REKAYASA 20 (2) (2022): 57-99

REKAYASA

Jurnal Penerapan Teknologi dan Pembelajaran

http://journal.unnes.ac.id/nju/index.php/rekayasa

Seismic Vulnerability Microzonation Based on Dominant Frequency and Amplification Using the HVSR Method in Wedi, Changewaro (Klaten) and Gendangsari (Yogyakarta)

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DOI: https://doi.org/10.15294/rekayasa.v20i2.9957
Submit: 2024-07-19; Revisi: 2024-08-07; Accepted: 2024-09-01

Abstract

The Yogyakarta region is prone to frequent earthquakes, highlighting the need for seismic vulnerability assessment and micro zonation analysis. This study aimed to evaluate the area's seismic vulnerability by utilizing microtremor methods to estimate dominant frequency, amplification, seismic vulnerability index, and shear wave velocity. Microtremor points were analyzed using the Horizontal Vertical Spectral Ratio method, with data processed through Geopsy software to obtain f0, A0, and H/V curves. The H/V curve was further inverted using Dinver software to derive ellipticity curves, ground profiles, and Kg values. The results revealed that the dominant frequency values ranged from 0.668 Hz to 18.271 Hz, with higher values prevalent. The soil types in the area were classified as type IV and type I, primarily consisting of older, hard sandy rocks and gravels. Amplification values ranged from 1.03 to 8.36, indicating low amplification levels and placing the area in zone 1. Kg values varied from 0.066 to 15.07 s^2/cm, suggesting moderate seismic vulnerability. If an earthquake occurs, the region would experience shaking, though damage would be moderate. Vs30 values ranged from 179.64 m/s to 681.82 m/s, categorizing the soil as hard, dense, soft, or medium.

Keywords: *earthquake damage predictions, Geopsy software, seismic risk, ground Profile, soil classification*

INTRODUCTION

Indonesia is highly earthquake-prone due to its location at the intersection of three active tectonic plates: the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. These plates move in different directions, with the Eurasian Plate moving north, the Indo-Australian Plate moving relatively north and subducting beneath the Eurasian Plate, and the Pacific Plate moving westward. These movements are driven by convection currents in the Earth's mantle and lead to natural hazards such as earthquakes, volcanic eruptions, tsunamis, and other geological events (Duarte & Schellart, 2016).

The microtremor method is used to identify earthquake-prone areas in Yogyakarta, especially in Gedang Sari District, and in Klaten, specifically in Gantiwarno and Wedi Districts. Microtremors, which are low-amplitude ground vibrations from natural or human activities (like wind, sea waves, or vehicles), help assess near-surface geological conditions (Fadilah & Muttaqin, 2022). Analyzing microtremor data is essential for understanding soil characteristics impacted by earthquakes, as it aids in studying ground motion and calculating surface sediment amplification factors. Amplified seismic ground motion due to soil deposits, weathered rock, and ground instabilities (e.g., landslides and liquefaction) significantly contribute to structural damage, as seen in global earthquake data (Vessia et al., 2021).

The Horizontal Vertical Spectral Ratio (HVSR) from the investigation is interpreted to assess resonance potential during earthquakes, with spectral acceleration ratios based on MSAA data used for comparison (Putra et al., 2016). Microtremor data will be processed using the HVSR method, and HVSR Inversion will then provide insights into subsurface lithology and ground profiles, which the HVSR method alone cannot reveal. Key outcomes of the HVSR method include the dominant frequency (f_0) and soil amplification (A_0), which aid in analyzing subsurface structures and vulnerabilities. With these values, the wave velocity at 30 meters (Vs_{30}) and the seismic vulnerability index (Kg) can also be determined. This approach, used in West Palu Bay's seismic vulnerability analysis, demonstrates the effectiveness of the HVSR method in seismic risk assessment (Madrinovella, 2023).

This study is expected to provide an overview of the level of vulnerability of areas in Yogyakarta and Klaten so that the community can consider building arrangements and regional development in carrying out development in earthquake-prone areas. If an area has a high soil vulnerability index zone, then in constructing a building, the foundation can be strengthened or a building that is resistant to earthquake shocks can be built. It is also recommended that buildings be constructed better in areas that have a low soil vulnerability index zone.

METHOD

The geophysical method used to map earthquake damage-prone areas is the microtremor method. Data for this study were obtained through measurements conducted by the Class I Geophysics Station of Sleman, Yogyakarta, in collaboration with PT GIS (Geographic Information System) using portable seismographs, geological compasses, GPS devices, and laptops.

Microtremor data were collected from 27 measurement points, covering areas in Yogyakarta's Gedangsari District and in Klaten's Gantiwarno and Wedi Districts. Specifically, 10 measurement points were located in Gedangsari District, 5 in Gantiwarno District, and 12 in Wedi District as shown in Figure 1.

The following tools and software were used for data processing and analysis: Laptop for data storage and processing, Geopsy Software for analyzing the HVSR, Dinver Software for HVSR Inversion to derive subsurface lithology, Surfer 11 Software for creating surface and contour maps, Microsoft Excel for organizing and calculating data, Microsoft Word for reporting, QGIS 3.26.1 for mapping and spatial analysis, Google Earth Pro for geospatial visualization and location verification The microtremor data collected were processed to determine the dominant frequency (f_0), soil amplification (A_0), shear wave velocity (Vs30), and seismic vulnerability index (Kg) in the study areas.

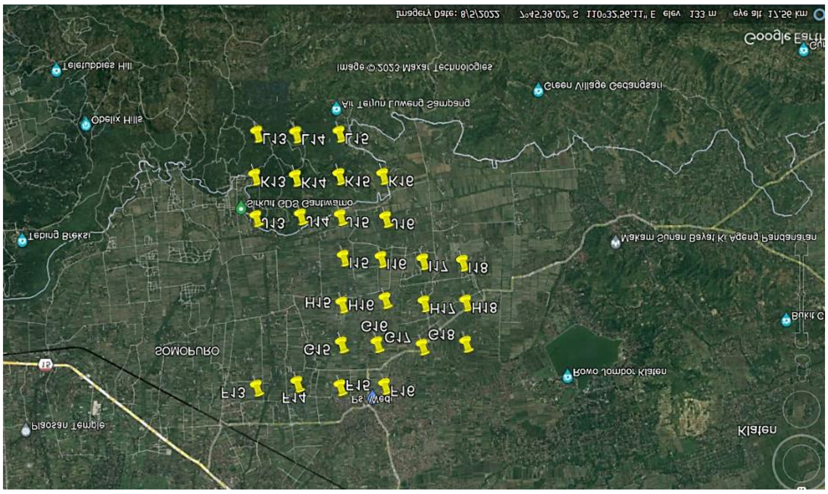

Figure 1. The Klaten area of research points, such as those in Gantiwarno District and Wedi District, using GPS coordinates.

Microtremor data processing uses the HVSR method to obtain the dominant frequency value (f_0), and amplification value (A0). The HVSR method is used to identify subsurface conditions from the spectrum peak in the form of dominant frequency values (f_0) and amplification factors (A0). The HVSR method is based on the comparison between the amplitude of the horizontal component spectrum and the vertical component (Xu and Wang, 2021). The comparison of the spectrum between the horizontal component and the vertical component is calculated using Equation 1. Where $H/V(f)$ = ratio of the horizontal and vertical component spectrum, A_{east} = EW component spectrum amplitude values, A_{north} = spectral amplitude value of NS component, and $A_{vertical}$ = amplitude value of the vertical component frequency spectrum. From the equation above, the H/V curve result will be obtained. The following is an example of the H/V curve shape shown in Figure 2.

$$H/V(f) = \frac{\sqrt{A_{east}(f)^2 + A_{north}(f)^2}}{A_{vertical}(f)^2} \quad (1)$$

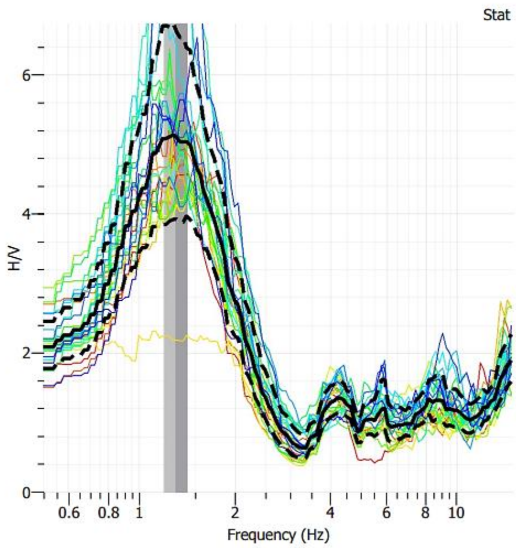

Figure 2. H/V curve from Seismic Vulnerability Microzonation study

Similar research indicates that the Seismic Vulnerability Index (Kg) of a region can be utilized to assess the susceptibility of a soil layer to deformation caused by earthquakes. The Seismic Vulnerability Index (Kg) is calculated using the dominant frequency (f_0) and the amplification factor (A_0). The equation used to determine the Vulnerability Index (Kg) is as follows equation 2. Where K_g = Seismic Vulnerability Index, A_0 = Amplification factor, f_0 = Dominant frequency. This index helps in identifying areas where the soil may be more prone to damage during seismic events.

$$K_g = \frac{{A_0}^2}{f_0} \quad (2)$$

High Seismic Vulnerability Index (Kg) values are typically found in regions with soft sedimentary rock structures, which indicate a higher susceptibility to earthquake damage. In these areas, the soil layers are more prone to deformation, increasing the potential for significant shaking and ground movement during seismic events.

On the other hand, lower Vulnerability Index values are generally observed in regions with strong and stable rock formations. These soils are more resistant to deformation, meaning that in the event of an earthquake, the area would experience milder shaking, resulting in lower vulnerability to damage.

To classify soil types and analyze geological conditions such as subsurface rock formations, shear wave velocity (Vs) is a key parameter that helps determine earthquake vulnerability. The Vs30 value refers to the shear wave velocity measured up to a depth of 30 meters and can be used to describe the subsurface lithology.

The higher the Vs30 value in a region, the harder the soil, leading to a lower level of seismic vulnerability. Conversely, lower Vs30 values indicate softer soil, resulting in a higher level of vulnerability. Below is a table summarizing the soil characteristics based on Vs30 values. This table helps illustrate how Vs30 values correlate with soil characteristics shown in Table 1., and their respective seismic vulnerability levels.

The Vs_30 value is considered an excellent indicator for characterizing the stiffness and strength of soil, as it reflects the properties of the underlying rock. The Vs_30 value is typically obtained using the following equation (Equation 3). Where Vs_{30} = Shear wave velocity averaged over the top 30 meters, di = thickness of the n-th soil layer, Vsi = Shear wave velocity of the n-th soil layer. This equation allows for the calculation of the average shear wave velocity over a 30-meter depth, providing a reliable parameter for assessing soil stiffness and the corresponding earthquake vulnerability in a given region.

$$Vs_{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{h_i}{Vs_i}\right)} \quad (3)$$

RESULT AND DISCUSSION

The results obtained from this study are the dominant frequency value (f_0), amplification value (A0), shear wave velocity at a depth of 30 meters (Vs_30), and vulnerability index value (Kg). In this study, microtremor data processing using the HVSR method produces a H/V curve, which is then continued with H/V curve processing using Dinver software and produces the Vs_30 value.

Table 1. Soil Characteristics Based on SNI 1726 – 2019 (BSN, 2019).

$\mathbf{Vs_{30}}$ value (m/s)	Soil classification
$\mathbf{Vs_{30}} \geq 1500$	hard rock
$750 \leq \mathbf{Vs_{30}} < 1500$	medium rock
$350 \leq \mathbf{Vs_{30}} < 750$	hard, very dense soil, and soft rock
$175 \leq \mathbf{Vs_{30}} < 350$	medium soil
$\mathbf{Vs_{30}} < 175$	soft soil

Dominant Frequency Analysis (f_0)

The natural or dominant frequency (f_0) is an inherent frequency of vibration present in a specific area, and its magnitude provides significant insight into the characteristics, local geology, and surface conditions of the region. The dominant frequency is directly related to the hardness of the surface rock layers. In general, a higher dominant frequency value (f_0) indicates harder soil or rock, resulting in lower seismic vulnerability. Conversely, lower dominant frequency values suggest softer soil types, which increase the area's susceptibility to earthquake damage.

The relationship between dominant frequency and soil hardness makes f_0 an important parameter in seismic vulnerability assessments. For instance, areas with higher dominant frequency values are typically more resistant to ground shaking and suffer less damage in the event of an earthquake. On the other hand, regions with lower f_0 values are prone to greater amplification of seismic waves, leading to more significant shaking and potential structural damage.

The distribution of dominant frequency values (f_0) in the study area, which includes Gedangsari District in Yogyakarta and Gantiwarno and Wedi Districts in Klaten, was mapped using Surfer 13 software. This map helps visualize the variation of soil hardness and seismic vulnerability across the region, offering critical information for mitigation and planning efforts aimed at reducing earthquake impacts.

Based on the map mentioned above, the dominant frequency (f_0) values range from 0.668363 Hz to 18.2714 Hz. The area with the highest dominant frequency is at point G17, located in Birit Village, Wedi District, Klaten, with a dominant frequency (f_0) value of 18.2714 Hz. Meanwhile, the area with the lowest dominant frequency is at point I16, located in Dengkeng Village, Wedi District, Klaten, with a dominant frequency (f_0) value of 0.668363 Hz. These variations in dominant frequency indicate the differences in soil types and hardness across the region, with higher values corresponding to harder soil or rock, suggesting lower seismic vulnerability, while lower values suggest softer soil, indicating higher vulnerability to earthquakes.

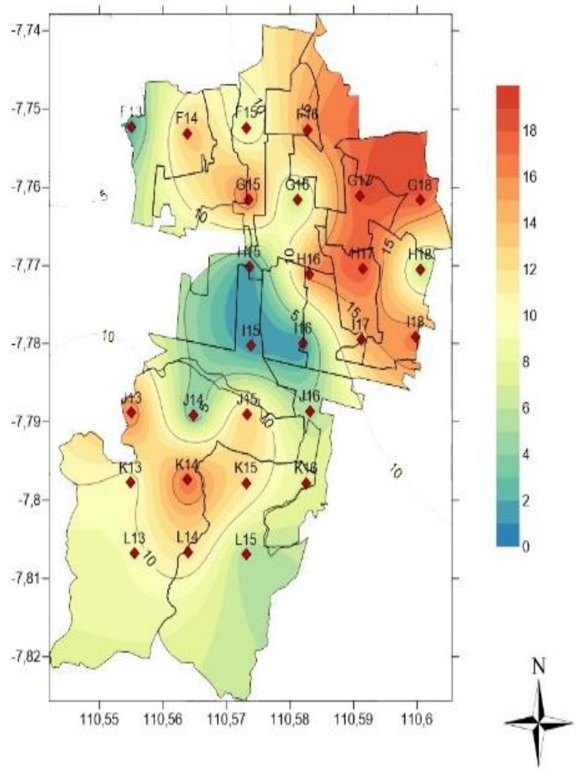

Figure 3. Map of distribution of f_0 values in the Yogyakarta area

In Figure 3, the points F13, H15, I15, and I16, marked in blue, have dominant frequency (f_0) values of 1.81011 Hz, 1.09286 Hz, 1.01905 Hz, and 0.668363 Hz, respectively. These points are classified as soil types I and II, as well as type IV, where the subsurface at these points consists of alluvial deposits formed by delta sedimentation, topsoil, and mud with depths greater than 30 meters. The sediment thickness at these four points is quite substantial, indicating that the level of vulnerability at these locations is very low.

At point J14, marked in green with an f_0 value of 3.0919 Hz, the area is classified as type III soil, the subsurface consisting of alluvial deposits thicker than 5 meters, composed of sandy gravel, hard sandy layers, clay, and loam. The thickness of the surface sediment in this area is categorized as thick, ranging from 10 to 30 meters, which also indicates relatively low vulnerability.

Meanwhile, points G16, H18, and L15, with f_0 values of 5.77291 Hz, 5.56096 Hz, and 4.92155 Hz, respectively, and marked in light green, belong to the type II soil classification. The alluvial deposits in these areas are around 5 meters thick and consist of sandy gravel, hard sandy layers, clay, and loam. The sediment thickness at these points is categorized as medium, ranging from 5 to 10 meters. Although their vulnerability is higher than the previous points, they still show a relatively moderate level of vulnerability.

At points F14, F15, F16, G15, G17, G18, H16, H17, I17, I18, J13, J15, K13, K14, K15, K16, L13, and L14, with each point having an f_0 value of 14.0088 Hz, 7.64079 Hz, 15.8817 Hz, 17.4526 Hz, 18.2714 Hz, 17.9285 Hz, 16.0106 Hz, 18.2454 Hz, 14.6217 Hz, 16.6811 Hz, 16.6059 Hz, 13.4942 Hz, 8.83425 Hz, 17.5159 Hz, 11.8487 Hz, 7.65769 Hz, 9.32836 Hz, and 11.9337 Hz, respectively, are marked in shades from orange to red. These points fall under soil type IV, category I, where, based on classifications, the subsurface consists of tertiary or older rocks, primarily hard sandy rock and gravel. The surface sediment layer is very thin and dominated by hard rock formations.

Based on the classification, the research points in Gantiwarno District and Wedi District in Klaten, as well as Gedangsari District in Yogyakarta, are predominantly in areas with high f_0 values, indicating low vulnerability. This suggests that in the event of an earthquake, these research locations are at a low risk of experiencing significant damage. Disaster risk management by local governments to comprehensively describe the types of rocks (Asnawi et al., 2022).

Amplification Analysis (A_0)

Amplification represents the peak amplitude derived from microtremor data analysis, and its factor value is influenced by wave velocity. When wave velocity decreases, the amplification factor increases, signifying a correlation with rock density; reduced rock density raises the amplification factor. This is due to soft sediments that slow down wave propagation, extending the duration of ground shaking in that area (Gomberg et al., 2021), which can result in increased shaking of buildings, and vice versa.

The higher the amplification factor, the greater the shaking experienced, which increases the risk of damage in an area. Conversely, the lower the amplification factor, the smaller the shaking, resulting in less damage. The scaling laws make it difficult to accurately estimate the near-field ground motion parameters because of the roles of control factors, such as tunnel geometry, damage zone distribution, and seismic source parameters (Wang et al., 2022). The following is a map showing the distribution of Amplification (A0) values in D.I Yogyakarta (Gedangsari District) and Klaten (Gantiwarno and Wedi Districts), obtained using Surfer 13 software, as shown in Figure 4.

Based on the distribution map above, the amplification values range from 1.03092 to 8.36024. The area with the lowest amplification value is located at point H16, specifically in Dengkeng Village, Wedi District, with an amplification (A0) value of 1.03092. Meanwhile, the area with the highest amplification value is at point F14, specifically in Ceporan Village, Gantiwarno District, with an amplification (A0) value of 8.36024. The minimum amplification value is achieved to provide an approximation that this area will not amplify the effects of future earthquakes (Tuncel et al., 2017).

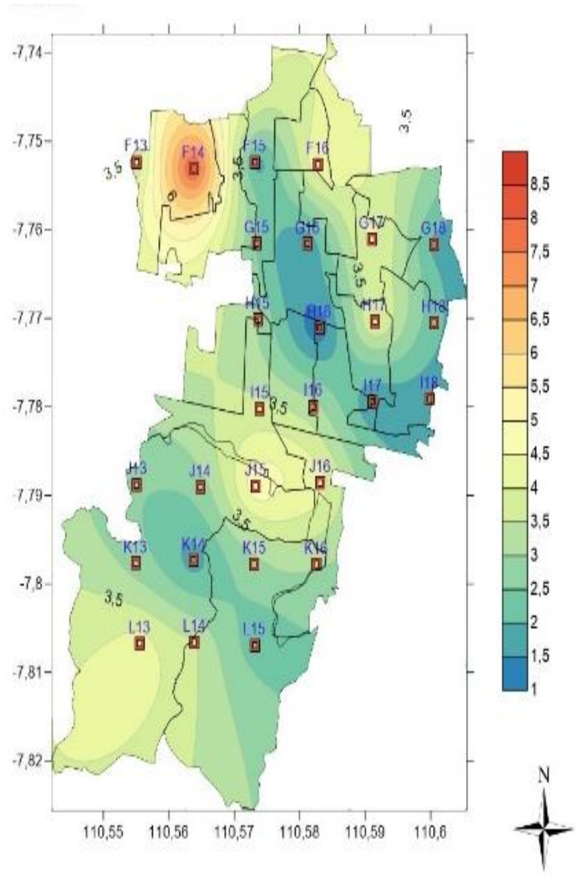

Figure 4. Map of Distribution of Amplification Values (A_0)

According to Figure 4, points F15, G15, G16, G18, H16, H18, I17, I18, J13, J14, K13, K14, K15, and L15, marked in green to blue, each have an A0 value of 1.66527; 2.43399; 1.52049; 1.79261; 1.03092; 2.14899; 1.491; 1.66424; 2.5733; 2.7177; 2.78088; 1.69631; 2.82237; 2.23296, classified in Zone 1 with low amplification. Points F13, F16, G17, H15, H17, I15, I16, J15, J16, K16, L13, and L14, marked in greenish-yellow, each have an A0 value of 3.49191; 4.52827; 4.17868; 3.00284; 4.1794; 3.64916; 3.17384; 4.8983; 4.2637; 3.03226; 4.25547; 3.54129, classified in Zone 2 with medium amplification. Point F14, marked in red, has an A0 value of 8.36024 and is classified in Zone 3 with high amplification. Based on these classifications, the research points in Gantiwarno District, Wedi District, Klaten, and Gedangsari District, Yogyakarta, are predominantly in areas with low A0 values, placing them in Zone 1.

Analysis of Shear Wave Velocity at a Depth of 30 meters (Vs_{30})

Vs_30 represents the shear wave velocity at a depth of up to 30 meters. The average shear wave velocity from the surface to this depth can serve as a parameter for analyzing geological conditions and earthquake vulnerability. The shear wave velocity (Vs) profile obtained at each measurement point reveals variations in subsurface rock types. Softer rock results in a lower shear wave velocity (Vs) because Vs is directly proportional to rock density. The lower the rock density, the lower the shear wave velocity; conversely, as rock density increases, the shear wave velocity also increases.

The higher the Vs_30 value in an area, the harder the soil type in that region, resulting in a lower level of vulnerability. Conversely, a lower Vs_30 value indicates softer soil, leading to higher vulnerability in that area. The following is a map showing the distribution of shear wave velocity values at a depth of 30 meters (Vs_30) in D.I Yogyakarta (Gedangsari District) and Klaten (Gantiwarno and Wedi Districts), obtained using Surfer 13 software.

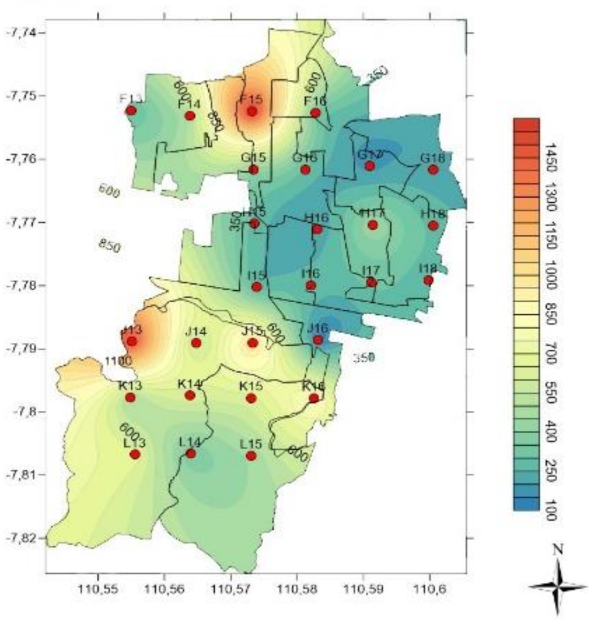

Figure 5. Distribution of Vs_30 Values in Wedi and Gantiwarno Districts

Based on the distribution map of Vs_30 values shown in Figure 5, the Vs_30 values range from 112.781 to 1578.947 m/s. The area with the highest Vs_30 value is at point F15, precisely in Kalitengah Village, Wedi District, with a Vs_30 value of 1578.947 m/s. Conversely, the area with the lowest Vs_30 value is at point J16, located in Karangturi Village, Gantiwarno District, with a Vs_30 value of 112.781 m/s.

At points F15 and J13, marked in red, with Vs_30 values of 1578.947 m/s and 1507.537 m/s respectively, the classification is hard rock. At points J15 and K16, marked in yellow, with Vs_30 values of 1034.482 m/s and 840.336 m/s respectively, the classification is medium rock. At points F14, G15, H17, J14, K13, K14, K15, L13, L14, and L15, marked in yellow-green, with respective Vs_30 values of 491.803 m/s, 410.958 m/s, 454.545 m/s, 555.556 m/s, 480.332 m/s, 635.593 m/s, 625 m/s, 681.818 m/s, 357.142 m/s, and 461.538 m/s, the classification is hard soil, very dense, and soft rock. Further, at points F13, F16, G16, G17, G18, H15, H16, H18, I15, I16, I17, and I18, marked in blue-green, with respective Vs_30 values of 300 m/s, 333.333 m/s, 288.333 m/s, 179.64 m/s, 208.333 m/s, 283.018 m/s, 202.702 m/s, 283.018 m/s, 260.869 m/s, 283.018 m/s, 315.789 m/s, and 256.41 m/s, are classified as medium soil. At point J16, marked in blue, with a Vs_30 value of 112.781 m/s, the classification is soft soil.

The shear wave velocity mapping results up to a depth of 30 meters (Vs_30) indicate that most of Wedi District, Gantiwarno District, and Gedangsari District have relatively moderate Vs_30 values, ranging from 179.64 m/s to 681.818 m/s. Based on these results, the study area falls into the categories of hard soil, very dense soil, soft soil, and medium soil. This classification suggests that the study area is vulnerable to damage in the event of an earthquake (Harirchian, et al., 2021)

Seismic Vulnerability Index Analysis

The seismic vulnerability index can describe the level of susceptibility of surface soil layers to deformation during an earthquake (Supriyadi et al., 2022). The seismic vulnerability index indicates the degree of risk associated with earthquake disasters based on the geological conditions of the area. The importance of shallow soil engineering geological classification is as a tool for early estimation of seismic response in large areas with minimal detailed data (Romagnoli et al., 2022).

The higher the value of the vulnerability index (Kg), the more the area is recognized as vulnerable to earthquakes, typically found in soil with soft sedimentary rock lithology. Conversely, a lower value of the seismic vulnerability index (Kg) indicates a reduced risk of earthquake vulnerability, generally associated with soil containing strong and stable rock components, resulting in only minor shocks during an earthquake. As the value of the seismic vulnerability index (Kg) increases in an area, the level of building damage caused by an earthquake also tends to rise. This is because a higher vulnerability index (Kg) reflects a lower stability of the soil structure, leading to a greater likelihood of building damage when an earthquake occurs. Structural damage is not only structure-dependent but is also related to the dynamic behaviour of soil layers and local soil conditions (Akkaya, 2020).

Based on the distribution map of the vulnerability index values as shown in Figure 6, the kg value ranges from 0.066380776 s2/cm – to 15.07154098 s^2/cm. The area with the lowest Kg value is at point H16, precisely in Dengkeng Village, Wedi District with a Kg value of 0.066380776 s^2/cm. This shows that the area is the most stable area and if an earthquake occurs, the point will not experience severe damage. Meanwhile, the area with the highest Kg value is at point I16, precisely in Dengkeng I Village, Wedi

District with a Kg value of 15.07154098 s2/cm. A context-based damage detection approach combines edge textures, spatial relationships, and multispectral grey tones. Damage is classified into three scales based on the debris-to-building area ratio: none (<25%), light (25–50%), and moderate (>50%) (Li & Tang. 2020).

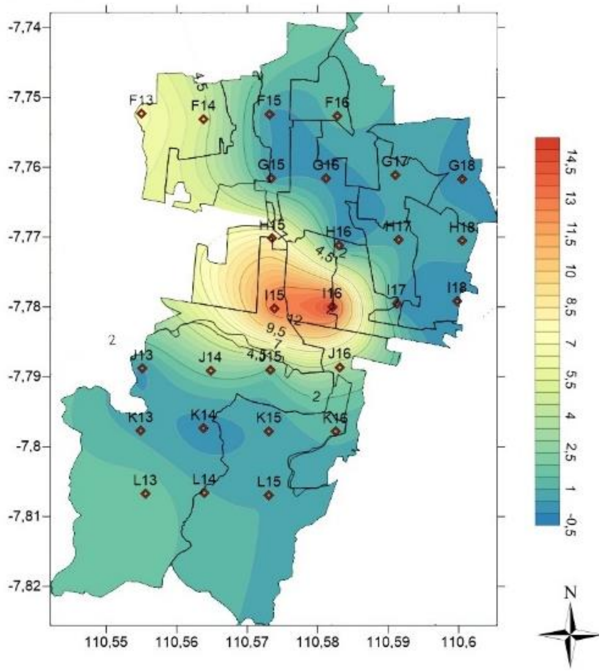

Figure 6. Distribution of Vulnerability Index Values

This shows that the area is the most unstable and if an earthquake occurs at that point, the damage will be the most severe. The highest values for all parameters, with a risk correlation above 74%, making it the area most vulnerable to earthquake damage (Loveka et al., 2021). The probability of building damage accurately predicts building vulnerability to earthquakes, with a prediction accuracy of about 75.81%, assessing both the safety and vulnerability of residential buildings (Saputra et al., 2017).

The seismic vulnerability index in Wedi District, Gantiwarno District, and Gedangsari District is included in the moderate category with a range of Kg values between 0.066380776 s2/cm – 15.07154098 s^2/cm. This is also supported by data on damage from the earthquake in Yogyakarta in 2006 which shows that Wedi District, Gantiwarno District, and Gedangsari District experienced building damage in the moderate category. The vulnerability index values reference can be used for regional development to classify whether it is safe or not to build in the area even though it is a fairly developed area (Edison et al., 2021).

CONCLUSION

The dominant frequency value (f_0) in the study area ranges from 0.668363 Hz to 18.2714 Hz, with the highest value at point G17 in Birit Village and the lowest at point I16 in Dengkeng Village, both located in Wedi, Klaten. The area is predominantly characterized by high f_0 values, indicating low vulnerability. The soil classification is type IV, consisting of Tertiary or older rocks, including hard sandy and gravel materials. Amplification values range from 1.03092 to 8.36024, with the lowest at point H16 in Dengkeng and the highest at point F14 in Ceporan, indicating low amplification in the study area. The amplitude bedrock motion and amplification factor are strongly correlated (Kumar et al., 2015).

The seismic vulnerability index (Kg) ranges from 0.066380776 s^2/cm to 15.07154098 s^2/cm, categorizing the seismic vulnerability in Wedi, Gantiwarno, and Gedangsari as moderate, suggesting that earthquake impacts will not be severe. Additionally, the Vs_{30} values are relatively moderate, between 179.64 m/s and 681.818 m/s, indicating a mixture of hard, very dense, soft, and medium soils in the research area.

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