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Evaluation of Seismic Vulnerability Index and Soil Classification in Sleman Regency Based on Microtremor Analysis and the HVSR Method

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Abstract

Kalasan District and Ngemplak District, located in Sleman Regency, Yogyakarta, are areas with significant seismic risk due to the subduction of the Indo-Australian and Eurasian plates south of Java Island. To support disaster mitigation and land-use planning, it is essential to understand the local geological structure and soil dynamic response. This study aims to evaluate the seismic vulnerability and soil classification using the Horizontal to Vertical Spectral Ratio (HVSR) method and Rayleigh wave ellipticity inversion modeling. Microtremor measurements were conducted at 27 points distributed across both districts. The HVSR method was used to obtain the dominant frequency and amplification values, while the ellipticity inversion of Rayleigh waves was employed to estimate the shear-wave velocity profile and calculate Vs_{30} values. The results show that the dominant frequency ranges from 0.713 Hz to 18.006 Hz, amplification values range from 0.569 to 4.193, and the seismic vulnerability index ranges from 0.010 to 12.060. Based on these parameters, Sleman Regency is generally categorized as having low to moderate seismic damage potential due to the relatively low amplification and vulnerability index. The Vs_{30} values indicate a variation in soil site classes, namely medium-density soil (SD) and very dense soil (SC). These findings provide essential data for seismic microzonation, contributing to more resilient urban development strategies.

Keywords: earthquakes, geological, inversion modelling, natural disasters, seismic susceptibility

INTRODUCTION

Wood is a material that is often found because it is easy to find and can be used for various things. Along with the production that often uses wood materials as the material, the remains of powder caused by wood cutting are becoming more and more. This only makes it waste, therefore one of the solutions to overcome these shortcomings while optimizing the use of wood is to process wood waste such as sawdust into particleboards (Zaini et al., 2018). Composite is a material produced from the combination of two or more basic materials that are arranged to obtain new materials (Gibson, 2016).

Indonesia is a country prone to natural disasters, including earthquakes. These disasters cause numerous negative impacts, including building damage, significant losses, loss of life, and much more. This is because Indonesia is located at the confluence of three tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. These three plates can meet and collide, causing earthquakes (Widiyantoro et al., 2020).

Yogyakarta faces a complex natural disaster threat due to the subduction of the Indo-Australian-Eurasian Plate, which is located the south of Java Island. Therefore, an understanding of Indonesia's geological structure is necessary to minimize the impact of these disasters. The presence of the Pacific Ocean Plate is one of the biggest factors in the occurrence of earthquakes (Fujie et al., 2023).

Micro seismic methods are used to study and determine the characteristics of sedimentary rocks and subsurface soil structures related to dynamic regions at a given measurement point. Micro seismic methods are commonly used to map the earthquake vulnerability level of an area (Pranata et al., 2014).

Earthquake susceptibility is a value that describes the level of vulnerability of the surface soil layer to deformation during an earthquake. Earthquake susceptibility aims to measure the vulnerability of soil or structures to earthquakes (Asnawi et al., 2023). Earthquake susceptibility is useful for predicting weak zones during earthquakes (Susilo et al., 2023). The earthquake susceptibility value is obtained by squaring the amplification divided by the natural frequency.

Natural, low-amplitude harmonic ground vibrations caused by natural or man-made events such as wind, ocean waves, or vehicle vibrations that can reflect near-surface geological conditions are called microtremors (Yatini, et al., 2023).

Microtremor measurements are used to determine earthquake-induced soil characteristics, as well as to study earthquake-induced ground movement and calculate the amplification factor of surface sediment layers. The microtremor analysis method can also be used to measure the depth of loose sediment (Bao et al., 2019).

To process microtremor data, the HVSR method is used. This method compares the horizontal spectrum with the vertical spectrum of the microtremor signal. This method produces information in the form of dominant frequencies and amplification. Furthermore, the seismic vulnerability index and the Vs_{30} value are obtained. HVSR is quite effective for studying the dynamic characteristics of the surface soil layer that causes the local site effect during an earthquake. The site effect (TSITE) in the surface sediment layer is determined by comparing the amplification factor of horizontal movement (TH) with the amplification factor of vertical movement (TV) (Wibowo & Huda, 2020). Through the study of microzonation, the amplification factor value ($A0$), micro zonation of the dominant frequency value ($f0$), the seismic vulnerability index and the Vs_{30} value can be used to determine the subsurface conditions of an area.

METHOD

The research was conducted in two sub-districts, namely Kalasan and Ngemplak, Sleman Regency. The number of measurement points was 27. Measurements were carried out using the micro seismic method with portable seismograph equipment, a geological compass, GPS, and a laptop. The portable seismograph was used to record ground vibrations, the geological compass to determine sensor orientation, GPS to mark the coordinates of each measurement point, and the laptop to manage data acquisition and initial verification value. The method used to identify the data was the HVSR method using microtremor data.

Microtremor measurement results with dominant frequencies greater than 1 Hz are generally linked to anthropogenic sources, while those below 1 Hz are attributed to natural background noise such as oceanic and atmospheric disturbances (Biswas & Baruah, 2017) HVSR is a method for determining the ratio of horizontal and vertical spectra obtained from microtremor signal measurements to determine the dynamic characteristics of the surface layer. The HVSR method is stated in Equation (1).

$$\mathrm{HVSR} = \frac{S_{HS}}{S_{VS}} = \frac{\sqrt{[(S_{Utara-Selatan})^2+[(S_{Barat-Timur})^2}}{S_{VS}} \quad (1)$$

S_{HS} epresents the horizontal spectrum in the sediment layer, while, while S_{VS} is the spectrum of the vertical component in the sediment layer. Data obtained from the field are processed in Geopsy software using the HVSR method. After the data is processed using the HVSR method, the dominant frequency (f0) and amplification factor (A0) values are obtained. These values are then used to calculate the seismic vulnerability index (Kg) using Equation (2), where Kg is based on the values of $\mathbf{A_0}$ and $\mathbf{f_0}$.

$$\mathrm{Kg} = A0^2/f0 \quad (2)$$

The H/V curve used for input in the Dinver software using the ellipticity curve method is obtained as shown in Figure 1. Inversion input parameters other than the H/V curve include Poisson's ratio, shear wave velocity, primary wave velocity, and density. After that, a ground profile is obtained from the ellipticity curve modeling. The ground profile used is the one with the lowest misfit, which is used as the basis for interpreting the sediment.

Next, on the Vs profile obtained from the inversion results, the shear wave velocity is calculated up to a depth of 30 m (Vs_{30}) 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. Classification of soil types based on the Vs_{30}value uses the SNI 1726:2019 soil type table as in Table 1.

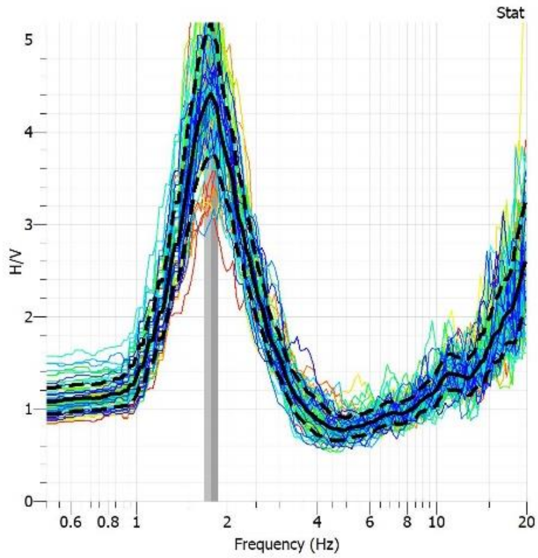

Figure 1. Curva HVSR

$$Vs_{30}=\frac{h30}{\sum\frac{hi}{vsi}} \quad (3)$$

Tabel 1. Soil Types Based on SNI 1726:2019

Site Classification	Share Wave Velocity (Vs) (m/s)
Hard Rock	Vs≥1500
Rock	750<Vs≤1500
Dense Soil	350<Vs≤750
Medium Soil	175<Vs≤350
Soft Soil	VS<175

RESULT AND DISCUSSION

Micro zonation of Dominant Frequency in Sleman Regency

The dominant frequency value of the soil is obtained from the x-axis value of the HVSR curve obtained from processing microtremor data using the HVSR method. The dominant frequency itself is a parameter that can indicate the physical condition of the soil related to its thickness. Relatively thin sediments are indicated by high dominant frequency values, while thick sediments correspond to low-frequency peaks (Biswas and Baruah, 2017). The dominant frequency is directly proportional to the shear wave velocity and inversely proportional to the sediment thickness (Wibowo and Huda, 2020). Biswas and Baruah (2017) also noted that frequencies below 2 Hz typically represent thick, soft sediments, while those exceeding 5 Hz suggest thin deposits or shallow bedrock. This classification helps to interpret subsurface conditions more accurately based on HVSR curve results.

The distribution of dominant frequency values in the study area is shown in Figure 3. The dominant frequency values range from 0,713 Hz to 18,006 Hz. The lowest dominant frequency value is in Surokerten, Selomartani, Kalasan District, and the highest dominant frequency value is in Sambiroto, Purwomartani, Kalasan District.

Based on the Kanai classification, dominant frequency values <2.5 Hz are classified as Type II and I, Type IV, with 10 measurement points described as Alluvial Rock, formed from delta sedimentation, topsoil, mud, etc., with a thickness of 30 m or more. The surface sediment thickness is very thick, indicated by a purple-blue color.

The dominant frequency value of 6,667-20 Hz is classified as Type IV, Type I, with 15 measurement points described as Tertiary or older rock. It consists of hard sandy rocks, gravel, and other rocks, indicated by a green-orange color. The surface sediment thickness is very thin, dominated by crustal rocks. For Type IV, type II, with a dominant frequency of 4-6,667 Hz, there are two points described as alluvial rock, with a thickness of 5 m. It consists of sandy gravel, sandy hard clay, loam, etc. The surface sediment thickness falls into the medium category, indicated by dark blue-dark green. In general, Type I and II are associated with soft and thick sediment layers that tend to amplify ground motion, while Type IV indicates thin sediment overlays or weathered rock above hard bedrock, resulting in lower amplification but potentially more localized effects (Susilo et al., 2023).

The low dominant frequency value is likely due to the weathered sediment and rock layers. Meanwhile, the relatively high dominant frequency value is interpreted as indicating a relatively thin sedimentary layer in the area (Wibowo et al., 2023). The volcanic sediment formation of young Mount Merapi is dominated by fine-grained pyroclastic deposits and tuff at the bottom and dominated by coarse-grained volcanic sand to gravelly sand at the bottom. It borders the Semilir formation in Prambanan District. The lithological conditions of the city are alluvial and have been well-deformed due to the interaction of faults, making these areas very vulnerable to earthquakes (Arifin, 2014).

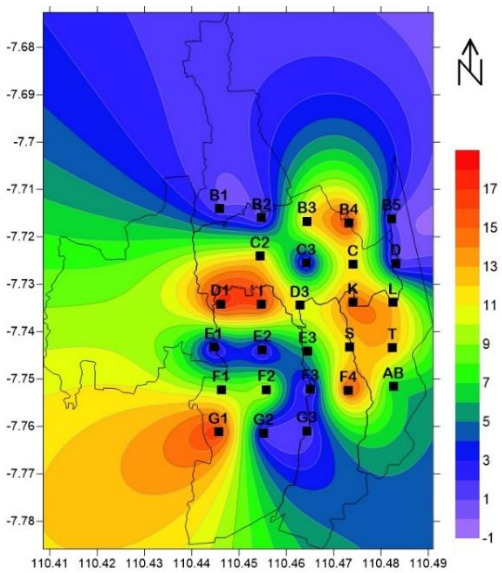

Figure 3. Dominant Frequency Micro zonation

Micro zonation of Amplification Factors in Sleman Regency

Reduced rock density increases the

amplification factor because soft sediment slows the duration of waves propagating in the area, resulting in shaking of buildings, and vice versa. Soft sedimentary rocks are known to amplify ground motion during earthquakes and therefore, on average, cause more severe damage than hard layer. The amplification factor is controlled by the impedance contrast between the soft layers and the bedrock (Zhong et al., 2022).

Variations in geological formation, thickness, and physical properties of soil and rock layers affect the amplification value, as rocks undergo deformation that changes their physical properties, so the presence of faults or faults can affect the amplification value (Anggraeni et al., 2023).

The distribution map of amplification values is shown in Figure 4. The amplification values in the study area range from 0,569 to 4.193. The smallest amplification value is in Kiyudan, Selomartani, Kalasan, and the highest amplification value is in Senden 1, Selomartani, Kalasan.

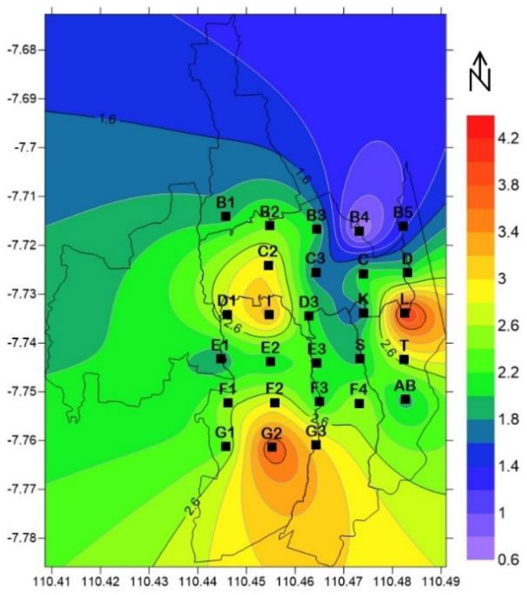

Figure 4. Micro zonation of Amplification Distribution

According to the amplification factor classification, there are 23 low-class points with amplification values <3, indicated by purple-yellow colors. There are four medium-class points with amplification values ≤A<6, indicated by dark yellow-orange colors, located in Purwomartani, Kalasan District. Variations in geological formation, thickness, and physical properties of soil and rock layers influence amplification values (Huang et al., 2021). For example, rocks undergo deformation that changes their physical properties, resulting in faults or faults that can affect amplification values (Anggraeni et al., 2023).

More specifically, the study area has an amplification value <3, indicating a relatively thin sedimentary layer and relatively hard rock. The potential for damage in this area is low compared to the high amplification values. The low amplification values are found in rock formations such as tuff, ash, breccia, agglomerate, and undisaggregated lava flows, which are classified as hard soil, resulting in lower amplification of earthquake waves passing through the area. The amplification in this area is classified as low, indicating that if an earthquake occurs, strong ground shaking is unlikely (Demulawa & Daruwati, 2021)

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

The seismic vulnerability index indicates the vulnerability of the surface soil layer to deformation during an earthquake. The higher the amplification value, the greater the vulnerability to earthquakes (Güven, 2022). The parameters influencing the earthquake vulnerability value (Kg) are the surface shear strain (γ) caused by surface layer deformation (δ) and the acceleration of seismic waves in bedrock (α), which is amplified when propagating in a lower-density medium, in this case the surface soil layer.

The study area has a seismic vulnerability index ranging from 0,010 to

12,060, as shown in Figure 5. The highest Kg values are found in Sambisari, Purwomartani, Kalasan District. Areas with high Kg values are characterized by low dominant frequency values and high amplification values. The higher the Kg value, the greater the level of damage due to the low level of soil stability in the area.

Low Kg values dominate the study area and are influenced by the region's geological conditions. Low Kg values are generally found in areas of young Merapi deposits, which are largely composed of compact rock layers, so they are not significantly affected by vibrations passing through them, making them relatively safe in the event of an earthquake. Considering the dynamic characteristics and soil profiles in the research area, building construction is recommended to follow the International Building Code (IBC) to reduce earthquake risk (Gazali et al., 2017)

Areas with soft soil have a higher risk of vulnerability, so appropriate mitigation is needed through risk planning, monitoring, and community participation (Sapountzaki, 2022). The results of data processing show variations in PGA values and seismic vulnerability indexes that can be used as a basis for regional planning to minimize potential damage and casualties due to earthquakes (Febriani et al., 2013)

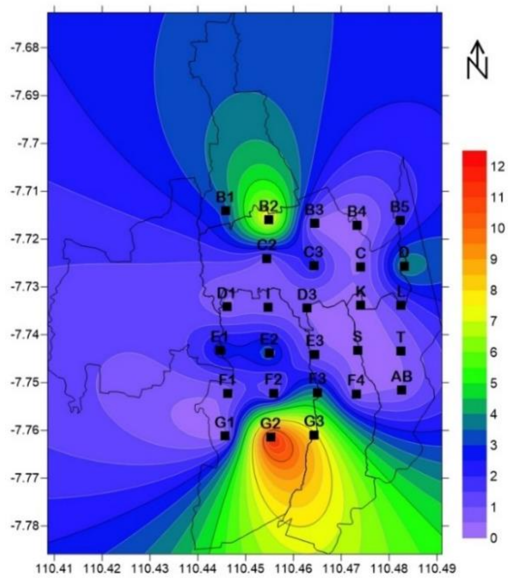

Figure 5. Micro zonation of the Distribution of the Seismic Vulnerability Index

Site Class Micro zonation in Sleman Regency

Softer soil composition is indicated by a lower Vs value, which generally correlates with greater amplification of seismic waves, while harder soil composition or hard rock is indicated by an increasing Vs value, reflecting better resistance to ground motion during an earthquake.

The distribution of soil site classes in the study area is shown in Figure 6. The obtained Vs_{30} values range from 193.548 m/s to 715.14 m/s. Low Vs_{30} values were found in Kiyudan, Selomartani, Kalasan District, while high Vs_{30} values were observed in Sempu, Wedomartani, Ngemplak District, all within Sleman Regency. Low Vs_{30} values (193.548–333.333 m/s) are represented by colors ranging from purple to dark blue, while high values (352.941–715.14 m/s) are shown in dark green to orange.

Soil site classification follows the Indonesian National Standard (SNI 1726:2019) on site classification based on Vs_{30} values from field and laboratory investigations. According to this standard, site class SD represents medium soil, SC represents very dense soil, and SB represents rock. Based on the analysis, the study area is dominated by medium soil (SD) and very dense soil (SC) site classes. These are associated with young volcanic sediment formations composed of tuff, ash, breccia, agglomerate, and undifferentiated lava.

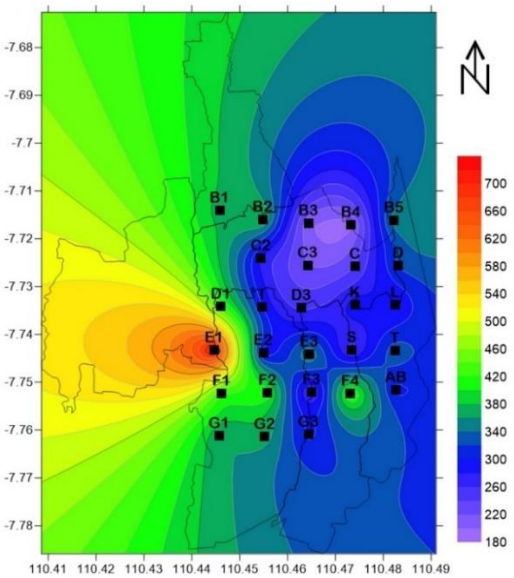

Figure 6. Micro zonation of Site Class Distribution

CONCLUSION

This study evaluates the seismic vulnerability and soil classification in Sleman Regency using microtremor data analyzed with the HVSR method. The dominant frequency (f_0) ranges from 0.713 Hz to 18.006 Hz, and the amplification factor (A_0) ranges from 0.569 to 4.193, indicating that most areas have relatively low ground shaking effects. The calculated seismic vulnerability index (Kg) ranges from 0.010 to 12.060, with most values falling into the low to moderate risk category, meaning the area is relatively safe from serious earthquake damage. In addition, the Vs_{30} values, obtained through Rayleigh wave inversion, range from 193.548 m/s to 715.14 m/s, showing variations in soil stiffness. Based on SNI 1726:2019, the soil in the study area is classified as medium soil (SD) and very dense soil (SC). These soil types are commonly found in areas with young volcanic deposits such as tuff, ash, breccia, and lava, which tend to reduce the impact of seismic waves. Overall, the results help to better understand the local soil conditions and seismic risk, which can support earthquake mitigation and safe land-use planning in Sleman Regency.

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