REKAYASA 21 (2) (2023): 62-70

REKAYASA

Jurnal Penerapan Teknologi dan Pembelajaran

http://journal.unnes.ac.id/journals/rekayasa

Site Classification Based on Shear Wave Velocity from H/V Curve Inversion in Prambanan Subdistrict, Klaten Regency for Earthquake Risk Mitigation

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DOI: https://doi.org/10.15294/rekayasa.v21i2.9863

Abstract

One of the areas that has become a historical tourist attraction in Klaten Regency is Prambanan District. Prambanan District in the south is directly adjacent to Kapanewon Prambanan which has an Opak Fault. This study aims to microzonate earthquake-prone areas based on microseismic parameters using a portable seismograph at 27 measurement points. Data analysis was performed using the Horizontal to Vertical Spectral Ratio (HVSR) method and the ellipticity curve with the help of Geopsy and Dinver software. The results showed that the range of f_0 values was between 0.9 and 18 Hz, which was predominantly included in the Type I classification. The A_0 values were in the range of 1.2-4 with the size of the distribution of A_0 being dominantly low. The value of Kg in this area is classified as low category with a range of 0.1-14. Prambanan District has v_{s30} values ranging from 234–1260 m/s which are classified into 3 sites namely B, C, and D. The results of this study indicate that Prambanan District has soil with a thick layer of sediment based on information on the distribution of shear wave velocity values to depth 30 meter. These results are relevant as an effort to mitigate earthquake disasters, especially in vulnerable areas such as Prambanan which has a history of seismic activity due to the presence of the Opak Fault.

Keywords: earthquake areas, ellipticity curve, microzonate, portable seismograph, sediment.

INTRODUCTION

Prambanan District is a flat district in the central part of Klaten Regency. It covers an area of 24.43 km2 and is divided into 16 villages. It borders Manisrenggo District to the north, Jogonalan District to the east and northeast, Gantiwarno District to the southeast, Prambanan District to the southwest and southwest, and Kalasan District to the west and northwest.

Differences in geological conditions play a significant role in the potential for earthquake impacts (Robiana et al., 2021). The morphology of Prambanan District is hilly, with lithologies including tuff, lapilli, claystone, siltstone, and tuffaceous sandstone, all with varying degrees of weathering (Kristanto & Indrawan, 2018). Meanwhile, it is known that the potential for danger from ground vibrations is greater due to the amplification and interaction of ground vibrations in areas with tuff-like geological conditions (Wibowo et al., 2018). Furthermore, based on geological maps, Prambanan District, which borders the Prambanan Subdistrict in Sleman, is crossed by the Opak Fault, which extends from the Bantul area of Yogyakarta to the border of Sleman and Klaten Regencies. The Opak Fault is an active fault that frequently causes earthquakes in Yogyakarta and its surrounding areas.

Prambanan District is located in one of the most seismically active zones in Yogyakarta, where past earthquakes have caused significant structural damage, highlighting the urgent need for detailed seismic vulnerability assessments in the area (Mubin & Nurcahya, 2014). This fact reinforces the urgency of researching seismic vulnerability in the Prambanan area to support mitigation and earthquake-resistant infrastructure development planning.

Based on the background presented, it is necessary to research seismic vulnerability in the Prambanan District and its surrounding areas to mitigate various disasters, especially earthquakes and landslides, because this district is one of the areas with many tourist destinations. The output of this research is a micro zonation map of various micro seismic parameters that can be useful for the public and regional planners in developing city infrastructure, so that in the construction of infrastructure facilities, they can consider soil lithology so that the infrastructure is strong and durable.

METHOD

This research was conducted in Prambanan District and its surrounding areas at 27 measurement points. The measurement points were selected to represent varied geological conditions across the district. A total of 27 points were chosen to ensure comprehensive spatial coverage and reliable microzonation analysis. Data collection was carried out using a geological compass, GPS, a laptop, and a portable digital TDL-303 seismometer sensor, with a 30-minute duration for each measurement point (Fatimah et al., 2022). This seismometer measures three wave components: the east-west (EW) component, the north-south (NS) component, and the up-down (vertical) component, which are required for microseismic analysis.

The microseismic data processing used the HVSR method with the aid of Sessaray Geopsy software shown in Figure 1. The HVSR analysis was performed after noise was removed from the signal during the cutting process, resulting in an H/V curve, dominant frequency (f0), and amplification factor (A0) values (Fatimah et al., 2022). The HVSR method is a non-invasive microtremor analysis technique widely adopted due to its efficiency in assessing site effects, particularly in seismic microzonation. The method used here follows the standard practices recommended in international guidelines (e.g., SESAME 2004), although some interpretations are aligned with Indonesian national standards (SNI 1726:2012)

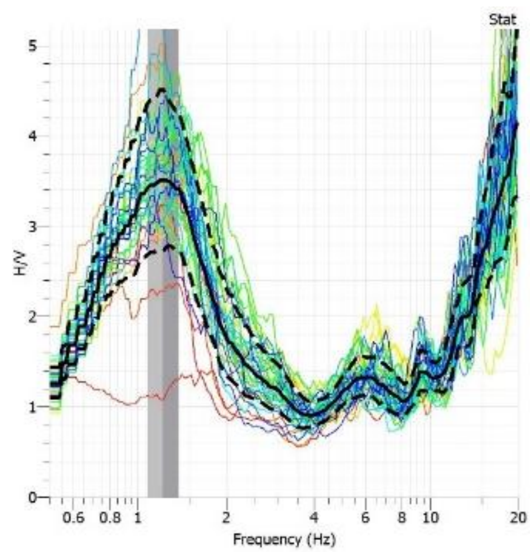

Figure 1. Frequency and Amplification Graph of HSVR

The dominant frequency value and amplification factor can be used to find the seismic vulnerability index of a location using Equation (1), where, Kg is the seismic vulnerability index, A0 is the amplification factor, and f0 is the dominant frequency

$$Kg = A0^2/f0 \tag{1}$$

The H/V curve derived from HVSR analysis can be further processed through Rayleigh wave ellipticity inversion using Dinver software. This method requires initial assumptions on vp, vs, Poisson's ratio, and density for each measurement point (Molnar et al., 2022). Siska et al. (2022) have also been effectively used to assess liquefaction-prone areas. The inversion results will provide information about the ground profile in the form of a vs value against the depth of the soil layer. This technique has been widely used for site effect analysis in Central Java as demonstrated by (Legowo et al., 2019).

The ground profile is considered accurate if the parameter values inputted during the inversion are close to the measurement data in the field, characterized by a good ellipticity curve and a small misfit (Abdialim et al., 2021). The amplification classification refers to Ratdomopurbo (2002), which categorizes ground amplification levels into low (<2), medium (2–4), and high (>4) to assess potential earthquake impacts. Then, 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 (2), 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.

$$Vs_{30} = \frac{h30}{\sum \frac{hi}{vsi}} \tag{2}$$

The equation calculation can be used to determine the characteristics of the soil type at each measurement point up to a depth. The Vs_{30} value from the equation calculation can be used to determine the characteristics of the soil type at each measurement point up to a depth of 30 m (Fatimah et al., 2022).

RESULT AND DISCUSSION

Earthquake wave propagation is influenced by the characteristics of the soil layers and geology. Earthquake waves will be amplified if an area has a thick sedimentary layer. The thickness and composition of a region's sediment can be determined using the dominant frequency parameter (Irham et al., 2021).

The dominant frequency is related to the depth of the wave reflection plane, which provides information about the boundary between the sedimentary layer and the bedrock layer. The thicker the sedimentary layer in an area, the lower the dominant frequency value in that area. According to the Kanai Classification, Prambanan District predominantly has a low dominant frequency (<2.5 Hz), which falls into the Type IV or Type I classification shown in Figure 2. The Type I classification describes the area's soil as composed of alluvial rock formed from delta sedimentation, topsoil, mud, and the like, with a very thick sediment depth of more than 30 meters. The lowest dominant frequency value was found at measurement point F, at 0.909041 Hz, located in Kebondalem Lor Village, Prambanan District, marked by the purple contour. The highest dominant frequency value was found at measurement point B09, at 18.1979 Hz, located in Joho Village, Prambanan District, marked by the red contour. This relationship between amplification, dominant frequency, and sediment thickness has also been identified in Sleman by Fadilah &

Muttaqin (2022), where the HVSR method effectively mapped site effect variation.

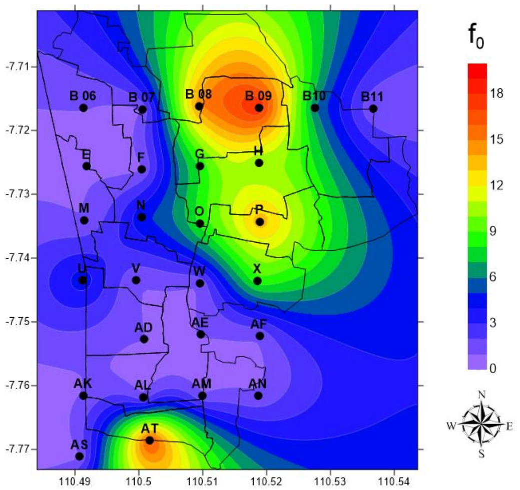

Figure 2. Microzonation of dominant frequency values (f0) in Prambanan District and its surroundings

According to Kurniawan et al. (2019), the response of buildings during earthquakes is influenced by sediment thickness, which acts as an earthquake magnitude amplifier. This is because seismic waves are amplified when passing through a softer medium than the one they previously passed through. Amplification occurs when the frequency trapped in a sedimentary layer matches the dominant frequency in that area, resulting in wave resonance. Areas with high amplification factors are more likely to experience significant damage during an earthquake. Furthermore, the amplification factor can increase if the rock has undergone deformation such as weathering, folding, and faulting, which alters its properties. Microzonation of amplification factor values (A0) in Prambanan District and its surroundings shown in Figure 3.

The distribution of amplification factor values in Prambanan District, according to Ratdomopurbo's classification, is mostly classified as low. However, in this study, five measurement points fell into the medium amplification criteria: AM, AN, AF, X, and AL. The highest amplification value was found at AM, with a value of 4.10884. This point is in Kotesan Village, Prambanan District, and is marked with a red contour. The topographic map shows that this point is adjacent to the Opak Fault line. It has previously been known that amplification factors can increase if rocks undergo deformation, such as faulting. This could be a factor in AM having a higher amplification factor value compared to other measurement points. Meanwhile, the area with the lowest amplification factor value is M, with a value of 1.2866, located in Kokosan Village, Prambanan District. This indicates that Kokosan Village has a lower risk of building damage during an earthquake compared to surrounding areas. The level of vulnerability of an area to an earthquake can be described using the seismic vulnerability index (Handayani et al., 2020).

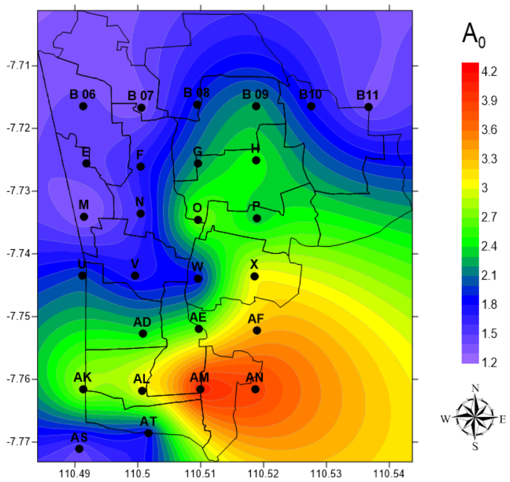

Figure 3. Microzonation of amplification factor values (A0) in Prambanan District and its surroundings

This parameter indicates the vulnerability of the soil layer that has undergone deformation due to an earthquake. Areas with a high seismic vulnerability index indicate that the area is susceptible to earthquakes. Similar results were obtained by Susilanto et al. (2016) in urban sedimentary zones with high vulnerability indexes. High seismic vulnerability index values are commonly found in areas with soft sedimentary layers. Conversely, if an area has a low seismic vulnerability index, it indicates that the soil in that area has a strong and stable rock structure, so the impact of the earthquake will be minimal (Kang et al., 2021).

Nakamura showed that areas considered safe from damage have a seismic vulnerability index value below 5 (Aditama et al., 2020). According to the seismic vulnerability index distribution map in Figure 4, most areas in Prambanan District have a relatively low seismic vulnerability index. The measurement point with the lowest Kg value is AT, with a value of 0.190549916, located in Pereng Kulon Village, Prambanan District, marked by a purple contour. Several points have seismic vulnerability index values above 5, namely: AD, AE, AF, AK, AL, AM, and AN. These points indicate areas with a higher earthquake vulnerability than the surrounding areas. The area with the highest seismic vulnerability index value is AM, with a Kg value of 14.4570987, located in Kotesan Kidul Village, Prambanan District, marked by a red contour.

Information on subsurface lithology is necessary in analyzing an area's vulnerability to earthquakes. Shear wave velocity (vs) is a microseismic parameter that can describe the subsurface lithology condition because it is directly related to the stiffness properties of the material. The definition of material stiffness in question is a measure of resistance to deformation which is related to the elastic modulus of the material (soil), which is described as the behavior of the soil under pressure. In the inversion process that has been carried out, the number of layers and sublayers in the modeling is set at 5 using linear increase. The value of vs against the layer depth obtained from the inversion process is used to calculate the value of Vs_{30} because the target depth studied is up to 30 meters (Rusydi et al., 2018).

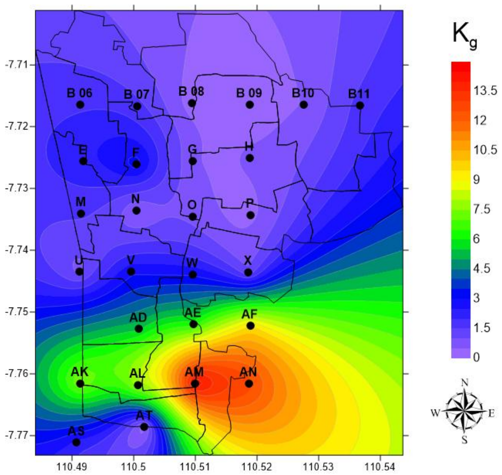

Figure 4. Microzonation of seismic vulnerability index values (Kg) in Prambanan District and its surroundings

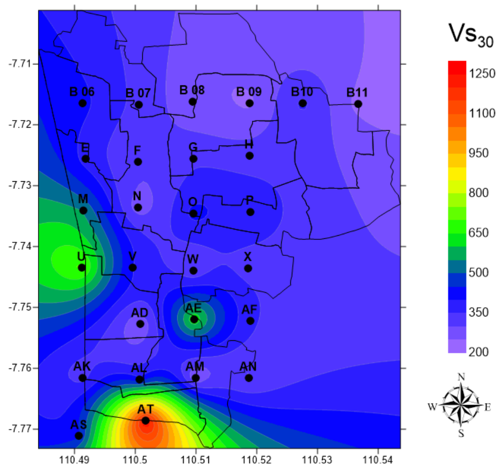

Figure 5. Microzonation of Vs_{30} values in Prambanan District and its surroundings

The variation in shear wave velocity mainly depends on the hardness and softness of the soil layer. The distribution of wave velocity values up to a depth of 30 meters (Vs_{30}) averaged from the HVSR curve inversion results is shown in Figure 5. The vs value in the study area is in the range of 234 – 1260 m/s. Similar seismic site classification techniques using HVSR and Rayleigh wave ellipticity inversion have been applied across Yogyakarta with consistent Vs_{30} values reflecting local geology (Zega et al., 2022).

Classification (Site)	Description	Measurement Points
B	Rock with moderate weathering	AT
C	Dense/Hard Soil and Soft Rock	B10, AF, E, P, V, AL, B06, O, AS, M, AE, U
D	Medium Soil	B11, B09, AM, AD, B08, N, AN, F, W, H, X, AK, B07, G

Based on the soil classification according to SNI 1726-2012 concerning Earthquake Resistant Building Planning, the distribution of Vs_{30} values in Prambanan District are included in three site classifications, namely sites B, C, and D. Wijayanto et al. (2022) also used this classification approach in Bantul District for regional seismic risk assessment.

The grouping results shown in Table 1 indicate that most of the measurement points fall into the medium soil (SD) classification. The medium soil in Prambanan District is composed of grayish-brown regosol with parent material consisting of ash and intermediate volcanic sand. Similar site classifications using HVSR and ellipticity methods have been applied in Sleman by Arimuko et al. (2020), showing consistent Vs30 values in volcanic sediment regions, supporting regional seismic hazard assessment studies.

The lowest Vs_{30} value was found at measurement point B11 at 234,893 m/s, located in Joton Village, Jogonalan District, indicated by the purple contour. A lower shear wave velocity indicates softer soil. Soft soil has low stiffness and therefore is less resistant to deformation. If deformation frequently occurs in an area, it will experience significant amplification during an earthquake. Meanwhile, the highest Vs_{30} value is found in areas classified as hard soil. Hard, compact soil tends to vibrate at a high frequency, resulting in a short wavelength. Energy from high-frequency waves is more easily absorbed by the medium through which the earthquake waves travel. Thus, earthquake intensity on hard soil will attenuate more quickly, minimizing the danger and impact of an earthquake in the area. In this study, the highest Vs_{30} value was found at the AT measurement point, at 1,260,504 m/s, located in Pereng Village, Prambanan District, marked by the red contour.

Spatially, the distribution of dominant frequency, amplification value, seismic vulnerability index, and Vs_{30} values follow a similar pattern. Based on the measurement data, the area at the AM measurement point has a higher seismic vulnerability index. This is related to the higher amplification value at the AM measurement point compared to other points. Furthermore, the dominant frequency value at the AM point is <2.5, indicating that the soil layer is composed of alluvial rock formed from delta sedimentation, topsoil, and mud, with a very thick sediment layer of over 30 meters. Furthermore, the relationship between these parameters is reinforced by the Vs_{30} value obtained from the shear wave velocity calculation using the ellipticity curve inversion process, indicating that the AM point has a low Vs_{30} value, thus categorizing it as site D, with a description of medium soil. The Vs_{30} value can also interpret the depth of bedrock in an area. The deeper the bedrock layer, the thicker the sediment layer in the area. A very thick sediment layer can cause severe damage to an area if an earthquake occurs in the area. According to SNI 1726:2012, the bedrock layer has a VS value of ≥ 750 m/s. Based on the ground profile obtained during the H/V curve inversion, it is shown that the bedrock layer at point AM is found at a depth of approximately 185 meters below the surface. Point AM, which is known to have a high level of earthquake vulnerability, is located close to the continuity of the Opak Fault line. The continuity between the values of several of these parameters is formed because in the fault zone, deformation occurs in the soil structure, which causes a continuously increasing amplification value. High amplification values make an area vulnerable to the danger of damage caused by earthquakes.

CONCLUSION

Prambanan District is generally characterized by low dominant frequency values, indicating the presence of thick sedimentary layers composed of alluvial deposits, topsoil, and mud resulting from delta sedimentation. The amplification factor in this district mostly falls into the low classification, suggesting a relatively small risk of structural damage during earthquakes. Similarly, the seismic vulnerability index (Kg) in most parts of Prambanan is categorized as low (Kg < 3). However, the average Vs_{30} values in the area predominantly belong to the medium soil classification, which indicates weak soil stiffness and potential susceptibility to deformation. Notably, point AM, located in Kotesan Village, exhibits the highest seismic vulnerability index in the study area, which correlates with its high amplification factor, low dominant frequency, and low Vs_{30} value. The subsurface profile at this location also suggests a deeper sedimentary layer. Therefore, while Prambanan District tends to exhibit lower seismic risk, specific locations such as point AM should be considered highly vulnerable to earthquake hazards.

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