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Analysis of Soil Dynamics and Ground Movement Vulnerability Using the HVSR Method Based on Microtremor Measurements in the Sempu area, Pasuruan

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Abstract

The Sempu Area, located in Cowek Village, Purwodadi Subdistrict, Pasuruan Regency, has a high potential for ground movement due to its lithological conditions, which consist of loose volcanic deposits and weathered sedimentary rocks, thereby increasing the risk of seismic wave amplification. This study aims to analyze the dynamics and soil vulnerability to ground movement phenomena using the Horizontal-to-Vertical Spectral Ratio (HVSR) method based on microtremor data. Data collection was conducted at 15 measurement points using a three-component seismograph, with a recording duration of 20 minutes per point. The data were analyzed using SeismoWin for signal filtering, Geopsy for extracting the fundamental frequency (f_0) and amplification values, and Surfer and ArcGIS for spatial visualization in the form of dominant frequency maps, amplification maps, and soil vulnerability index (Kg) distribution. The results showed that the dominant frequency values ranged from 2.75 to 5.92 Hz, with a maximum amplification value of 6.18. The most vulnerable zones were identified in the central part of the hamlet, specifically at points 10 and 14, which exhibited the highest Kg value of 14.12. These findings indicate the presence of significant local resonance zones arising from unconsolidated lithology, thereby increasing the risk of damage from seismic shaking. The implications of this study support land-use planning based on seismic microzonation and the development of more precise disaster mitigation strategies in areas prone to ground movement.

Introduction

The phenomenon of ground movement is a form of geological instability that can cause significant damage to infrastructure, the environment, and the quality of life for communities.

This instability arises from a combination of factors, including topographic conditions, lithology, extreme rainfall, seismic activity, and human interventions through land-use changes or infrastructure development, often without adequate geotechnical studies [1,2]. In the context of geological disaster mitigation, studying soil vulnerability is crucial for understanding subsurface dynamics and developing adaptive, risk-based spatial planning strategies. Mapping hazard zones using geophysical approaches, particularly those based on soil dynamics in response to seismic vibrations, has gained increasing attention in recent research [3,4].

One area showing strong indications of potential ground movement is the Sempu Area, located in Cowek Village, Purwodadi Subdistrict, Pasuruan Regency. This area features undulating topography with steep slopes and lithological conditions dominated by unconsolidated volcanic deposits and weathered sedimentary rocks, which reduce soil strength and increase susceptibility to deformation. The combination of saturated soil structures, low bearing capacity, and dynamic loads further enhances instability, particularly during the rainy season or under seismic excitation. While several landslide events have been recorded by the local disaster management agency, no comprehensive seismic microzonation study has been conducted using the Horizontal-to-Vertical Spectral Ratio (HVSR) method.

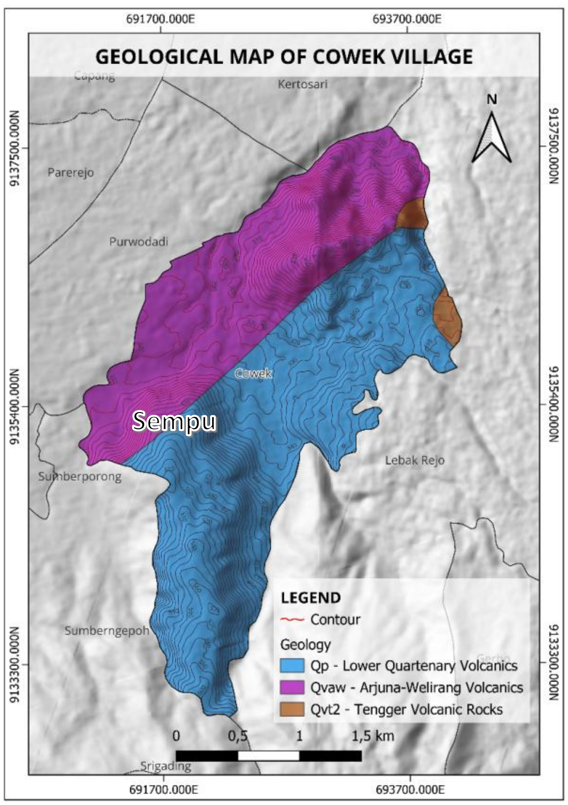

Figure 1. Geological Map of Cowek Village

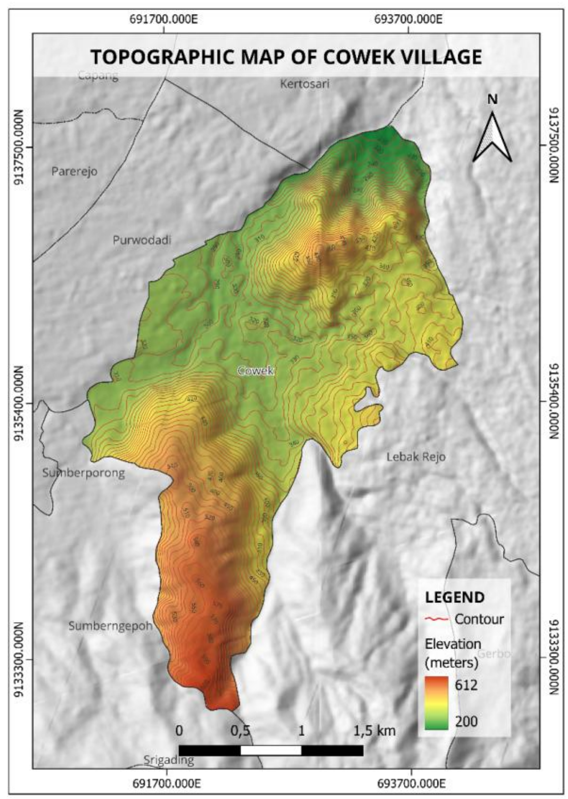

Figure 2. Topographic Map of Cowek Village, Pasuruan Regency

The Sempu area is situated within the Lower Quaternary Volcanic (Qpv) unit, composed of lava, breccia, and tuff that have undergone extensive weathering, resulting in highly porous and poorly consolidated materials, as shown in Figure 1. Such conditions weaken interparticle bonding and substantially increase the potential for ground instability, especially under saturated conditions[5]. The topography ranges between 500–540 m above sea level, characterized by steep slopes and dense contour lines (as shown in Figure 2). Most observation points are located along steep slopes or at slope-to-plain transitions, where subsurface water pathways and stress accumulation zones commonly develop. These factors collectively amplify the risk of ground movement, making the integration of geological, topographic, and microtremor data crucial for hazard assessment [6,7]. Previous studies have also demonstrated that unconsolidated volcanic deposits generally lead to low-to-intermediate dominant frequencies and high amplification [8,9].

Comparable studies reinforce the importance of microtremor analysis in areas prone to hazards. In Candipuro District, Lumajang, 16 microtremor points revealed amplification values of 2.7–8.7 and low dominant frequencies of 0.5–1.4 Hz, with Vs30 classified as medium to hard soil, indicating a heterogeneous subsurface [10]. Similarly, at the Ngipik landfill site in Gresik, the HVSR method proved effective in assessing seismic site effects in urban and landfill settings [10,11]. For the Sempu area, this research provides a novel case study in semi-rural terrain with mixed lithological characteristics, bridging the gap between urban-focused and volcanic-slope-focused investigations. Expert analyses from the Institut Sepuluh Nopember (ITS) further reveal that ground displacement is frequently triggered by rainwater infiltration through surface cracks, which accelerates soil softening and mass detachment. The combination of loose volcanic lithology, steep slopes, and intense rainfall has been identified as a primary driver of ground movement in East Java [7,12].

The integration of dominant frequency (f_0), amplification (Ag), vulnerability index (Kg), and shear strain (Y) in this study provides a multi-parameter approach to site-effect analysis, extending beyond conventional HVSR mapping. This methodology is consistent with previously validated approaches [13,14,15], while offering new insights into distinguishing "resonance-vulnerable" and "high-deformation" zones. Similar frameworks have been adopted by [16, 17]; however, the explicit identification of anomalous zones in densely populated volcanic slopes highlights the urgency of this research. The significance of these findings is reinforced by the ground movement event of 28–31 January 2025, which forced the displacement of residents. According to the East Java Provincial Government, further geophysical studies are urgently needed to determine whether the Sempu area remains habitable or requires permanent relocation. This urgency is further exacerbated by climate change, which intensifies rainfall variability and increases the frequency of slope failures [18,19]. Therefore, this study directly contributes to seismic microzonation and disaster mitigation strategies for vulnerable transitional environments.

Experimental Method

This study employed a combined approach of literature review and empirical investigation to analyze soil vulnerability to ground movement phenomena in Sempu Area, Cowek Village, Purwodadi Sub-district, Pasuruan Regency.

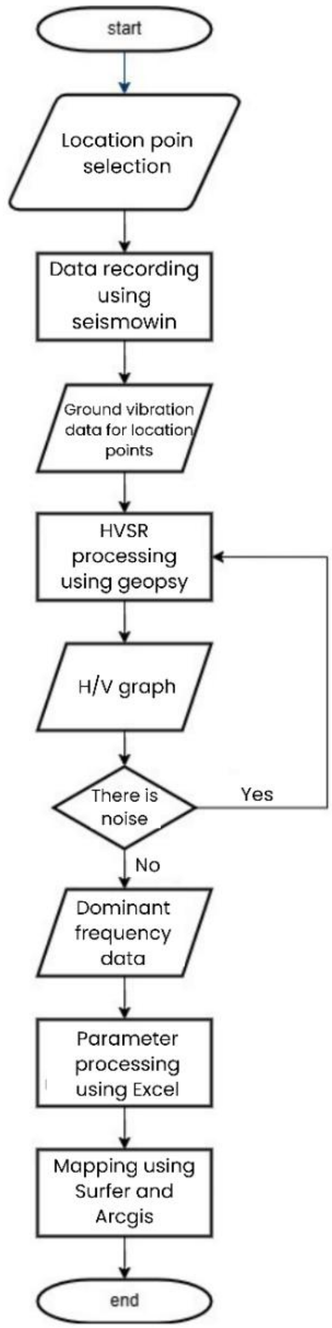

Figure 3. Data Processing Flowchart

Based on Figure 3, the process began with the selection of measurement points based on geological conditions and the spatial distribution of the study area. Data acquisition was carried out on Monday, January 31, 2025, from 09:00 to 12:00 local time (WIB), under clear weather conditions to minimize external disturbances. Measurements were conducted at 15 points using a three-component seismograph with a recording duration of 20 minutes per point. The recorded ground vibration data were then extracted and formatted using SeismoWin software to remove noise and filter out unstable signals.

The next stage involved HVSR analysis using Geopsy software to generate H/V curves and extract the dominant frequency (f_0), amplification factor (Ag), and seismic vulnerability index (Kg). H/V graphs displaying excessive noise were excluded from further analysis. Parameter values that passed the selection were processed in Excel for further calculations, such as shear strain (*Y*) and bedrock depth (*h*).

The final data were then mapped spatially using Surfer and ArcGIS software to produce distribution maps of seismic parameters. These maps were overlaid with aerial imagery, land-use maps, and landslide history data to identify zones with high vulnerability. This approach aligns with microzonation studies in Kendari and Lumajang, which have demonstrated the effectiveness of the HVSR method for non-invasive and efficient soil vulnerability assessment [10, 20].

Figure 4. Map of the research area selected from https://earthengine.google.com/

The observation area in this study includes 15 microtremor measurement points distributed across the Sempu Area, as shown in Figure 4. These points were strategically selected based on a combination of geological and topographical parameters, as well as indicators of landslide susceptibility. Previously, Figure 4 illustrated that the Sempu Area is a residential area located on a steep slope adjacent to vegetated regions with high gradients, making it prone to ground movement. Each measurement point was determined by considering the slope angle, type of weathered volcanic lithology (Qpv), and the history of structural damage in settlements that indicate soil instability. This study is motivated by the absence of geophysics-based microzonation research in Sempu, despite the area's high susceptibility to ground movement. The HVSR method was chosen not only for its efficiency but also because it has been proven reliable in detecting site effects and dynamic soil parameters in complex volcanic regions.

Data acquisition was conducted using the microtremor method with a three-component seismograph to record natural ground vibrations without the use of an active seismic source.

The collected data were then analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method to identify the dominant frequency (f_0) and detect impedance contrasts between soft and hard subsurface layers [21,22]. In this study, special attention was given to signal quality, including a 20-minute recording duration and spectral windowing to minimize noise and ensure stability of the HVSR peak. This procedure follows established recommendations [14,15], thereby increasing the statistical reliability of the obtained resonance peaks. This technique has proven effective in mapping hazard zones in tropical volcanic regions such as Indonesia [23].

To determine the amplification factor, sediment thickness, natural frequency, subsurface seismic displacement, and soil vulnerability factor, mathematical formulations based on the method cited in [21] were applied, linking microtremor spectral analysis to the dynamic characteristics of the subsurface layers. The amplification factor is obtained from the horizontal-to-vertical spectral ratio (HVSR), while the natural frequency is identified as the peak of the HVSR curve, representing the dominant response of the sediment layer to ambient vibrations. Sediment thickness is subsequently estimated from the relationship between the dominant frequency and shear wave velocity, and the vulnerability factor is calculated as an indicator of the degree to which the soil is susceptible to wave amplification and seismic deformation.

Ground shear deformation or ground shear strain (ϒ) at the soil surface can be estimated using the following equation:

$$\Upsilon = Ag \, x \, \frac{\delta}{h} \tag{1}$$

where Ag represents the amplification factor, h is the sediment thickness, and δ denotes subsurface seismic displacement. If the S-wave velocities in the bedrock and surface layers are expressed as *Cb* and *Cs*, respectively, and the natural frequency is denoted by f_0, then:

$$f_0 = \frac{Cb}{4A_g \, x \, h} \tag{2}$$

Subsurface acceleration can be described by,

$$a_b = (2\pi f_0)^2 \, x \, \delta \tag{3}$$

Thus, by substituting Equations (1 - 3), the resulting expression becomes:

$$\Upsilon = \frac{Ag^2}{f_0} \, x \, \frac{a_b}{\pi^2 C_b} \tag{4}$$

If the efficiency of the seismic force is assumed to be a static force of $e\%$, then the effective shear strain can be expressed as $\boldsymbol{\gamma_e}$:

$$\Upsilon_e = K_g(e) x \, a_b \tag{5}$$

$$K_g(e) = e \, x \, \frac{\frac{\left(\frac{Ag^2}{f_0}\right)}{\left(\frac{a_b}{\pi^2 C_b}\right)}}{100} \tag{6}$$

The value of Cb is assumed to be nearly constant over a wide area. If Cb is taken as 600 m/s, then $1/(\pi^2 \, X \, C_b) = 1.69 \times 10^{-6}$ s/cm, and if e = 60%, then the vulnerability index **Kg(e)** is given by [21] :

$$K_g = \frac{A_g^2}{F_g} \quad (7)$$

Result and Discussion

The soil vulnerability analysis in Sempu Area, Cowek Village, Purwodadi District, Pasuruan Regency, was conducted using the Horizontal-to-Vertical Spectral Ratio (HVSR) method based on microtremor measurements to understand the soil characteristics in an area identified as having a seismic acceleration of 0.175–0.2 g. This region is dominated by volcanic deposits and weathered sedimentary rocks, which contribute to a high potential for ground movement, especially when the soil is saturated with water. Measurements using a seismograph were conducted at several points to record natural seismic vibrations, which were then analyzed to determine the dominant frequency and soil amplification, as shown in Table 1 below.

Table 1. Results of data processing at the Sempu Area landslide point

Point	f_0 (Hz)	Ag	*Kg*	*Y*	*h* (m)
1	5.23	6.18	7.29	0.00423	4.64
2	5.92	3.91	2.58	0.00149	6.48
3	5.62	3.19	1.81	0.00105	8.36
4	5.36	2.37	1.05	0.00060	11.81
5	3.27	2.89	2.55	0.00148	15.87
6	3.11	3.33	3.56	0.00206	14.47
7	3.11	4.69	7.06	0.00409	10.27
8	3.19	4.90	7.53	0.00436	9.59
9	5.92	4.16	2.92	0.00169	6.09
10	2.89	6.01	12.50	0.00725	8.63
11	4.62	2.76	1.65	0.00095	11.76
12	4.86	3.83	3.03	0.00175	8.06
13	5.63	3.91	2.71	0.00157	6.82
14	2.96	6.47	14.12	0.00819	7.82
15	2.75	4.07	6.01	0.00348	13.40

Based on the results of microtremor data processing using the Horizontal to Vertical Spectral Ratio (HVSR) method at 15 points in the Sempu Area, Pasuruan, the obtained dominant frequency (f_0) values range from 2.75 to 5.92 Hz. These values reflect the diversity of subsurface characteristics, particularly in terms of sedimentary layer thickness and soil stiffness. Points with low F_0 values, such as Point 15 (2.75 Hz) and Point 14 (2.96 Hz), indicate the presence of thick and soft sediment layers that are more susceptible to seismic wave amplification. This is consistent with [21], who stated that soft soil layers with significant thickness would lower the dominant frequency and increase the risk of soil resonance during an earthquake. Meanwhile, points with high f_0 values, such as Point 2 and Point 9 (5.92 Hz), exhibit characteristics of relatively stiffer and shallower soils, which tend to have a lower risk of amplification; however, this does not eliminate the possibility of structural deformation due to a mismatch between the natural frequency of the soil and the building.

Moreover, high amplification (*Ag*) and vulnerability factor (*Kg*) values at certain points, such as Point 14 (Ag = 6.47; Kg = 14.12) and Point 8 (Ag = 4.90; Kg = 7.53), further reinforce the indication that these areas have a high potential for seismic wave amplification. The high values of the ground shear-strain parameter (*Y*) at these points also support the interpretation that the soil in these locations behaves dynamically in response to vibrations, which can trigger ground movement when subjected to dynamic loads such as earthquakes. A study by [8] demonstrated that soils with Kg > 6 are classified as highly susceptible to resonance and amplification, requiring special attention in structural planning and risk mitigation. Additionally, the sediment layer thickness parameter (*h*) at points such as Point 5 (15.87 m) and Point 6 (14.47 m) further strengthens the indication of landslide potential, as the combination of thick and soft sediment layers reduces slope stability and increases the risk of soil deformation when saturated [24]. These results can thus be mapped through HVSR signal processing, as shown in Figure 5 below.

These findings are consistent with previous studies in Southern Italy [25], where weathered volcanic slopes with thick unconsolidated deposits produced similarly high Kg values (>12) and amplified ground motion, placing the area into critical hazard zones. Comparable results were also obtained by [26] in several landslide-prone regions of West Java, Indonesia, where HVSR analysis revealed that low f_0 (2–4 Hz) combined with high amplification factors strongly correlated with areas that had previously experienced ground movement. This comparison further validates the reliability of the Sempu results and underscores the broader geophysical principle that unconsolidated volcanic and sedimentary environments, both in Indonesia and abroad, tend to amplify seismic response and intensify ground instability risks.

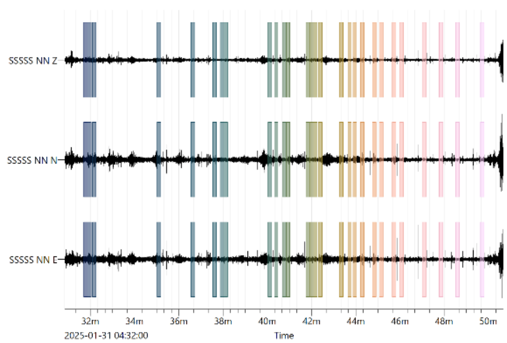

Figure 5. HVSR Signal Processing Results Point 10, Sempu Area

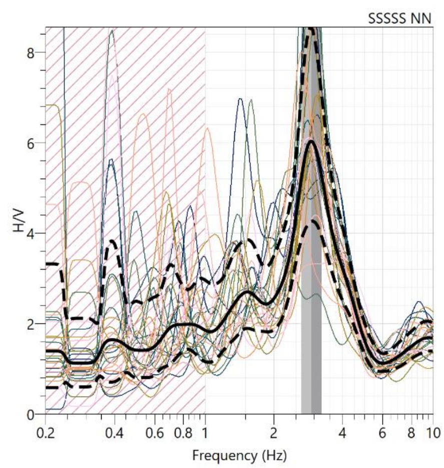

Figure 6. HVSR Graph Point 10, Sempu Area

The HVSR signal processing in Figure 5 shows three-component ambient vibration records taken from point 10 in Sempu Area. The signal, acquired over 20 minutes, exhibits a consistent amplitude distribution and clear temporal intervals of low-noise segments, which were carefully selected for Fourier transformation. Using Geopsy software, the processed signal yielded a natural frequency (f_0) of 2.89 Hz and a seismic vulnerability index (Kg) of 12.50, with an amplification factor (Ag) of 6.01 and a shear strain (Υ) of 0.00725 (Table 1). These values suggest a moderate-to-high seismic resonance response, which is typically associated with shallow, unconsolidated, and weathered volcanic deposits. The geological map (Figure 1) confirms that point 10 lies within the Qpv (Lower Quaternary Volcanics) unit, which is known to be composed of fractured breccia, tuff, and porous volcanic ash, significantly reducing the shear modulus of the ground [27].

In Figure 6, the HVSR curve exhibits a sharply defined peak around 2.8–3.0 Hz with high amplitude (~6.0), suggesting a well-developed impedance contrast between the soft soil layer and the underlying stiffer layer. This implies a localized site effect where surface layers amplify seismic waves, a phenomenon widely documented in seismically active regions [8, 9]. The steep topography shown in Figure 2 indicates that point 10 is situated along an inclined slope. This slope geometry, in combination with a soft and saturated substrate, enhances the risk of lateral soil deformation under dynamic loading. Thus, point 10 represents a geotechnically sensitive zone with potential for both strong seismic amplification and structural vulnerability, requiring detailed zonation and risk mitigation efforts.

The results from the Sempu Area reveal not only consistent geophysical behavior but also a specific risk context. For instance, previous studies in Southern Italy [25] have documented that volcanic slopes dominated by tuff deposits generate site-resonance effects that are strongly correlated with recurrent slope failures threatening nearby settlements. Meanwhile, research in West Java [26] showed that HVSR peaks in the range of 2–3 Hz coincided with structural damage in low-rise buildings, highlighting the resonance interaction between natural ground frequency and common building typologies. These comparative insights suggest that the resonance frequency observed at point 10 overlaps with the natural frequency range of typical residential structures in Sempu, meaning that even moderate earthquakes could induce amplified shaking and structural failures. This underlines not just the geological sensitivity of the site but also its direct implications for habitability and disaster risk management.

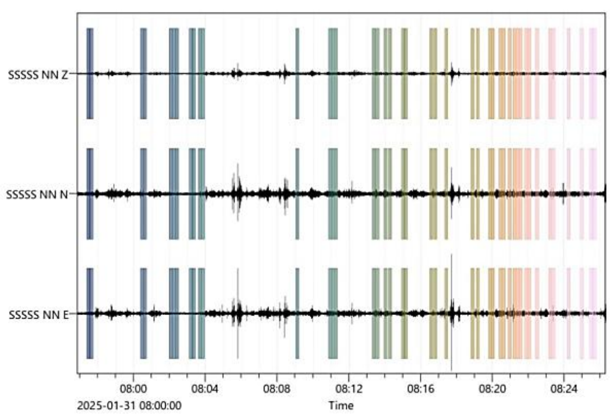

Figure 7. HVSR Signal Processing Results Point 14, Sempu Area

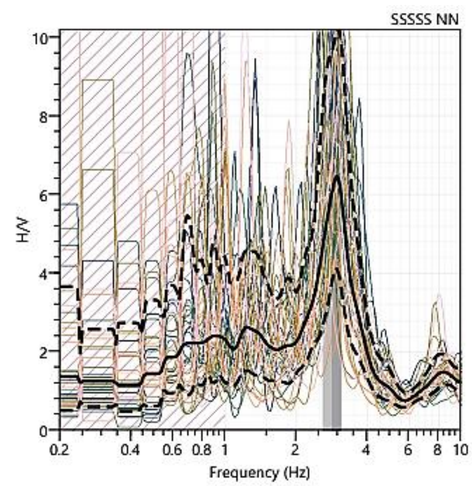

Figure 8. HVSR Graph Point 14, Sempu Area

The waveform signal captured in Figure 7 reflects the ground motion characteristics at Point 14. Compared to point 10, the signal here displays slightly more irregular fluctuations, possibly due to local heterogeneity or micro-topographic effects. Despite this, time windows for analysis were clearly extracted with a clean signal-to-noise ratio. Data processing yielded a dominant frequency (f_0) of 2.963 Hz, a Kg value of 14.123, an amplification factor (Ag) of 6, and a shear strain (*Y*) of 0.00819 (Table 1). These values represent the highest vulnerability index and strain recorded across all measurement points, highlighting this location as a critical seismic hotspot. Notably, such high *Kg* and *Y* values often correspond to soils with very low stiffness and high porosity—conditions frequently associated with landslide-prone areas during intense seismic shaking [17,25].

A distinct and tall HVSR peak centered at approximately 2.9 Hz characterizes the seismic response at point 14, indicating strong site resonance. This suggests the presence of shallow soft-soil layers overlying a denser, stiffer lithologic boundary, a condition that significantly amplifies seismic energy. The HVSR curve clearly illustrates this resonance (as shown in Figure 8). Topographically, point 14 lies at a transition zone between steep slopes and the built environment, which increases both horizontal acceleration and the susceptibility to ground displacement. In terms of geological setting, it is fully situated within the Qpv lithology (Figure 1), confirming the role of widespread surface weathering in shaping site effects. From the perspective of seismic microzonation, point 14 can thus be considered a key reference location for identifying extreme ground response behavior, representing not only the influence of subsurface stratigraphy but also the worst-case scenario of soil–structure interaction in Sempu Village.

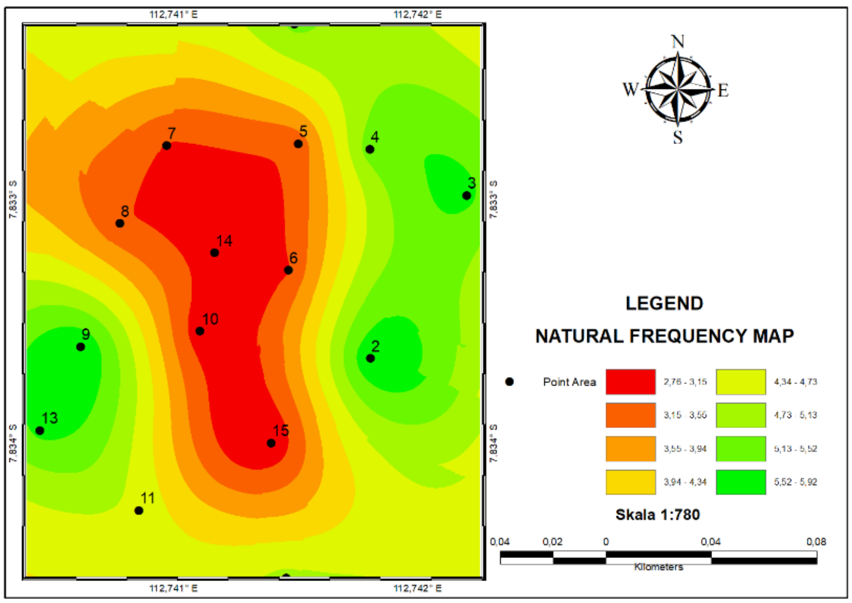

Figure 9. Natural Frequency Map (f_0)

Based on Figure 9, the Natural Frequency Map of the Sempu Area, Cowek Village, the values of dominant frequency (*f_0*) vary significantly across measurement points, ranging from 2.76 Hz to 5.92 Hz. The central region of the map, prominently marked in red, exhibits the lowest f_0 values, ranging from 2.76 to 3.15 Hz, which correspond to points 10 and 14. These two points are of particular concern due to their low-frequency response, indicating thicker and softer sediment layers that are highly prone to seismic wave amplification and ground deformation during strong ground motions. This is consistent with the high seismic vulnerability index (Kg > 12) and shear strain (Υ > 0.007) observed in these locations, making them critical zones for seismic risk assessment and microzonation.

Surrounding points, such as points 7 and 8, also fall within the same low-frequency zone, but with slightly lower vulnerability indices, indicating that transitional areas experienced gradual changes in sediment thickness. In contrast, peripheral areas, such as points 3, 4, and 13, marked in green and yellow, display higher f_0 values (> 5.0 Hz), which are typically associated with shallow and denser subsurface materials, such as compact volcanic tuff or weathered bedrock. These spatial variations in frequency are a direct reflection of subsurface heterogeneity, influenced by geological units such as the Qpv (Lower Quaternary Volcanics) and the complex topography observed in the area. The concentration of low-frequency zones around points 10 and 14 thus highlights these locations as seismically sensitive targets that require focused mitigation planning and structural reinforcement strategies [9,25].

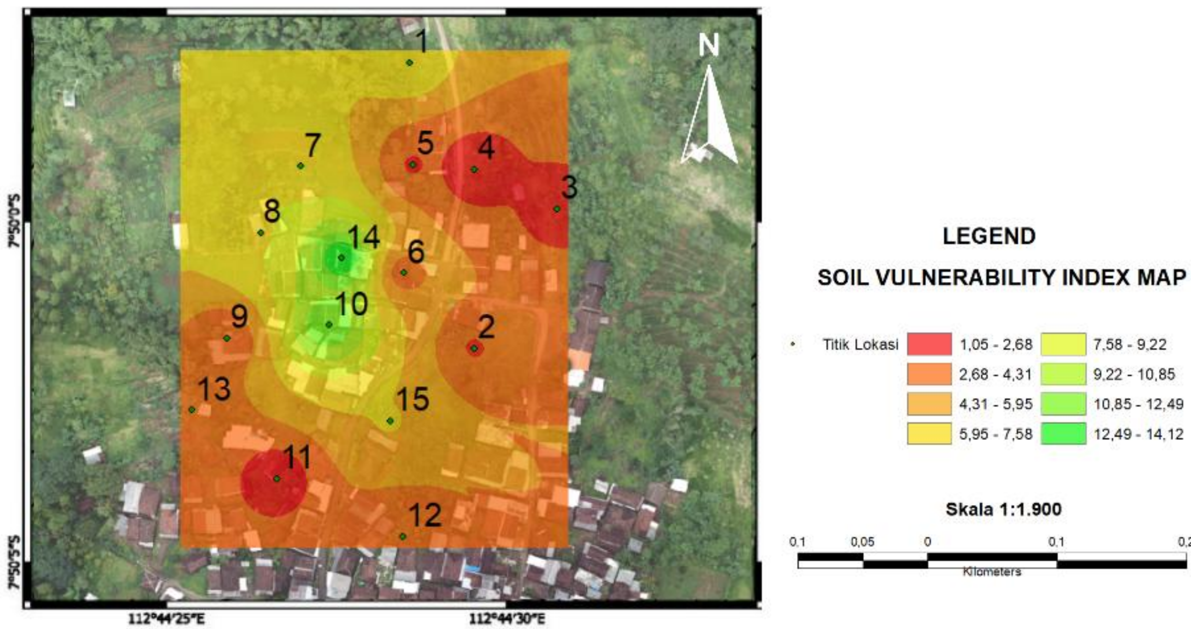

Figure 10. Soil Vulnerability Index (Kg) Map

Figure 10 illustrates the spatial distribution of the Soil Vulnerability Index (Kg) across the Sempu area, providing critical insight into subsurface instability potentially triggered by seismic events. The map reveals a clear concentration of high Kg values (coloured in deep green to yellowish shades), particularly around points 10 and 14, indicating zones with the most pronounced soil vulnerability. These spatial patterns align with underlying geological and geomorphological conditions, where terrain morphology and lithological characteristics play a decisive role in the dynamic response of the soil.

From a theoretical standpoint, areas with a high Soil Vulnerability Index ($Kg > 9$) are generally indicative of soft soil layers or unconsolidated deposits, which are highly susceptible to amplification during seismic shaking [15, 27]. In this study, point 10 ($Kg = 12.50$) and point 14 ($Kg = 12.47$) emerge as the most critical locations, reflecting extremely weak subsoil structures coupled with low fundamental frequencies (4.02 Hz and 4.57 Hz, respectively) and relatively high amplification values (12.50 and 8.33). This condition suggests that the soil at these points may consist of volcanic weathered materials, loose sediments, or have a high moisture content, which can amplify seismic energy propagation [28, 29].

Furthermore, as illustrated in Table 1, ground shear strain (Y) at points 10 and 14 is also among the lowest (0.00725 and 0.00819), suggesting relatively stable conditions despite high vulnerability indices. This apparent contradiction can be explained by the fact that although shear strain values are low, the corresponding high vulnerability index (Kg) indicates a critical resonance potential, particularly for light masonry and reinforced concrete buildings that dominate settlements in the Sempu Area. According to the NEHRP site classifications, such a condition reflects soft to medium soil prone to resonance when exposed to seismic energy, which amplifies risks despite low strain values. Compensating geological factors, such as compacted weathered volcanic materials, may provide some resistance, but their resonance characteristics pose risks to structures.

In contrast, point 3, with a low Kg of 1.05 and ϒ of 0.00060, falls into a scenario of low vulnerability but significant deformation potential. This situation likely stems from local factors such as a shallow water table and loose sediment deposits. Such inconsistencies emphasize the critical role of geological and site-specific conditions in shaping soil response, as also highlighted in previous microtremor-based studies [27, 29, 30]. Generally, Kg values under natural stable conditions range between 1.5 and 7.0, while ground shear strain (ϒ) typically falls between 0.0001 and 0.0020; however, deviations beyond these ranges should be interpreted carefully by considering both dynamic amplification effects and slope stability thresholds [30, 31].

These findings affirm that points 10 and 14 are critical monitoring areas in the Sempu region, not only due to their high vulnerability indices but also because they are located within densely populated zones with steep slopes. Therefore, soil vulnerability maps, such as those in Figures 13 and 15, are essential tools for site classification, early warning systems, and the design of slope–stability–resilient infrastructure in landslide-prone regions.

Conclusion

The HVSR-based microtremor analysis in the Sempu Area reveals clear spatial variations in dominant frequency (f_0), amplification (Ag), soil vulnerability index (Kg), and ground shear strain (ϒ), indicating significant differences in subsurface responses to dynamic loading. Zones characterized by low f_0 and high Ag and Kg values are predominantly associated with unconsolidated volcanic deposits and weathered sediments, which are highly susceptible to seismic wave amplification and deformation. The spatial correlation between these geophysical indicators and historical records of ground movement demonstrates that areas identified as high-risk coincide with previous failure zones, confirming the reliability of the applied approach for hazard assessment. Particularly, the exceptionally high Kg values (>14) and elevated shear-strain anomalies observed at points 10 and 14 suggest that substantial portions of the Sempu Area present unsafe conditions for permanent settlement following the ground movement event of 28–31 January 2025, as reported by the East Java Government. In contrast, sectors exhibiting moderate f_0 (3–5 Hz) and relatively low Kg (<5) may remain conditionally suitable for habitation, provided that rigorous engineering control and land-use regulation are implemented. Therefore, it is recommended that local governments adopt seismic microzonation results as the primary reference for resettlement planning, hazard mitigation, and the establishment of strict building regulations in the affected zones.

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