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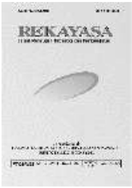

Site Effect Analysis in Prambanan District and Surroundings Using Shear Wave Velocity and Ellipticity Curve Method from Microtremor Data

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Abstract

The shear wave velocity (Vs) is a crucial parameter for determining subsurface layers by averaging the Vs value to a depth of 30 meters, known as Vs30. This study aims to analyze the subsurface soil layers, calculate the Vs30 value, and assess the potential seismic site classifications in Kapanewon Prambanan and its surrounding areas. The research utilizes secondary microtremor data from 27 observation points in the form of MSD files. The microtremor data was processed using Geopsy software with the HVSR method to generate an H/V curve. This curve was further analyzed with the Ellipticity Curve method via Dinver software to obtain the Vs profile at various depths. The findings suggest that the subsurface layers in Kapanewon Prambanan are predominantly composed of hard, very dense soil, soft rocks, and solid rocks, based on the Vs30 values. The Vs30 distribution across the region ranges from 267.857 m/s to 1675.977 m/s, classified into site categories A, B, C, and D. However, the majority of the area falls under site classes B and C. These classifications indicate that the regions under B and C have a relatively lower potential for significant earthquake wave amplification. Nonetheless, attention should still be given to areas categorized under sites D and E, particularly for earthquake disaster mitigation efforts. This detailed Vs30 analysis provides critical insights for seismic assessments, regional planning, and mitigation strategies in Kapanewon Prambanan.

Keywords: Shear wave velocity, Subsurface layer analysis, Microtremor data, Ellipticity curve, Earthquake

INTRODUCTION

Indonesia is situated in an active seismic zone that is vulnerable to earthquakes due to its location at the convergence of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. This geological condition makes studies related to seismic risk and geotechnical characteristics of an area highly significant. The collision between these plates leads to the formation of subduction zones in several locations, which act as sources of seismic activity. Regions that are prone to and frequently experience earthquakes are generally located near these subduction zones (Hasegawa et al., 2020). Intermediate and deep earthquakes, reaching depths of 678 km, follow the Wadati-Benioff zones of subducting slabs, with seismicity influenced by factors like oblique convergence, lithospheric age, mantle temperatures, and plate velocity, while shallow seismicity presents major hazards due to megathrusting, crustal, and intraslab faulting (Hutchings & Mooney, 2021). Deterministic seismic hazard analysis often involves subjective predictive decisions, particularly regarding earthquake potential, based on the collective insights and judgments of seismologists, engineers, risk analysts, economists, social scientists, and ultimately government officials (Ansari et al., 2021).

Yogyakarta is one such area at risk of earthquakes because it lies on the Eurasian continental plate, close to the subduction zone formed by the collision between the Eurasian Plate and the Indo-Australian Ocean Plate. Additionally, the presence of the Opak fault and the Oyo fault further contributes to Yogyakarta's vulnerability to earthquakes, especially in densely populated areas like Kapanewon Prambanan and its surroundings.

On May 27, 2006, a tectonic earthquake measuring 6.3 on the Richter scale struck the Special Region of Yogyakarta and Central Java, with a depth of 17 km, centered at coordinates 8° S and 110° E. Several sub-districts, including Imogiri, Jetis, Pleret, Piyungan, Wedi, Gantiwarno, and Bambanglipuro, experienced the most severe damage due to the shifting of the Opak fault. The level of damage was greatly influenced by surface topography and geological conditions. One method for mapping earthquake-prone areas is through microtremor surveys. (Aswad & Massinai, 2018; Asnawi et al., 2020).

Site effects play a crucial role in seismic risk assessment as they can amplify or attenuate seismic waves reaching the ground surface. Therefore, analyzing microtremor data to evaluate the subsurface soil layers based on shear wave velocity (Vs) in Kapanewon Prambanan and its vicinity is of great importance. The results of this analysis are expected to be beneficial for earthquake disaster mitigation, particularly since traditional drilling methods can be costly and invasive (Idham et al., 2020). By utilizing the Ellipticity Curve method, microtremor data can be analyzed to estimate shear wave velocity (Vs), which illustrates the mechanical properties of subsurface layers. Softer rocks are at a greater risk of shaking from seismic waves due to higher amplification compared to denser rocks. Microtremor measurements are commonly used to observe soil characteristics based on seismic wave propagation, including wave velocity, amplitude variations, as well as frequency and wave period.

The Horizontal to Vertical Spectral Ratio (HVSR) method is still commonly used in this analysis because it provides information about soil type and sediment layer thickness. However, to gain more detailed insights into subsurface lithology, Herak (2008) developed an inverse modeling method. One of the methods in inverse modeling is the ellipticity curve, which is used to determine the surface shear wave velocity (Vs) from microtremor data. The inversion process involves iterations to enhance the accuracy of the results, where smaller error values (misfit) indicate a better shear wave velocity profile.

Classifying different soil types based on dominant frequency values provides critical insights for seismic risk assessment. Soil Type IV areas, which have low-frequency values, are more prone to seismic amplification due to the thick, soft sediments present. In contrast, Soil Type I areas, with high-frequency values, are less susceptible to amplification, as they consist of thinner sediment layers and firmer ground.

Damaged areas exhibit a moderate to high seismic vulnerability index, indicating a greater susceptibility to earthquake impacts (Saputra et al., 2022).

These classifications help identify varying seismic vulnerabilities across different locations. Regions with Soil Type IV are associated with greater ground motion potential during earthquakes due to their ability to amplify seismic waves. Conversely, Soil Type I regions, characterized by hard rock and minimal sediment, are more stable and less prone to shaking. This information is vital for improving seismic hazard assessments and guiding the development of earthquake-resistant infrastructure in the affected regions (Asefa & Ayele, 2021; Karimzadeh et al., 2014).

This study aims to analyze site effects in Kapanewon Prambanan and its surroundings using microtremor data processed through the Ellipticity Curve method. The primary focus of this research is to determine the shear wave velocity values at various subsurface layers, which are key parameters in assessing the potential for seismic amplification in an area. The results of this study are expected to make a significant contribution to efforts in mitigating earthquake risks in this region and serve as a reference for developing more earthquake-resistant infrastructure.

METHOD

Data Collection

The secondary microtremor data was collected from 27 research locations in the Kapanewon Prambanan area, Sleman (17 points), Kapanewon Gedangsari, Gunungkidul (4 points), Microzonation of dominant frequency (f0) involves determining the specific dominant frequencies in different locations within a region to assess seismic risk. Prambanan Sub-district, Klaten (2 points), and Gantiwarno Sub-district, Klaten (3 points). The microtremor data is formatted as .MSD files. The software tools employed for data processing and analysis include Geopsy, Dinver, Surfer 11, QGIS, Google Earth, and Microsoft Office.

Data Processing with HVSR Method

Apply the HVSR method, which involves dividing the average horizontal component of the signal by the vertical component at each frequency.

The formula for HVSR is as in equation 1.

$$HV(f) = \frac{\sqrt{E(f)^2 + N(f)^2}}{Z(f)} \qquad [1]$$

Where E(f) = East-West component at frequency f, N(f) = North-South component at frequency f, Z(f) = Vertical component at frequency f, The result of this analysis is the H/V curve, which shows peaks at certain frequencies.

Identifying Dominant Frequency (f0)

The dominant frequency (f0) is the frequency at which the H/V curve shows a clear peak. This peak indicates the natural frequency of the ground at that location, which is primarily controlled by the local soil and sediment conditions. Importance of f0: The value of f0 is crucial because it helps in understanding how seismic waves will amplify in specific areas. Areas with low f0 values are typically associated with soft sediments that can amplify low-frequency seismic waves.

Microzonation Mapping

Once the f0 values are determined for each measurement point, these values can be mapped to show the spatial distribution of dominant frequencies across the study area. Zonation: Group the area into zones based on ranges of dominant frequencies (e.g., low, medium, high). These zones will reflect different levels of seismic hazard potential. Tools: GIS software such as *QGIS* or *ArcGIS* can be used to create maps of the f0 microzonation, which visually represents the seismic response of the ground in the region.

Interpretation for Seismic Risk

The final map will provide insight into which areas are more susceptible to seismic amplification based on their dominant frequencies. Lower f0 values (softer ground) tend to pose a higher seismic risk compared to higher f0 values (harder ground). This microzonation can guide earthquake preparedness, building codes, and infrastructure development to mitigate earthquake impacts.

Processing Microtremor Signal Data

The initial stage of processing the microtremor signal data involves using the Geopsy software. The microtremor signal consists of three components: two horizontal components represented by the E (East-West) spectrum and N (North-South) spectrum, and one vertical component represented by the Z spectrum. To extract critical information from the data, the Horizontal to Vertical Spectral Ratio (HVSR) method is applied. This technique is employed to determine the dominant frequency (f0), amplification value (A0), and H/V curve. The resulting H/V curve is further analyzed using the Ellipticity Curve method implemented in Dinver software. The analysis yields the ground profile based on shear wave velocity (Vs) at various depths.

Calculation of Vs30

The calculation of Vs30 (the average shear wave velocity down to a depth of 30 meters) requires information on the thickness of each layer from 0 to 30 meters and the shear wave velocity of the n-th layer. The following equation 2 is used to determine Vs30.

$$Vs_{30} = \frac{30}{\sum \frac{h_i}{Vs_i}} \qquad [2]$$

Where Vs30 is Average shear wave velocity down to a depth of 30 meters (m/s), hi is thickness of the i-th layer from 0 to 30 meters (m), Vsi is Shear wave velocity of the i-th layer (m/s). This equation incorporates the cumulative thickness of the layers and their respective shear wave velocities to provide a comprehensive assessment of seismic response characteristics in the study area.

RESULT AND DISCUSSION

Microzonation of Dominant Frequency (f0)

The thickness of sediment and the average wave propagation velocity beneath the surface significantly influence the natural frequency of a given area. This suggests that variations in the depth of reflecting surfaces beneath the ground lead to different dominant frequency values at each measurement point.

In regions with thicker sediment layers, the average wave propagation speed is lower, which increases the likelihood of ground motion amplification at lower frequencies. Conversely, in areas with thinner sediment layers, the average wave propagation speed is higher, and the potential for ground motion amplification at higher frequencies decreases.

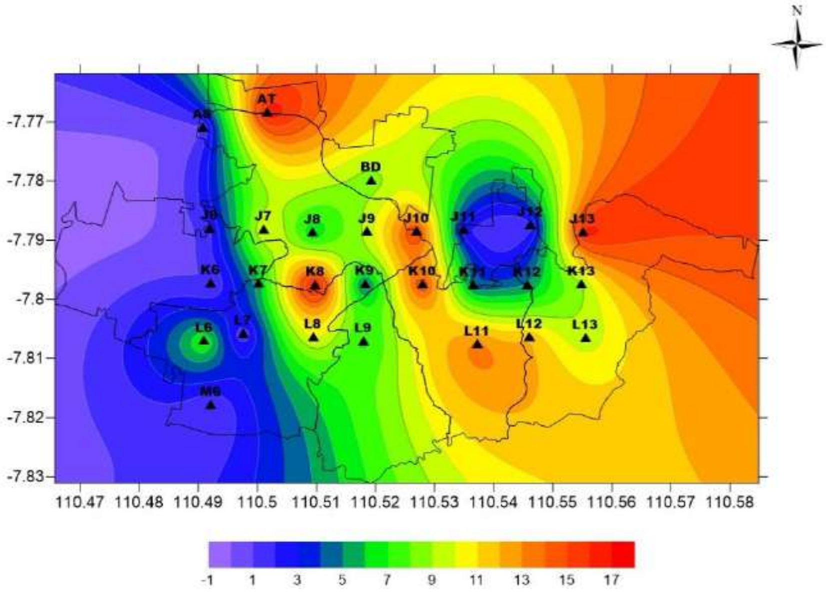

Figure 2. Microzonation Map of Dominant Frequency Values (f0)

The data processing yielded dominant frequency values (f0) ranging from 0.908 Hz to 17.511 Hz across the study area. This wide range reflects the diversity in sediment thickness and subsurface conditions in the region, with lower f0 values indicating softer, deeper sediments, and higher f0 values corresponding to harder, shallower layers. The variation in f0 values highlights areas that are more susceptible to seismic wave amplification, which is crucial for assessing seismic hazard potential and informing risk mitigation strategies.

These findings provide a foundation for microzonation mapping, helping to identify areas that may experience greater ground shaking during an earthquake based on their natural frequencies. Consequently, these results can inform the development of building codes and disaster preparedness plans to ensure greater resilience to seismic events in different parts of the region.

The research points AS, J6, K6, L7, and M6 (Kapanewon Prambanan, Sleman), J11, J12 (Gantiwarno Sub-district, Klaten), and L12, L13 (Kapanewon Gedangsari, Gunungkidul) have dominant frequency values of less than 2.5 Hz. These locations are classified as Soil Type IV, characterized by very thick sediment layers with alluvial rock depths of 30 meters or more, indicating generally soft soil properties.

Research points K7, K9, K12, L9 (Kapanewon Prambanan, Sleman), and K11 (Gantiwarno Sub-district, Klaten) exhibit dominant frequencies ranging from 4 to 6.667 Hz. These locations are classified as Soil Type II, which is described as having medium sediment thickness, typically ranging between 5 to 10 meters.

On the other hand, research points AT, BD (Prambanan Sub-district, Klaten), J7, J8, J9, J10, K8, K10, L6, L8, L9 (Kapanewon Prambanan, Sleman), and J13, K13 (Kapanewon Gedangsari, Gunungkidul) display dominant frequency values between 6.667 and 20 Hz. These points are classified as Soil Type I, which is characterized by very thin sediment layers, predominantly hard rock, and generally hard soil properties.

Microzonation of Amplification Factor (Ao)

The amplification factor (Ao) is influenced by various factors such as geological formation variations, soil layer thickness and characteristics, and the depth of bedrock. In earthquake engineering studies, softer lithologies pose a higher risk when shaken by earthquakes, as they tend to experience greater wave amplification compared to more compact rock formations.

In the eastern part of the Opak Fault zone, amplification factors ranged from 1.260 to 5.227. Areas with amplification values less than 3 were found at research points AS, AT (Prambanan Sub-district, Klaten), J7, J10, K7, K8, K9, K12, L8 (Kapanewon Prambanan, Sleman), J11, J12 (Gantiwarno Sub-district, Klaten), J13, K13, and L12 (Kapanewon Gedangsari, Gunungkidul). These locations are classified under Amplification Zone I, indicating low amplification factors due to the predominant geological and soil conditions that do not significantly amplify seismic waves.

On the other hand, areas with amplification values between 3 and 6 were identified at research points J6, J8, J9, K6, K10, L6, L7, L9, L11, M6 (Kapanewon Prambanan, Sleman), BD (Prambanan Sub-district, Klaten), K11 (Gantiwarno Sub-district, Klaten), and L13 (Kapanewon Gedangsari, Gunungkidul). These locations fall into Amplification Zone II, characterized by moderate amplification factors. The soil and geological conditions in these areas tend to moderately amplify seismic waves (Forte et al., 2019).

The classification of these amplification zones indicates that the study area falls within relatively safe amplification zones. Most regions exhibit low to moderate amplification, suggesting reduced risk of excessive seismic wave magnification during an earthquake. This information is valuable for assessing the area's seismic risk and guiding the development of earthquake-resistant infrastructure. Other hand, geological analysis shows that Prambanan generally has bedrock depths of 80 to 100 meters, with variations in sediment composition and thickness across different areas, including a deeper basin in Berbah and southern Prambanan where bedrock reaches depths of 120 to 160 meters (Perdhana & Nurcahya, 2019).

Microzonation of Seismic Vulnerability Index (Kg)

The seismic vulnerability index (Kg) measures the susceptibility of soil layers to deformation during an earthquake. This index is derived from both the dominant frequency and amplification factor values. Higher Kg values typically occur in areas with thick sediment layers and low dominant frequencies, indicating greater susceptibility to seismic deformation.

In this study, the seismic vulnerability index ranged from 0.190 cm/s² to 14.051 cm/s², demonstrating varying degrees of vulnerability across different research locations. Areas with higher Kg values, particularly those with thick sediment and lower dominant frequencies, are more prone to seismic deformation. These findings provide valuable insight into the regional seismic risks and can inform preparedness and mitigation strategies for future earthquakes.

Amplification values less than 3 were observed at the research points AS, AT (Prambanan Sub-district, Klaten), J7, J10, K7, K8, K9, K12, L8 (Kapanewon Prambanan, Sleman), J11, J12 (Gantiwarno Sub-district, Klaten), J13, K13, and L12 (Kapanewon Gedangsari, Gunungkidul). These areas fall under Amplification Zone I, characterized by low amplification factors.

In contrast, amplification values ranging from 3 to 6 were identified at points J6, J8, J9, K6, K10, L6, L7, L9, L11, M6 (Kapanewon Prambanan, Sleman), BD (Prambanan Sub-district, Klaten), K11 (Gantiwarno Sub-district, Klaten), and L13 (Kapanewon Gedangsari, Gunungkidul). These locations are classified under Amplification Zone II, indicating moderate amplification factors.

The classification of these amplification zones indicates that most areas within the study region fall into zones with low to moderate amplification. This suggests that the region is relatively safe in terms of seismic wave amplification, reducing the potential for excessive ground shaking during an earthquake.

These findings are crucial for developing accurate seismic hazard maps and guiding the construction of earthquake-resistant infrastructure in the area. Microzonation of Seismic Vulnerability Index at Batubesi Dam involved data acquisition from 25 points to assess seismic risk based on dominant frequency (f0) and amplification factor (A0) using HVSR spectral ratio. The seismic vulnerability index (Kg) ranged from 0.28 to 43.42, with an estimated Modified Mercalli Intensity (MMI) of VII-IX, indicating medium to very high earthquake risk across the dam area (Sunaryo, 2017). The seismic vulnerability index (Kg) depends on the dynamic properties of the soil and is used to evaluate a site's vulnerability to strong ground motion. This study recorded HVSR microtremor measurements at over 200 points in the Van region, revealing a high seismic vulnerability index near Van Lake and densely populated city centers, with an 80 percent correlation between building damage from the 2011 earthquake and Kg values (Akkaya, 2020). The seismic vulnerability index (Kg) in the southern area of Klaten Regency was determined using dominant frequency (f0) and amplification factor (A0) from microtremor data processed through HVSR analysis. The results show f0 values between 4.104 Hz and 9.300 Hz, A0 values from 1.326 to 2.328, and Kg values ranging from 4.259×10^{-5} s²/cm to 59.873×10^{-5} s²/cm, with the lowest Kg found in Pedan and the highest in Prambanan (Koesuma & Putera, 2019)

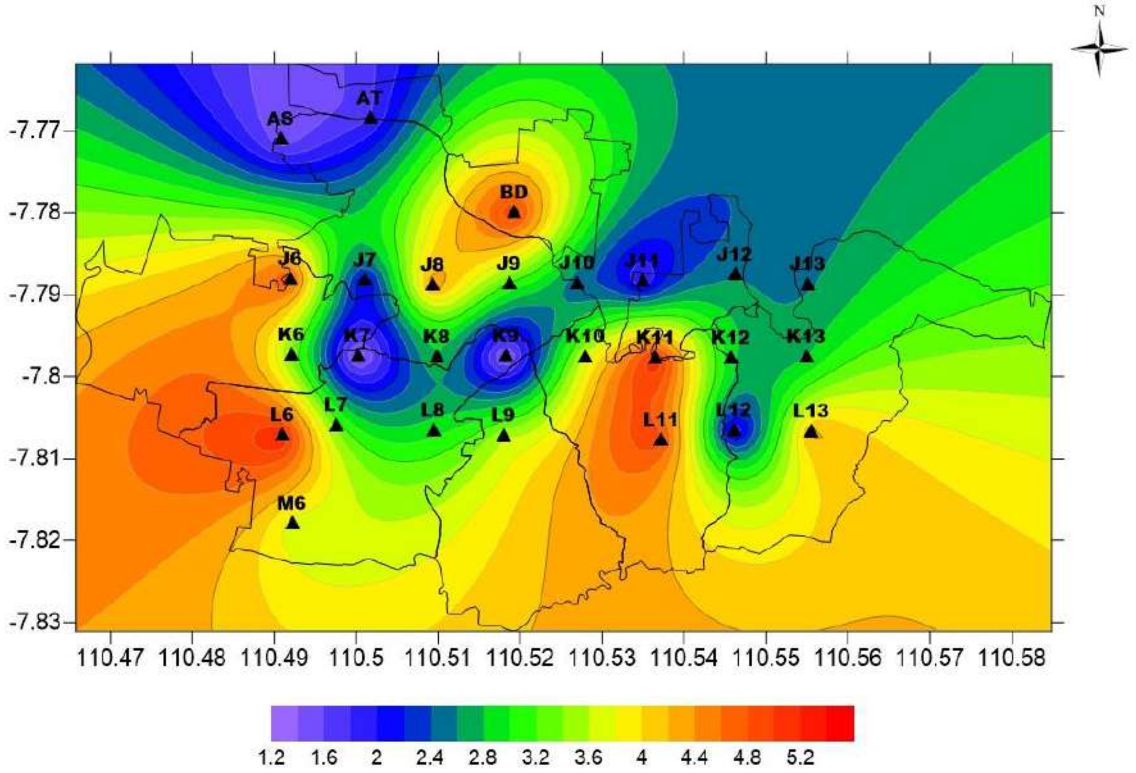

Figure 3. Microzonation Map of Amplification Value (A0)

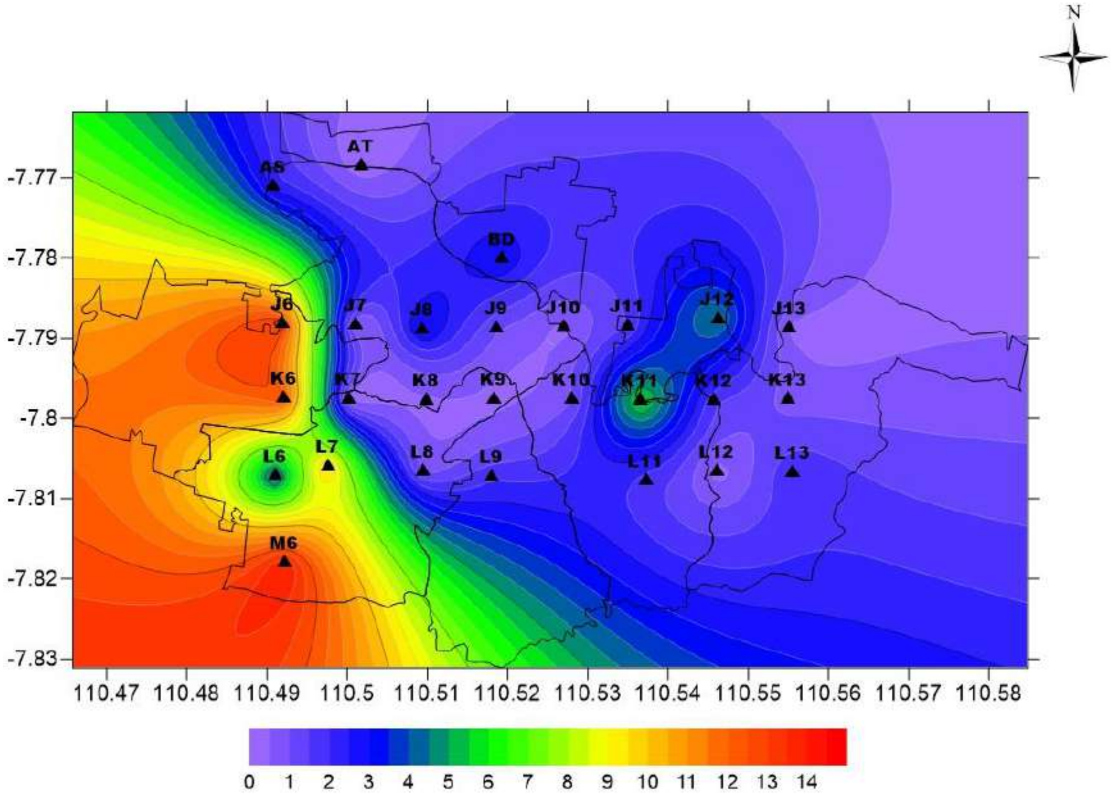

Figure 4. Microzonation Map of Seismic Vulnerability Index Values (Kg)

The results obtained from the Horizontal-to-Vertical Spectral Ratio (HVSR) method used for classifying soil types are considered to be relatively general, as they primarily provide information about the soil characteristics and sediment thickness. To achieve a more specific understanding of the subsurface layers in a given area, an inverse modeling approach using the ellipticity curve method can be employed.

The ellipticity curve method requires the determination of several parameters with initial values to establish an accurate subsurface model. Key parameters include the shear wave velocity (Vs), compressional wave velocity (Vp), Poisson's ratio, and rock density. By accurately determining these parameters, the ellipticity curve method can enhance the understanding of subsurface geological structures and provide more detailed insights into the soil's response to seismic activity (Vessia et al., 2021).

This method is particularly useful in areas where detailed geological information is sparse, allowing for more accurate modeling of seismic behavior. By integrating the findings from the HVSR method with the ellipticity curve analysis, a comprehensive assessment of the seismic vulnerability of the area can be achieved, ultimately aiding in the development of effective earthquake mitigation strategies. From the ellipticity curve method, the shear wave value (Vs) is then obtained at each microtremor measurement location point at each layer depth as seen in the ground profile.

Colours other than red and black on the ellipticity curve show the modelling curve with various misfit values (Widyadarsana & Hartantyo, 2021). An example of an ellipticity curve display can be seen in Figure. 5. An example, East Tanjung Karang, Bandar Lampung, identified areas with high ground fissure potential due to excessive groundwater exploitation, with bedrock depths and slopes revealing significant geological hazards, providing a basis for authorities to mitigate subsidence-related disasters. (Ipmawan et al., 2021)

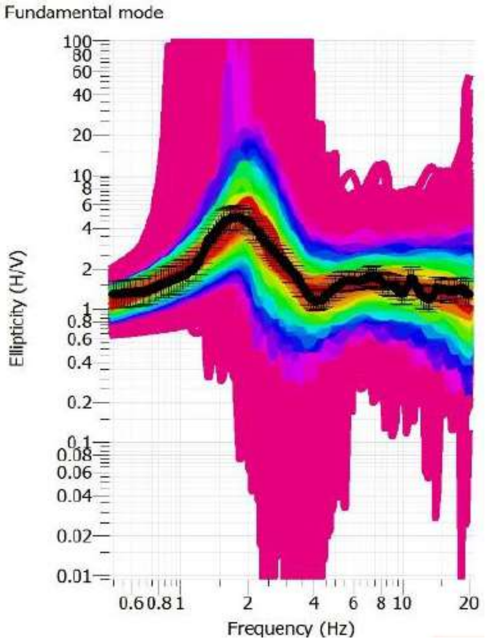

Figure 5. Ellipticity curve using Dinver software

Microzonation of Vs30 Values

The shear wave velocity (Vs) values for each soil layer facilitate the classification of rock types and the interpretation of subsurface lithology. In a given site, a low Vs value indicates thicker sediment layers, while a high Vs value typically suggests the presence of hard bedrock. Furthermore, when considering the amplification factor, sites with thicker sediment layers tend to exhibit higher amplification.

The Vs30 value serves as a benchmark for earthquake mitigation efforts, as only the top 30 meters of soil layers significantly influence the amplification of seismic waves (National Standardization Agency, 2019). According to this agency, soil classification is divided into five categories, ranging from Class A to Class E. The Vs30 values in the study area range from 267.857 m/s to 1675.977 m/s. Site E: Areas with Vs30 < 175 m/s are classified as Site E, with a representative research point at J8 in Kapanewon Prambanan, Sleman. This site is characterized by soft soil layers. Site D: The classification of Site D includes points J6, K6, and L7 (Kapanewon Prambanan, Sleman), K11 (Kecamatan Gantiwarno, Klaten), and L12 (Kapanewon Gedangsari, Gunungkidul), with Vs values in the range of 175 < Vs ≤ 350 m/s, indicating medium soil layers.

Site C: Points AS, J7, K7, K10, L11, M6 (Kapanewon Prambanan, Sleman), J11, J12 (Kecamatan Gantiwarno, Klaten), K13, and L13 (Kapanewon Gedangsari, Gunungkidul) fall within Site C, characterized by Vs values of 350 < Vs ≤ 750 m/s. These sites contain hard, dense soil layers and soft rock. Site B: Points J9, J10, K8, K9, K12, L6, and L9 (Kapanewon Prambanan, Sleman), as well as AT and BD (Kecamatan Prambanan, Klaten), are classified as Site B with Vs values of 750 < Vs ≤ 1500 m/s, indicating rocky layers.

Site A: Points L8 (Kapanewon Prambanan, Sleman) and J13 (Kapanewon Gedangsari, Gunungkidul) have Vs30 values ≥ 1500 m/s, classifying them as Site A, which indicates hard rock layers. The classification results indicate that the study area is predominantly comprised of Sites B and C, mainly located in Kapanewon Prambanan, Sleman. This correlation aligns with the geological formation in the region, which consists of Young Merapi Volcano Deposits (Qmi), characterized by tuff, ash, breccia, and lava flows. The amplification of seismic waves increases with lower shear wave velocity (Vs), and conversely, a higher Vs leads to reduced amplification. Therefore, the Kapanewon Prambanan area and its surroundings, dominated by Sites B and C, possess hard and dense soil layers, alongside soft rocks with sufficient thickness (at least 30 meters deep), which suggests a relatively safe condition against seismic amplification.

Moreover, the development of seismic microzonation maps, based on Vs30 values, is essential for assessing seismic hazards in urban areas. Vs30 data from microtremor was used to correct USGS data, which was then used to determine Peak Ground Acceleration (PGA), showing that seven out of eight districts in Palu City fall within the high earthquake hazard class (Rusyidi & Efendi, 2018). The Vs30 value is crucial for evaluating the earthquake resistance of building foundations in Central Java, Indonesia, where elliptical curve modeling reveals a soil profile ranging from hard and very dense to soft rock (Darmawan *et al.*, 2023). The estimation of shear wave velocity at a depth of 30 meters (Vs30) can be conducted through microzonation using the HVSR method. The results classify the target area into three soil types (C, D, and S1) based on Vs30 values, natural frequency, amplification, and bedrock depth, according to Eurocode 8 and N-SPT standards (Dewi et al., 2016). In Montreal, a geostatistical approach combining borehole data, f0 from the H/V method, and limited shear wave velocity measurements produced a composite model that proved more accurate (reducing errors by 40%) than other models, offering a reliable method for microzonation in areas with limited Vs surveys (Rosset et al., 2015).

CONCLUSION

The subsurface layers in Kapanewon Prambanan and its surroundings, based on Vs values up to a depth of 30 meters, are predominantly composed of hard, dense soil, along with soft rocks. The research sites exhibit Vs30 values ranging from 267.857 m/s to 1675.977 m/s, classifying them into Sites A, B, C, and D. However, the majority of these sites are located in Kapanewon Prambanan, primarily classified as Sites B and C. Areas classified as Sites B and C have a relatively low likelihood of experiencing significant seismic wave amplification; nevertheless, it remains essential to consider the potential risks associated with Sites D and E in disaster mitigation efforts.

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