low dominant frequencies and significant amplification effects. As reported by Pranata et al. (2018), these geological conditions contribute to increased seismic vulnerability in several parts of the basin.

In contrast, regions with intermediate K_g values (3.0 - 6.0) are depicted in yellow, while low K_g zones (< 3.0), concentrated in the southern and western areas, suggest relatively stable ground conditions with reduced susceptibility to seismic amplification. However, the maximum K_g value observed in this study (22.8) is relatively lower than those reported in some highly amplified sedimentary basins, suggesting that additional geological factors influence the local site response. The presence of the Lembang Fault and the Sukasari anticline likely introduces structural heterogeneity that modifies seismic wave propagation and redistributes energy, thereby limiting extreme amplification in certain areas. This highlights the importance of considering both lithological and structural controls in seismic hazard assessment.

From a mechanistic perspective, the spatial coincidence of high T_0 and high K_g values in the northern and southeastern zones indicates the combined effect of increased sediment thickness and reduced material stiffness. These conditions lower the natural frequency of the ground and promote the trapping of seismic energy within the sediment column, which enhances resonance effects. Similar relationships between dominant period and amplification have been emphasized in recent studies, such as Molnar et al. (2022), reinforcing the interpretation that areas underlain by thick unconsolidated deposits are particularly susceptible to seismic amplification.

The spatial variation of F_0, A_0, and K_g obtained in Sukasari Village has direct implications for earthquake risk mitigation and local development planning. Zones with low F_0 (< 4 Hz) and high K_g (> 6.0), primarily located in the central and southeastern lowlands, should be considered as high-risk areas. These zones are unsuitable for the construction of mid to high-rise buildings due to the potential for resonance effects. In contrast, hilly areas with high F_0 (> 10 Hz) and low K_g (< 3.0) provide relatively stable ground conditions and may be prioritized for critical infrastructure development. Integrating this site-effect information into spatial planning and building regulations will support the local government of Sumedang in enhancing earthquake resilience.

4. CONCLUSION

This study successfully characterized the seismic site conditions of Sukasari Village, Sumedang Regency, using the Horizontal-to-Vertical Spectral Ratio (HVSR) method based on ambient noise data. Analysis of 72 measurement points revealed clear spatial variations in A_0, F_0, T_0, and K_g. These variations confirm that near-surface materials in Sukasari are heterogeneous and strongly influenced by geological and geomorphological conditions.

Quantitatively, F_0 range from 1.1 - 19.1 Hz, T_0 from 0.058 - 1.788 s, A_0 from 1.4 - 7.3, and K_g from 1.0 - 22.8, reflecting strong geological control by sediment thickness and stiffness. Zones with low F_0 (< 4 Hz), high A_0 (> 5), and high K_g (> 6.0) contain thick, unconsolidated Quaternary sediments highly susceptible to seismic amplification, while upland regions with high F_0 (> 10 Hz), low A_0 (< 3), and low K_g (< 3.0) correspond to compact volcanic breccia and tuff layers that effectively damp seismic energy and provide greater stability.

The correlation among A_0, F_0, T_0, and K_g reveals that soft and thick sediments tend to amplify seismic waves, whereas rigid volcanic formations exhibit minimal amplification. Lower stiffness and greater sediment thickness significantly enhance ground motion response, which is consistent with previous studies on site amplification (Kanai, 1983). Structural elements such as the Lembang Fault and Sukasari anticline locally increase A_0 and K_g confirming the influence of fault-induced amplification in the study area.

These findings provide an important scientific basis for seismic microzonation and earthquake-resilient land-use planning in Sumedang Regency. Areas exhibiting low F_0 values together with high A_0 and K_g values indicate higher seismic vulnerability and should therefore be prioritized in risk mitigation strategies and carefully considered in future development planning, particularly for multi-story structures. In contrast, hilly regions dominated by stiff volcanic bedrock generally exhibit lower amplification potential and may be more suitable for the development of essential and critical infrastructure.

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