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Identification of Seismic Vulnerability in Sleman Regency Based on Site Effect Analysis Using Microtremor Data

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Abstract

Yogyakarta is a province in the southern part of Java Island which is close to volcanoes. In this area there are sedimentary materials, such as silt, sand, tuff, breccia, agglomerate and conglomerate so that they are at risk of being affected by local site effects when an earthquake occurs. This study aims to determine earthquake vulnerable zones in several areas in Sleman Regency, including Berbah, Kalasan and Prambanan Districts based on site effect analysis with dominant frequency parameters (f0), amplification factor (A0) and seismic vulnerability index (Kg) using micro seismic data with data of 27 points which are then processed using the Horizontal to Vertical Spectral Ratio (HVSR) method and micro zonation using Geographic Information System (GIS). The results of data processing show that the site class in Sleman Regency is divided into 3, namely SD (Medium Soil), SC (Very Dense Soil) and SB (Rock). Areas with rock formations with soft soil structures are the most vulnerable areas to earthquakes. The lowest Vs_{30} value is at point M1 located in Tegaltirto Village, Berbah District, Sleman Regency with a value of 190,476 m/s, so it can be concluded that this area is the most vulnerable area to earthquakes compared to other areas in this research area.

Keywords: amplication factor, earthquake, geographic system, sedimentary materials, volcanoes

INTRODUCTION

Yogyakarta is a province located in the southern part of Java Island, close to volcanoes, making it an area prone to volcanic earthquakes and volcanic eruptions. Furthermore, the province is also close to the subduction zone of the Indo-Australian plate under the Eurasian plate and the active Opac fault, making it prone to earthquakes. On May 27, 2006, a major earthquake measuring 6.3 MW struck Yogyakarta, with an epicenter at 8.03°S 110.32°E and a hypocenter at 11.3 km. This resulted in 5,716 deaths, 126,326 homes being severely damaged, and 1,275 infrastructure being severely damaged (Arifudin, 2021). The risk of earthquakes and tsunamis in the Yogyakarta region can be minimized through mitigation efforts to prevent similar incidents from recurring in the future.

In this study, the Yogyakarta region

studied is Sleman Regency, specifically in Berbah District, Kalasan District and Prambanan District. The area is the eastern region, namely the dry land area and the source of white stone materials with plains of the Young Merapi Volcanic Sediment Formation (Qmi) and young limestone formations, namely the Semilir Formation (Tms), so that this area contains sedimentary materials, such as silt, sand, tuff, breccia, agglomerate and conglomerate which cause a high risk of being affected by local site effects when an earthquake occurs (Burjanek et al., 2014; Panzera et al., 2013).

In earthquake disaster mitigation, a classification of land vulnerability is needed based on the parameters of the dominant frequency value (f0), amplification factor (A0) and seismic vulnerability index (Kg) with HVSR method. Areas with higher amplification factors tend to coincide with unconsolidated deposits (Nuraeni et al., 2018). This study aims to identify earthquake-prone zones in Berbah, Kalasan, and Prambanan Districts based on site effect analysis with these parameters using microseismic data. Several studies have successfully used the HVSR method to identify site effects and estimate local seismic parameters, such as those conducted by Maimun et al. (2020) in Tangerang and Prasisila et al. (2021) in Bengkulu. The HVSR method was chosen because it is practical, non-destructive, and capable of effectively estimating f0 and A0 parameters using microtremors (Nakamura, 2019). HVSR analysis has been applied in urban areas to assess site effects and characterize local sediment thickness (Mendoza, 2019).

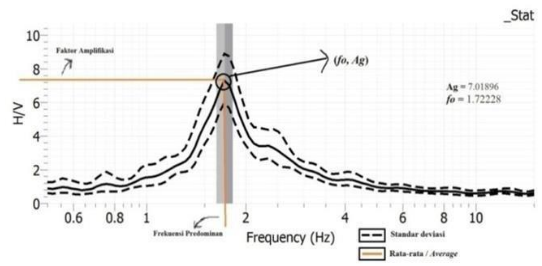
METHOD

The research was conducted in Sleman Regency, namely in Berbah District, Kalasan District and Prambanan District using the microseismic method, namely using portable seismograph equipment, geological compass, GPS, and laptop, with a total of 27 measurement points. The operational standard for measurements with this equipment with a measurement time of 30 minutes for each point (Nakamura, 2019). The dominant frequency (f0) and amplification factor (A0) values in this microseismic data processing were obtained from the HVSR curve using the Horizontal to Vertical Spectral Ratio (HVSR) method. The HVSR method's reliability has been validated through constrained H/V approaches and comparative site investigations (Castellaro & Mulargia, 2015). The H/V curve is obtained from the following Equation (1), where $A_{(U-S)}(f)$ is the amplitude value of the North-South component of the frequency spectrum, $A_{(B-T)}(f)$ is the amplitude value of the West-East component of the frequency spectrum, and $A_{(V)}(f)$ is the amplitude value of the Vertical component of the frequency spectrum.

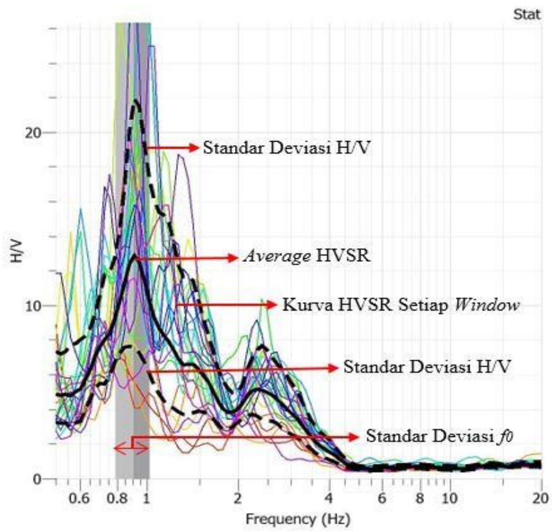
$$HVSR = \frac{\sqrt{(A_{(U-S)}(f))^2+(A_{(B-T)}(f))^2}}{(A_{(V)}(f))} \qquad (1)$$

The HVSR curve generated from processing microseismic data to obtain the dominant frequency (f0) and amplification factor (A0) shown in Figure 1a and Ib. The HVSR method has been widely adopted in regional-scale vulnerability assessments (Putri, et al., 2016). The accuracy of f_0 estimates can be assessed by analyzing the stability and statistical variation of individual HVSR windows (Martínez-Cuevas, et al., 2021).

The seismic vulnerability index (Kg) is obtained using equation (2) by entering the parameters of the dominant frequency value (f0) and the amplification factor (A0) shown in Equation (2), which are derived from site response measurements (Tanjung et al., 2017)



(a)



(b)

Figure 1. HVSR Curve Results: (a) Final HVSR Curve with f_0 and A_0; (b) Windowed Curves with Average and Standard Deviation

$$Kg = \frac{{A_0}^2}{f_0} \tag{2}$$

where, Kg is the seismic vulnerability index, A0 is the amplification factor, and f0 is the dominant frequency. The results of the microseismic data processing are then continued to create microzonation for each parameter using GIS.

Vs_{30} is the shear wave velocity up to a depth of 30 meters from the surface, the value of which can be used to determine the standards for earthquake-resistant buildings. The shear wave velocity (Vs) is obtained from the H/V curve analysis using the elliptical curve inversion method using the Dinver program with soil parameters sourced from the research of Socco et al., (2014). The results of the HVSR curve inversion method are ground profiles of shear wave velocity (Vs). The red line in the ground profiles in Figure 2 shows the model with the best misfit value. Surface wave methods and ellipticity curve inversion are essential for estimating Vs_{30} (Foti et al., 2017).

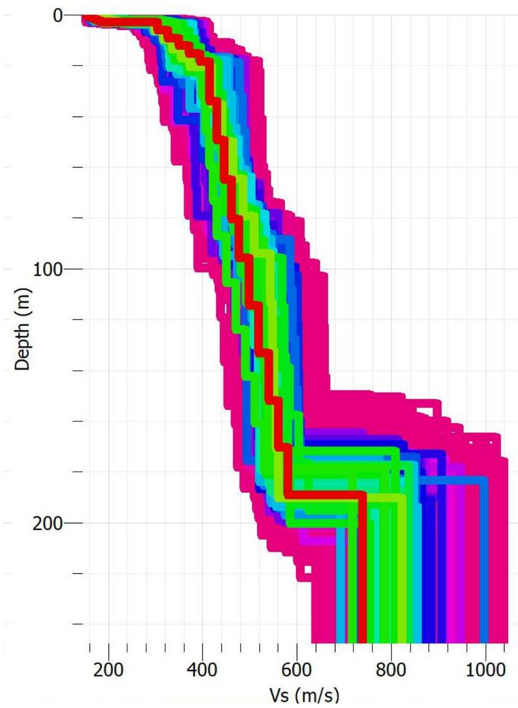


Figure 2. Results of Ground Profiles I4

After the shear wave velocity (Vs) at each research point is obtained, Vs_{30} can then be calculated using Equation (3), where h_i and vs_i respectively state the thickness in meters and the shear wave velocity (m/s) in the-i layer of a total of N layers above 30 m.

$$Vs_{30} = \frac{30}{\sum_{i=1}^{n} \frac{h_i}{Vs_i}} \tag{3}$$

In addition to being used to design earthquake-resistant building standards, the Vs_{30} value is also used to determine rock classification based on the strength of earthquake vibrations due to local effects. The classification of rock types based on Vs_{30} shown in Table 1.

Tabel 1. Soil Types Based on SNI 1726:2019

Site Class	**V_{s30} (m/s)**
SA (Hard Rok)	> 1.500
SB (Rock)	750 – 1.500
SC (Hard, Very Dense Soil and Soft Rock)	350 – 750
SD (Medium Soil)	175 – 350
SE (Soft Soil)	< 175

RESULT AND DISCUSSIOIN

Micro zonation of Dominant Frequency (f0) in Sleman Regency

Analysis of the dominant frequency map distribution is used to identify vulnerable zones. The dominant frequency is inversely proportional to the soil vulnerability. The lower the dominant frequency value, the thicker the sediment layer. This is because seismic waves trapped in thick, soft sediment for a long time make areas with thick, soft sediment layers highly susceptible to damage from seismic waves. Conversely, if the dominant frequency value is high, an area tends to have a low level of vulnerability due to the thin sediment layer, which tends to be more compact. The characteristics of subsurface rocks can be identified from their dominant frequency values, based on the 1983 Kanai classification by Arifin et al. (2014).

In general, the distribution of f0 values in Sleman Regency follows a uniform pattern with the geological formations in the area. Based on data processing, the variation in f0 values in Sleman Regency ranges from 0,810 to 17,709 Hz, as shown in Figure 3.

Based on the Kanai classification in 1983, areas with frequencies < 2.5 Hz (points AI, AJ, G2, G3, H1, H2, H4, I1, I2, I3, I4, J1, J2, J5, K1, K2, M1, M2, M4, and M5) have soil type IV criteria which are described as alluvial plains. The classification results are in accordance with geological conditions, where the measurement points are areas in Kalasan and Berbah Districts which are in the Young Merapi Volcanic Sediment Formation (Qmi). Meanwhile, areas with higher frequencies (> 6.25 Hz), namely points AR, G1, H3, J4, L4, and L6 which are mostly located in Prambanan District are in the Young Merapi Volcanic Sediment Formation (Qmi) and young limestone formations, namely the Semilir Formation (Tms). Based on the Kanai classification, frequencies > 6.25 Hz are in the criteria for soil types I and II, where in these areas there is a thinner sediment layer, dominated by hard rocks, thus causing the area around the research point with a high dominant frequency value to not have the potential to experience damage during an earthquake due to seismic wave shocks. The relationship between dominant frequency, sediment thickness, and shear wave velocity is also confirmed in recent studies (Wibowo & Huda, 2020).

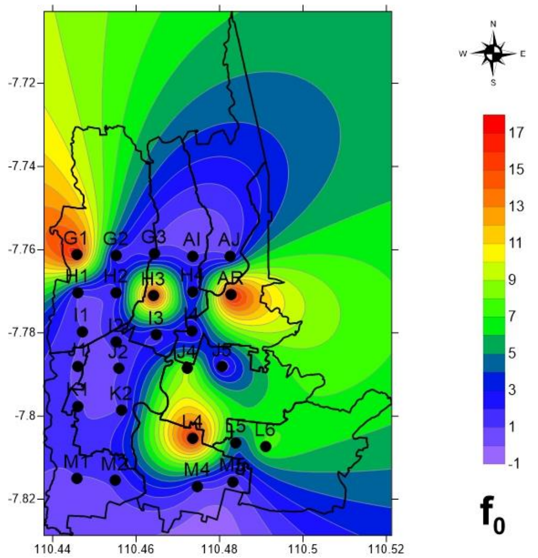


Figure 3. Micro zonation of Dominant Frequency (f0) in Sleman Regency

Micro zonation of Amplification Factors (A0) in Sleman Regency

The amplification factor is a factor related to wave amplification. Based on earthquake engineering studies, areas with softer lithology are at higher risk of damage during earthquakes. This is because these areas experience greater wave amplification compared to more compact rocks. Therefore, an area with a high amplification value is likely to experience strong shaking during an earthquake due to its softer material composition. Conversely, areas composed of harder materials are likely to experience less damage during earthquakes due to their lower amplification values. This condition is strongly influenced by local geological conditions.

Based on data processing, the variation in A0 values in Sleman Regency ranges from 2,341 to 5,228, as shown in Figure 4.

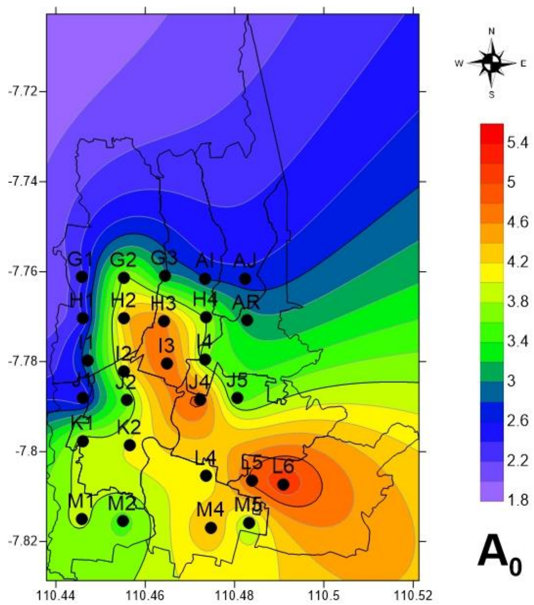


Figure 4. Micro zonation of Amplification Factor (A0) in Sleman Regency

Based on the data processing results, the higher A0 values are at the measurement points AR, G2, G3, H2, H3, H4, I2, I3, I4, J2, J4, J5, K1, K2, L4, L5, L6, M1, M2, M4, and M5 with an amplification value of > 3 (according to the Kanai classification) located in Prambanan District, Berbah District and Kalasan District which are plains containing sandstone or alluvial. This condition is in accordance with the geological formations in these districts, namely the Semilir Formation (Tms) and the Young Merapi Volcanic Sediment Formation (Qmi). The alluvial plain formation (Qa) which is composed of gravel, sand, silt and clay is a material that is included in the sedimentary material category. Areas dominated by sedimentary material have the possibility of increasing amplification if an earthquake occurs (Yilmaz & Bulut, 2016). This indicates that the areas at these research points tend to have a higher potential for resonance, which can cause strong shaking during an earthquake, because they consist of a softer surface layer than the low-value A0 point. Meanwhile, low A0 values are found at measurement points AI, AJ, G1, H1, I1, and J1, located in Kalasan District with the Young Merapi Volcanic Sediment Formation (Qmi). Low A0 values represent that the subsurface layers in these formations tend to be less likely to experience wave resonance during an earthquake.

Micro zonation of the Seismic Vulnerability Index (Kg) in Sleman Regency

The seismic vulnerability index (Kg) represents the level of vulnerability of the surface soil layer to deformation during an earthquake (Tanjung et al., 2019). Factors influencing the seismic vulnerability index include sediments with low solidity, while more solid and stable rocks tend not to cause amplification. The seismic vulnerability index depends on the value of the amplification factor (A0). The higher the seismic vulnerability index, the greater the level of danger and damage to buildings during an earthquake. High Kg values indicate a higher vulnerability to seismic shaking, particularly in sedimentary zones with thick deposits (Syah et al., 2017).

Based on the results of data processing, the seismic vulnerability index in Sleman Regency varies from 0,319 to 18.399368, as shown in Figure 5, with a high concentration of seismic vulnerability index (> 6), namely points AI, AJ, G2, G3, H2, H4, I1, I2, I3, I4, J1, J2, J5, K1, K2, L5, M1, M2, M4, and M5 are predominantly located in Berbah District and Kalasan District. Meanwhile, for the low concentration of seismic vulnerability index (< 3), namely points AR, G1, H3, J4, and L4 are predominantly located in Prambanan District and Kalasan District. Wibowo & Huda (2020) concluded that the effects of earthquakes can occur in areas with a range of seismic vulnerability index values of 20 to 100, so that based on this statement, Sleman Regency (Berbah District, Kalasan District and Prambanan District) is still in a safe zone against the impact of earthquakes because based on data processing it was obtained that all seismic vulnerability index values in this measurement point were <20. The Prambanan area, which shows relatively lower Kg values, aligns with findings from previous microtremor studies in the same region (Utami et al., 2017).

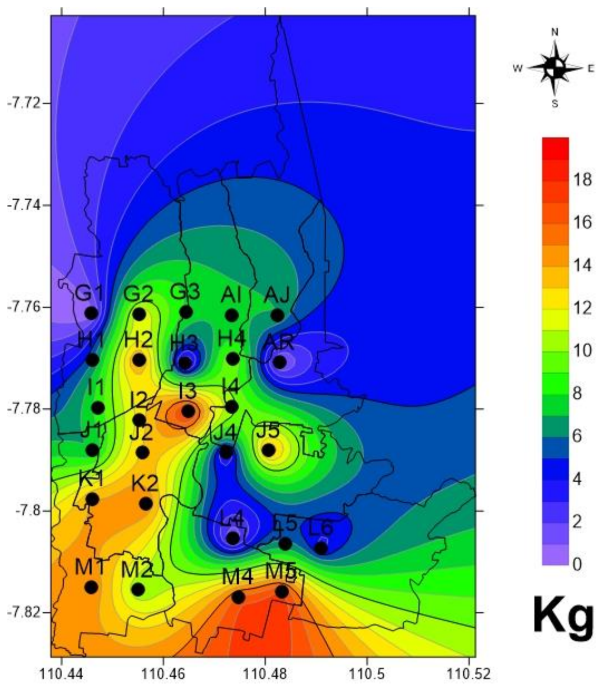


Figure 5. Micro zonation of Seismic Vulnerability Index (Kg) in Sleman Regency

Site Class Micro zonation in Sleman Regency

Vs_{30} value analysis is used to determine the surface soil classification down to a depth of 30 meters. The 1D shear wave velocity (Vs) profiles generated at each measurement point also show differences in subsurface rock types according to their soil composition. The softer the rock, the lower the Vs_{30} value. This is because the Vs_{30} value is directly proportional to the rock's density. The lower the rock's density, the lower the Vs_{30} value, and vice versa. Low Vs_{30} values correlate with areas dominated by sedimentary material, while high Vs_{30} values indicate areas dominated by denser and more compact material. Surface soil characteristics can be identified from their Vs_{30} values, based on the classification in Table 1.

Based on data processing, Vs_{30} values in Sleman Regency vary between 190,476 m/s and 1136,364 m/s, as shown in Figure 6. Areas with low Vs_{30} values (<350 m/s) are located northeast of Bantul Regency. Meanwhile, areas with high Vs_{30} values are located northeast of Bantul Regency, approaching Bantul Regency, which borders the Semilir Formation (Tms) and the Young Merapi Volcanic Deposits (Qmi).

For a surface-based building, formulating seismic design criteria for determining peak earthquake acceleration amplification can be done by first classifying the site (National Standardization Agency (SNI) 1726, 2019). The site class classification in Sleman Regency, based on SNI 1726:2019, indicates SD (Medium Soil), SC (Very Dense Soil), and SB (Rock) site classes. Areas dominated by the Young Merapi Volcanic Sediment Formation (Qmi) fall within the SD and SC site classes, while the SB site class is predominantly found in areas bordering the Semilir Formation (Tms). This demonstrates the alignment of site classification with the geological formations in the study area.

The Young Merapi Volcanic Sediment Formation (Qmi), composed of volcanic breccia, lava, and tuff, falls within the SD (Medium Soil) and SC (Very Dense Soil) site classes. Based on Figure 6, Sleman Regency

(Berbah District, Kalasan District, and Prambanan District) is predominantly located in the SD (Medium Soil) site class. Areas included in the SD (Medium Soil) classification are more vulnerable to earthquakes than points included in other site class classifications. The lowest Vs_{30}value is at point M1 located in Tegaltirto Village, Berbah District, Sleman Regency with a value of 190.476 m/s, so it can be concluded that this area is the most vulnerable to earthquakes compared to other areas in this research area. However, if the points in the D site class are analyzed based on the relatively low values of the seismic vulnerability index and amplification factor, it can be concluded that the impacts in the future will not be too significant.

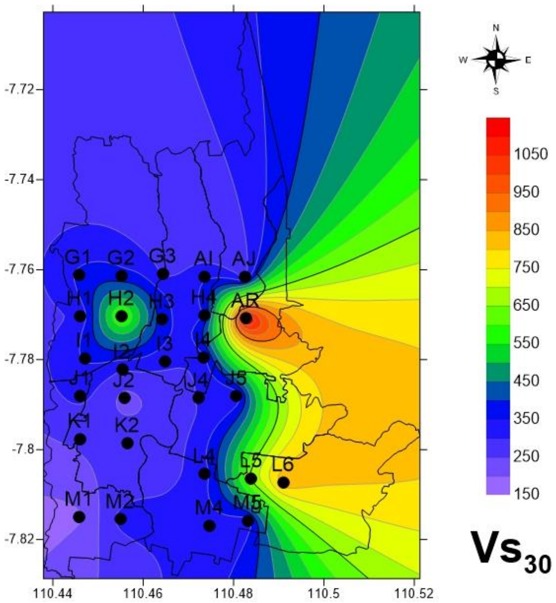


Figure 6. Vs30 Micro zonation in Sleman Regency

CONCLUSION

The dominant frequency (f_0) values in Sleman Regency range from 0.8195 Hz to 17.7087 Hz. Low-frequency zones (< 2.5 Hz) are predominantly located in Kalasan and Berbah sub-districts, which are underlain by the Young Merapi Volcanic Deposits Formation (Qmi). Meanwhile, higher frequency values (> 6.25 Hz) are observed in the Prambanan sub-district, which lies within the Qmi Formation and the younger limestone unit known as the Semilir Formation (Tms). The amplification factor (A_0) in the study area ranges from 2.34 to 5.23, with values exceeding 3 primarily found in Prambanan, Berbah, and Kalasan, concentrated in the Tms and Qmi formations. In contrast, lower A_0 values were recorded in parts of Kalasan within the Qmi formation. The seismic vulnerability index (Kg) varies between 0.3189 and 18.3994, with high Kg values (> 6) mainly distributed in Berbah and Kalasan, while lower Kg values (< 3) are more prevalent in Prambanan and parts of Kalasan. The site classification in Sleman Regency is categorized into three classes: Class D (Medium Soil), Class C (Very Dense Soil), and Class B (Rock). Areas classified as Site Class D are considered more vulnerable to seismic events than other site classes. The lowest Vs_{30} value was found at point M1 in Tegaltirto Village, Berbah Sub-district, with a value of 190.48 m/s, indicating that this area is the most susceptible to earthquake impacts in the study region. However, when considering the relatively low seismic vulnerability index and amplification factor values at Class D locations, the overall potential impact may not be significantly severe.

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