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Microzonation Of Seismic Vulnerability Index Based on Horizontal to Vertical Spectral Ratio Method In Kapanewon Prambanan, Sleman Regency

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ABSTRACT

Prambanan Sub-district, Sleman Regency, is located in the Yogyakarta Basin, which has complex geological characteristics. This area consists of thick sedimentary deposits, making it vulnerable to increased seismic wave amplitude. This geological complexity plays a major role in increasing seismic risk, which occurred during the 2006 Yogyakarta Earthquake, where this area was on the VII MMI intensity scale and experienced quite severe infrastructure damage. Therefore, a study of seismic vulnerability microzonation is needed as a step to mitigate earthquake disaster risk. This study uses the Horizontal to Vertical Spectral Ratio (HVSR) method by comparing the spectrum of horizontal and vertical components of microtremor waves to produce dominant frequency values, amplification factors, and seismic vulnerability indexes. Furthermore, the HVSR curve is inverted using the Particle Swarm Optimization (PSO) method to obtain the average shear wave velocity value up to a depth of 30 meters V_{S30}. The results of the analysis show that the dominant frequency values in the study area range from 0.98 Hz to 17.13 Hz, while the amplification factor is in the range of 1.06 to 11.69. The V_{S30} value varies from 114 m/s to 726 m/s, and the seismic vulnerability index ranges from 0.18 to 7.46. Geologically, the Madurejo, Sumberharjo, and Bokoharjo Village areas located in the Young Merapi Formation have high seismic vulnerability values. This is due to the dominance of soft soil material and thick sediment layers. In contrast, areas with the Semilir and Kebobutak Formations dominated by hard rocks and hilly topography show lower vulnerability values. Based on these results, areas with high vulnerability levels need to be prioritized in earthquake-resistant infrastructure development planning and sustainable disaster mitigation strategies.

ABSTRAK

Kapanewon Prambanan, Kabupaten Sleman, berada di cekungan Yogyakarta yang memiliki karakteristik geologi yang kompleks. Daerah ini berada di lapisan sedimen yang tebal sehingga rentan terhadap peningkatan amplitudo gelombang seismik. Karakteristik geologi yang kompleks berkontribusi besar terhadap pada peningkatan risiko kegempaan, sebagaimana ditunjukkan pada peristiwa gempa bumi Yogyakarta tahun 2006 pada skala intenistas VII MMI dan mengalami kerusakan infrastruktur yang cukup parah. Oleh karena itu, diperlukan penelitian mikrozonasi kerentanan seismik sebagai salah satu langkah mitigasi risiko bencana gempa bumi di masa depan. Metode yang digunakan yaitu metode HVSR, yaitu dengan membandingkan spektrum komponen horizontal dan vertikal dari gelombang seismik untuk menghasilkan nilai frekuensi dominan, faktor amplifikasi dan kerentanan seismik. Kurva H/V dari metode HVSR dilakukan inversi untuk mendapatkan nilai V_{S30}. Hasil penelitian menunjukkan distribusi nilai frekuensi dominan berkisar 0,98 Hz – 17,13 Hz, faktor amplifikasi berkisar 1,06 – 11,69, V_{S30} berkisar 114 m/s – 726 m/s dan nilai kerentanan seismik berkisar 0,18 – 7,46. Daerah yang memiliki nilai kerentanan seismik rendah berada di Desa Boko Harjo, Desa Madu Rejo, dan Desa Sumber Rejo yang berada pada Formasi Semilir dan Formasi Kebobutak. Sementara itu, daerah yang memiliki nilai kerentanan seismik sedang hingga tinggi berada di Desa Boko Harjo, Desa Madu Rejo, dan Desa Sumber Rejo yang berada pada Formasi Merapi Muda. Secara geologis, Desa Madurejo, Sumberharjo, dan Bokoharjo yang berada di Formasi Merapi Muda memiliki nilai kerentanan gempa yang tinggi. Hal ini disebabkan karena didominasi oleh tanah lunak dan lapisan sedimen yang tebal. Sebaliknya, daerah di Formasi Semilir dan Kebobutak yang didominasi oleh batuan keras dan topografi berbukit memiliki nilai kerentanan yang lebih rendah. Berdasarkan hasil penelitian menunjukkan bahwa wilayah dengan tingkat kerentanan tinggi sebaiknya diprioritaskan dalam perencanaan pembangunan infrastruktur tahan gempa dan penyusunan strategi mitigasi bencana yang berkelanjutan.

1. INTRODUCT.ION

Prambanan Sub-district, in Sleman Regency, Special Region of Yogyakarta, is one of the areas in Java Island that is directly affected by high seismic activity. This area is located in the Yogyakarta basin, which has complex geological conditions with thick layers of sediment. In the Yogyakarta earthquake on May 27, 2006, Prambanan Sub-district and its surroundings were at the MMI intensity scale VII. The earthquake caused significant damage because the epicenter was located close to Prambanan Sub-district, which further worsened the impact on the area (Rizki Aditama et al., 2020). The phenomenon of seismic wave amplification occurs when earthquake waves moving through thick layers of sediment experience increased intensity due to the physical properties of the soil, such as density, elasticity, and layer thickness. This effect can increase the risk of damage to buildings and infrastructure standing on land that is vulnerable to seismic shocks. Therefore, it is necessary to conduct in-depth research related to seismic vulnerability in the Kapanewon Prambanan area, Sleman Regency to identify potential risks an take appropriate mitigation steps.

The method that can be used to analyze seismic vulnerability is the Horizontal to Vertical Spectral Ratio (HVSR) method by utilizing microtremor data to determine the comparison between the horizontal and vertical components of seismic waves. This method has the advantages of being economical, shorter time and more efficient data collection because it requires simpler sensors. HVSR is able to identify the dominant frequency of the soil (F_o) and the amplification factor (A_o), which are related to the thickness and characteristics of the subsurface layer. In the context of seismic microzonation, this method is used to compile a seismic vulnerability index map (Kg) to identify areas that are vulnerable to the impact of earthquakes and support decisions in urban infrastructure development (Fajarningrum & Wibowo, 2023).

Complex geological conditions can influence the results of the curve, necessitating interpretation through inversion. The inversion results will yield a shear wave velocity profile extending to a depth of 30 meters (Vs30). The research is noteworthy because Kapanewon Prambanan, located in Sleman Regency, is situated in an area of significant historical, cultural, and economic importance. The microzonation map aims to facilitate more effective spatial planning, enhance infrastructure development, and improve disaster mitigation strategies to minimize the future impact of earthquakes (Nakamura, 1997).

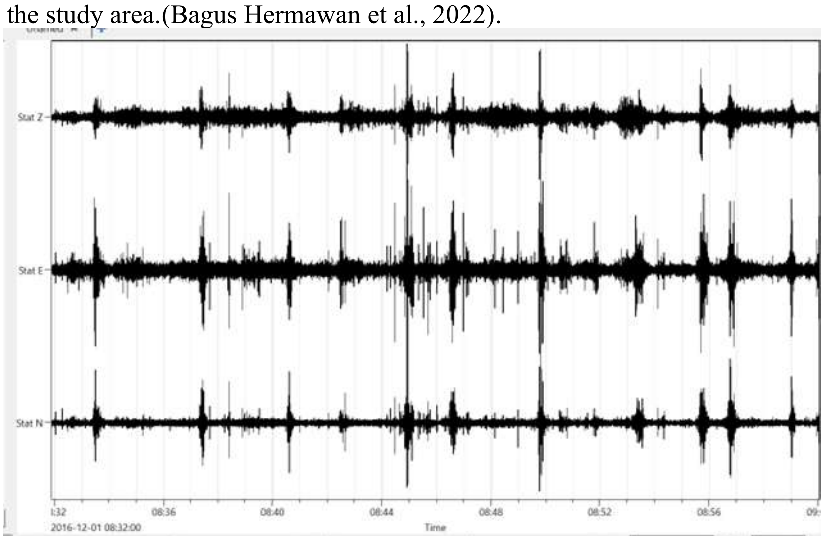
2. METHOD

2.1. Data Collection

Secondary data in the form of microtremor recordings at the research site were obtained through soil vibration measurements recorded by microtremor sensors from the Class I Geophysical Station in Sleman, Yogyakarta. The method used to analyse soil dynamics characteristics was the HVSR method. This method was carried out by comparing the horizontal and vertical component spectra. Mathematically, it is formulated as follows:

$$H/_V = \frac{S_{HS}}{S_{VS}} = \frac{\sqrt{(S_{WE})^2 + (S_{NS})^2}}{S_{VS}} \tag{2.1}$$

$H/_V$ is the HVSR ratio spectrum. S_{HS} is the frequency spectrum value of the horizontal component, S_{NS} is the frequency spectrum of the north-south horizontal component, S_{WE} is the frequency spectrum of the west-east horizontal component, and S_{VS} is the frequency spectrum of the vertical component indicated by stat z in the microtremor data in the study area.(Bagus Hermawan et al., 2022).



Picture 1. Microtremor data for point 20 in MSEED format

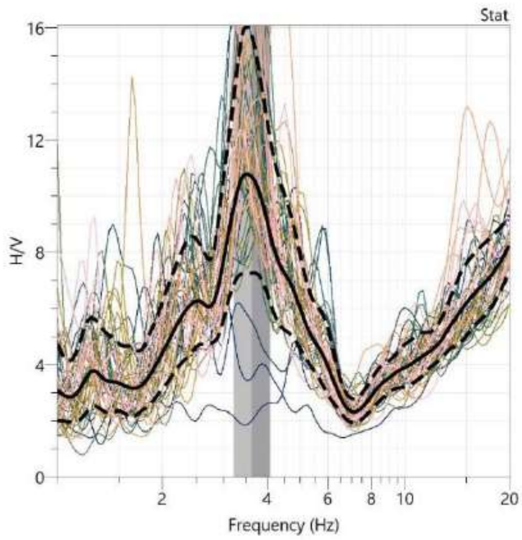
2.2. Fourier transform

The microtremor signal processing process uses Geopsy software, which aims to produce the average value of the $H/_V$ curve. Geopsy software will visualise the $H/_V$ curve graph, which contains parameters in the form of dominant frequency values on the x-axis and amplification factors on the y-axis. This curve comes from Fourier Transformation, which converts microtremor data from the time domain to the frequency domain of each component (Kusuma, 2021). The Fourier Transform is defined as follows:

$$x(w) = \int_{-\infty}^{\infty} x(t)e^{-iwt}dt \quad (2.2)$$

$$x(w) = \int_{-\infty}^{\infty} x(t)\cos(wt)\,dt - i\int_{-\infty}^{\infty} x(t)\sin(wt)\,dt \quad (2.3)$$

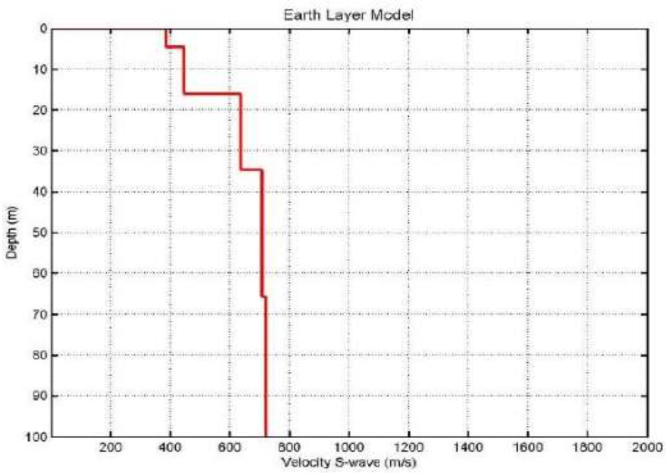
Where $x(t)$ is the signal function in the time domain, e^{-iwt} is the kernel function, and $x(w)$ is the function in the frequency domain. The concept of Fourier transformation is to break down a wave signal into a sinusoidal harmonic wave with various different frequencies in graphical form.



Picture 2. H/V curve at research point 20

2.3. Inverse curve HVSR

The basic principle of the HVSR inversion method lies in adjusting the HVSR curve resulting from modelling with the HVSR curve resulting from research. This method adjusts the model parameters so that they can represent the soil structure model that best suits the actual conditions in the research area. The method used in HVSR curve inversion is the PSO Inversion method. In the PSO Inversion method, determining important modelling parameters is crucial for optimising algorithm performance and finding the best solution. The model parameters considered include layer thickness and shear wave velocity (Zaenudin et al., 2022).



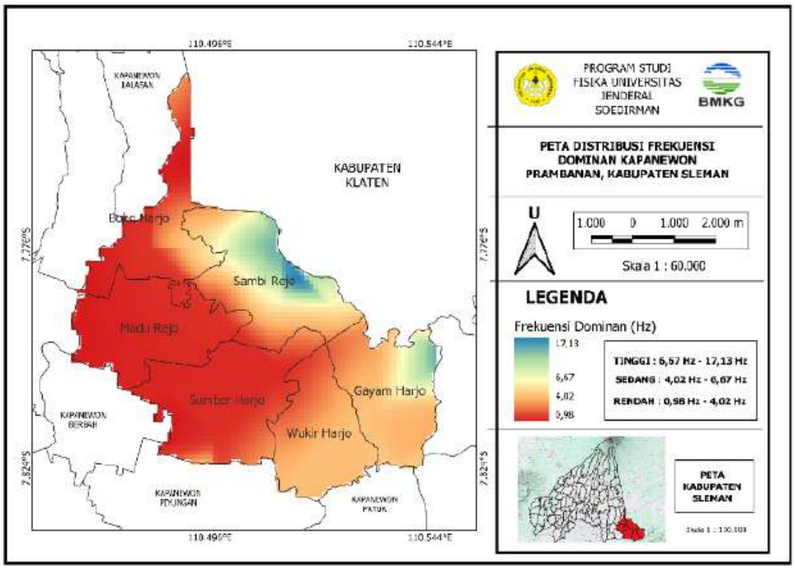
Picture 3. Inversion results at research point 2

2.4. Microzonation of Seismic Vulnerability Index Values

The seismic vulnerability index value (K_g) is obtained by finding the relationship between the dominant frequency value (F_o) and the amplification factor (A_O). The K_g value varies from the lowest to the highest according to the soil conditions in the study area. Once the seismic vulnerability index values have been obtained, the next step is to create a map based on the parameters obtained using QGIS software version 3.28.2, referencing geological maps and Digital Elevation Model data in Kapanewon Prambanan, Sleman Regency. Additionally, spatial planning and appropriate mitigation plans can be analysed in the study area based on the distribution of dominant frequency values (F_o), amplification factors (A_O) shear wave velocity up to a depth of 30 m (V_{s30}), and seismic vulnerability (K_g).

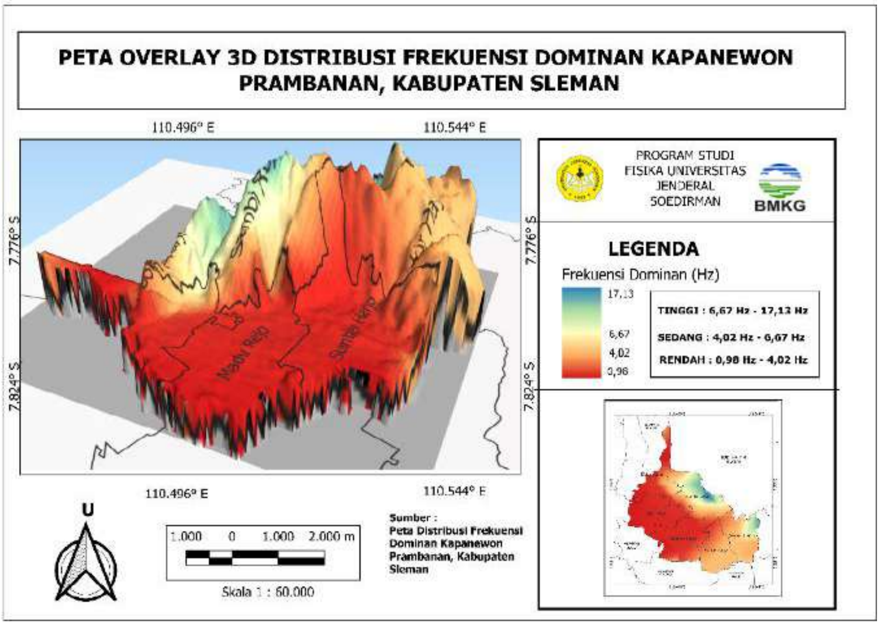
3. RESULT AND DISUCUSION

3.1. Dominant frequency



Picture 4. Distribution of dominant frequency values in Kapanewon Prambanan, Sleman Regency

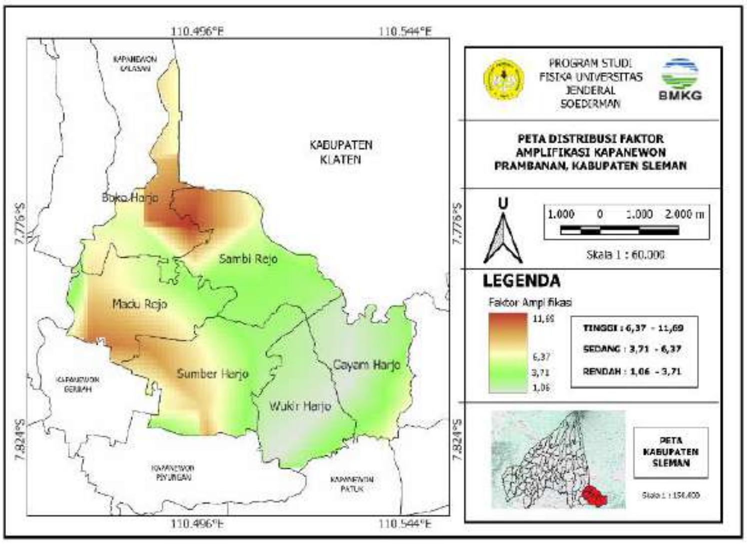
The dominant frequency is shown on the horizontal axis of the HVSR curve, which affects the shear wave velocity value and indicates the thickness of the sediment layer beneath the surface. The microzonation map of the dominant frequency value is used to determine the lithology and topographical influence in the study area. Low dominant frequencies ranging from 0.98 Hz to 4.02 Hz are found in the Merapi Muda Formation, which consists of soft rocks formed by a combination of volcanic materials from Mount Merapi. The progressive thickening of sediments from the summit of Merapi indicates the development of soft and substantial soil layers within the Young Merapi Formation(Bahar et al., 2024). Medium dominant frequencies ranging from 4.02 Hz to 6.67 Hz are found in Gayam Harjo and Wukir Harjo villages in the Semilir Formation. Soil bearing capacity and stability in the Semilir Formation are better than in the Merapi Muda Formation. The dominant high frequency ranges from 6.67 to 17.13 Hz in Sambi Rejo Village, which is located in the Kebobutak Formation. The area in the Kebobutak Formation is dominated by hard rocks and old tertiary rocks such as breccia, agglomerate, and sandstone (Surono, 2008)



Picture 5. Overlay map of the distribution of dominant frequency values in Kapanewon Prambanan, Sleman Regency

Areas with low dominant frequency values have lower elevations, while areas with high dominant frequency values are located in hilly areas. This is because the geological structure in hilly areas is more stable with less deformation compared to lowlands with thick sediment layers (Yulianto et al., 2025).

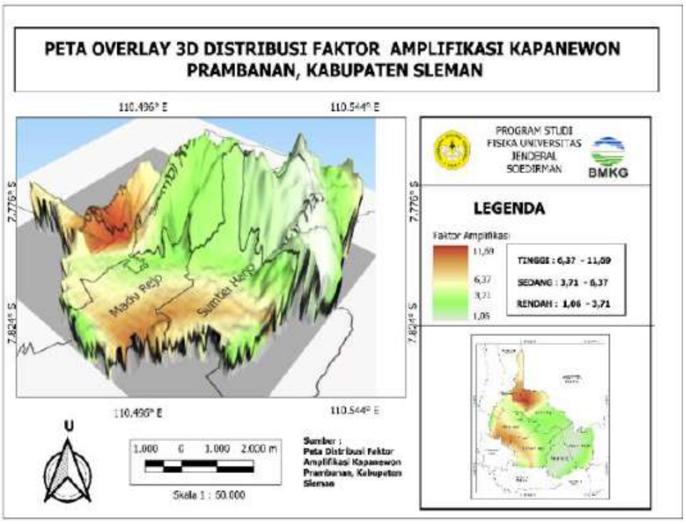
3.2. Amplification Factor



Picture 6. Distribution of amplification factor values in Kapanewon Prambanan, Sleman Regency

Amplification maps can be used to map areas that are potentially prone to high amplification based on weathering processes that cause deformation. Amplification factors are obtained from the peak of the HVSR curve, which indicates the hardness or softness of a rock. The amplification factor is influenced by the impedance contrast between the surface layer and the underlying layer. A greater contrast in impedance results in a higher amplification factor, while a lower contrast yields a lower factor (Amirudin et al., 2023). Most of the Kapanewon Prambanan area in Sleman Regency has moderate amplification values ranging from 3.71 to 6.37. This area includes the villages of Sambi Rejo, Gayam Harjo, and Wukir Harjo, which are located in the Semilir Formation and Kebobutak Formation. The rocks in these formations have characteristics that are not too soft with high density, resulting in moderate amplification values. Areas with low amplification are found in several points in Wukir Harjo and Gayam Harjo villages, ranging from 1.06 to 3.71. Although small, these points reflect areas with more stable soil characteristics, so seismic waves do not experience significant resonance. Amplification increases to a range of 6.37–11.69 in the villages of Boko Harjo, Madu Rejo, and Sumber Harjo within the Merapi Muda

Formation. Although located in the same rock formation, each area may have varying amplification due to weathering that alters the geological structure of a region, making it distinct from others (Demulawa, M., dan Daruwati, 2021).



Picture 7. Overlay map of amplification factor value distribution in Kapanewon Prambanan, Sleman Regency

The amplification value has an inverse relationship with elevation, as shown in Figure 4.4. The amplification factor will be high when the elevation is low. This is due to the presence of sedimentary basins with thicker sediment layers located in low-lying areas. Seismic waves become trapped in the sediment layers, causing resonance between the layers below with different impedance values (Jannah et al., 2024).

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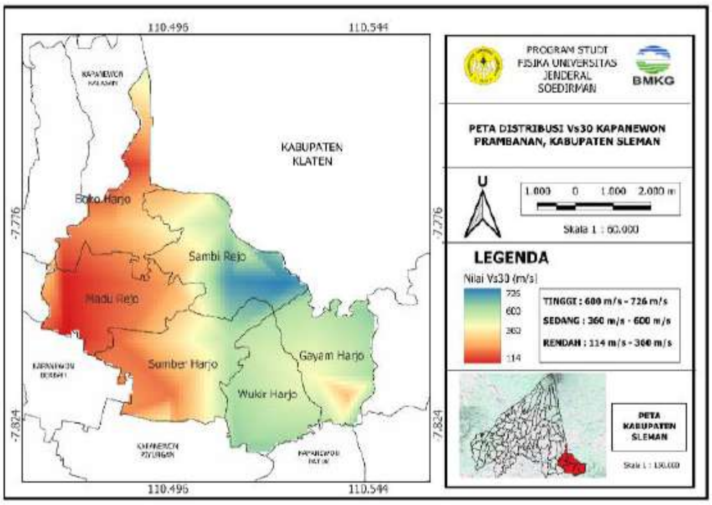
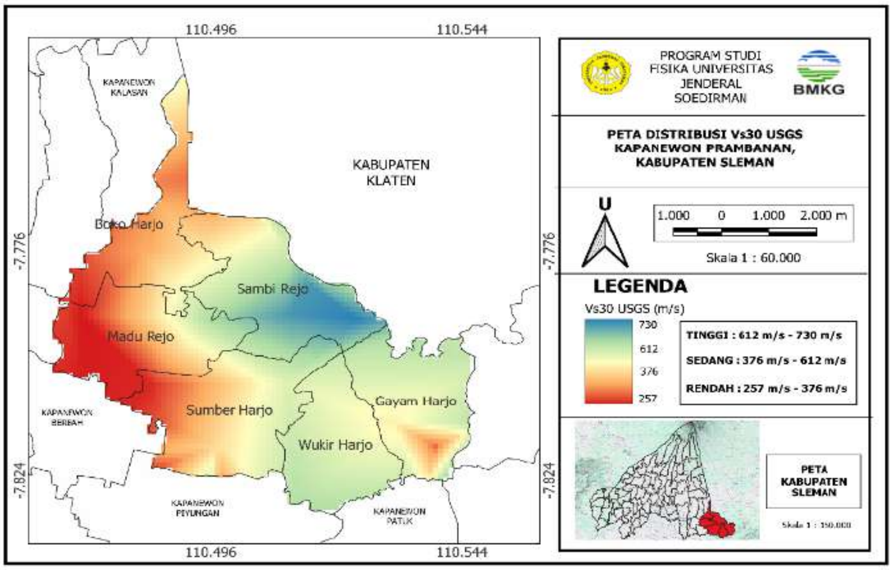
3.3. V_{S30}



Picture 8. Map of V_{S30} value distribution in Kapanewon Prambanan, Sleman Regency

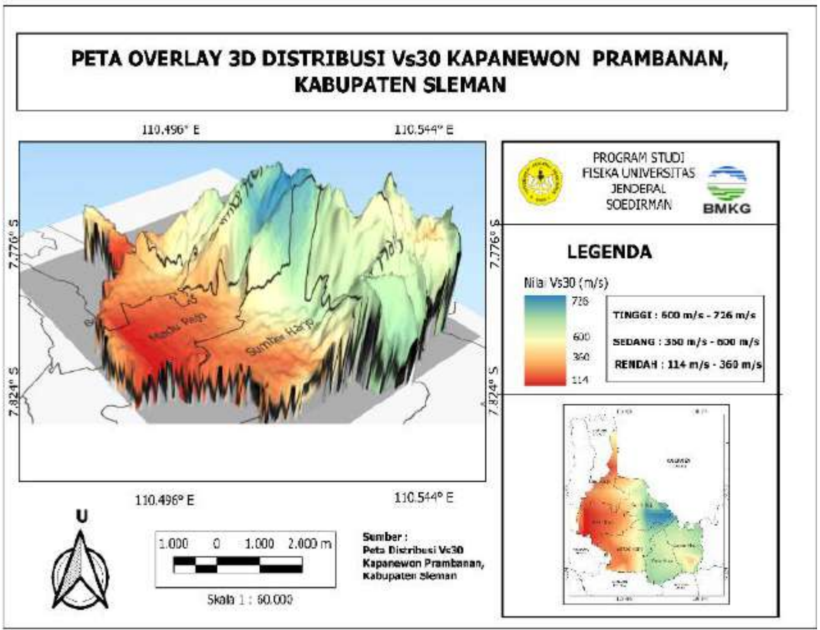
The inversion of the HVSR curve in the study area yielded a shear wave velocity profile at each depth, which could be calculated up to a depth of 30 m based on reference data from borehole logs in Kapanewon Prambanan, Sleman Regency. As an indicator of rock stiffness, Vs30 can theoretically be correlated with rock density, thereby enhancing the precision of geological modelling (Khalilidermani et al., 2025). Density was found to increase with depth in most boreholes, which is proportional to the increase in value V_{S30}. Low V_{S30} values ranging from 114 m/s to 360 m/s were found in Sumber Harjo Village, Madu Rejo Village, and Boko Harjo Village, which are geologically located in the Merapi Muda Formation. The rocks in the Merapi Muda Formation are not well consolidated, causing shear waves to propagate more slowly due to their low density and particle spacing. The

V_{S30} value makes the rocks more susceptible to deformation. Moderate V_{S30} values are found in Gayam Harjo and Wukir Harjo villages, which are located in the Semilir Formation. The rocks in this formation have a higher density than soft rocks and lower than high-density rocks, ranging from 360 m/s to 600 m/s. Meanwhile, the high V_{S30} value is found in Sambi Rejo Village within the Kebobutak Formation, which has more compact rocks with high density.



Picture 9. Map of V_{S30} value distribution USGS in Kapanewon Prambanan, Sleman Regency

Distribution of V_{S30} values compared with V_{S30} values derived from USGS data to validate the inversion that has been performed. The distribution pattern of USGS V_{S30} values in Figure 9 shows a pattern similar to the V_{S30} inversion results, where low V_{S30} values are found in the Merapi Muda Formation ranging from 257 m/s to 376 m/s, moderate V_{S30} values are found in the Semilir Formation ranging from 376 m/s – 612 m/s, and high V_{S30} values ranging from 612 m/s – 730 m/s are found in the Kebobutak Formation. Although the V_{S30} values in both methods have different value ranges for each rock formation, the differences in these ranges still fall within the same rock classification.

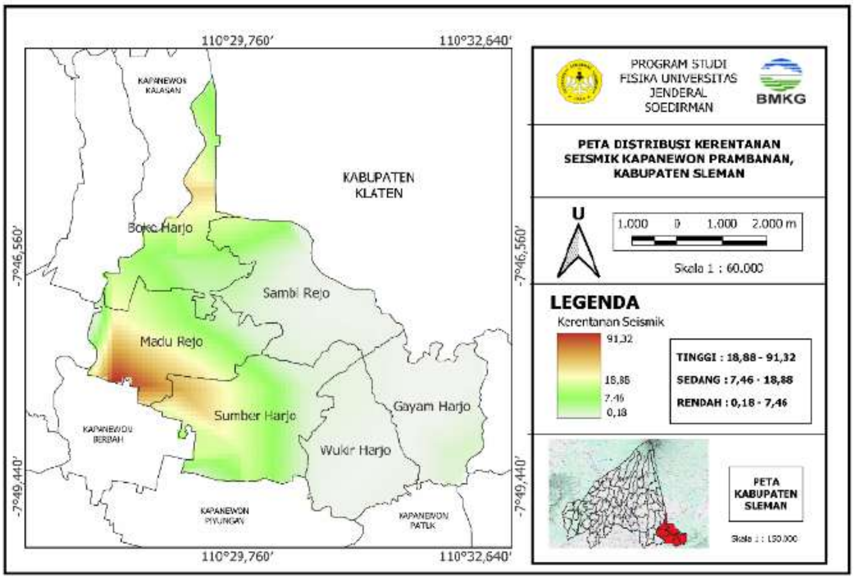


Picture 10. Overlay of the V_{S30} value distribution map in Kapanewon Prambanan, Sleman Regency

Hilly areas produce higher V_{S30} values than lowlands with thick sediment layers dominated by soft soil. The hilly area of Kapanewon Prambanan, Sleman Regency, is dominated by hard and dense soil, which accelerates shear wave propagation. High shear wave velocity values will reduce the degree of rock deformation. Information on V_{S30} values can be used in sustainable spatial planning based on SNI 1726:2019. The hilly areas with high

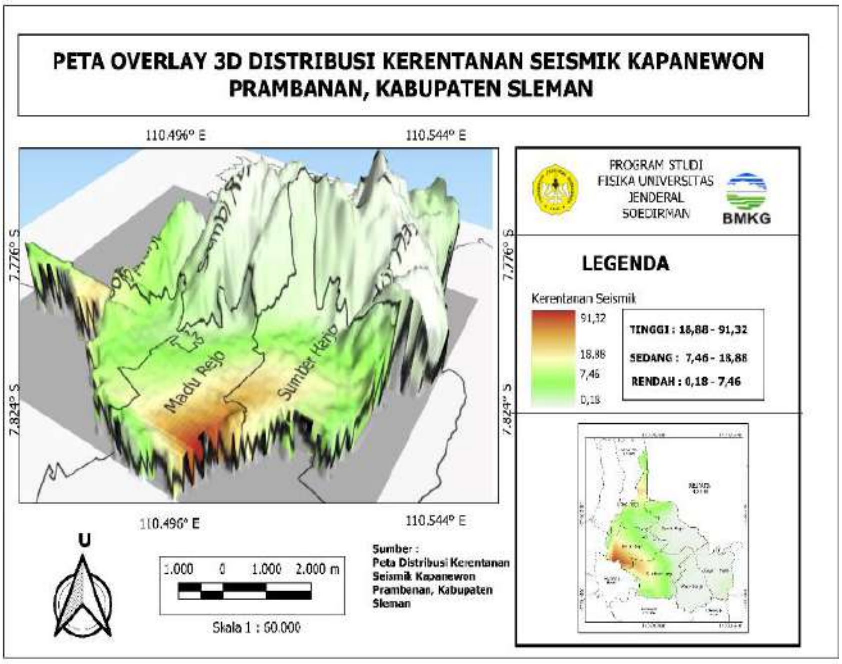
V_{S30} values in Kapanewon Prambanan, Sleman Regency, are the most suitable areas for land development for residential settlements and natural tourist areas (Kristanto & Budi, 2018). To Avoid structural resonance damage, ensure that building frequencies do not coincide with the dominant frequencies of soil (Prasetya et al., 2024).

3.4. Seismic Vulnerability



Picture 11. Map of value seimic vulnerability distribution in Kapanewon Prambanan, Sleman Regency

Seismic vulnerability values are used to assess the level of damage in an area due to seismic wave amplification. In Figure 11, low seismic vulnerability values ranging from 0.18 to 7.46 are found in the villages of Sambi Rejo, Gayam Harjo, and Wukir Harjo, which are located in the Semilir and Kebobutak Formations. Prambanan Subdistrict, Sleman Regency, is located in the Yogyakarta basin and has complex geological conditions, resulting in very high seismic vulnerability of 91.32. Areas with high seismic vulnerability include Madu Rejo, Sumber Harjo, and Boko Harjo villages. Meanwhile, moderate seismic vulnerability values are found in parts of the Semilir Formation, with values ranging from 7.46 to 18.88.



Picture 12. Overlay map of seismic vulnerability distribution in Kapanewon Prambanan, Sleman Regency

Overall, elevation plays a role in determining the level of seismic vulnerability in an area. Based on the distribution of seismic vulnerability values, areas that require disaster mitigation strategies, disaster-resistant infrastructure development, and disaster management monitoring should be focused on the lowlands of Kapanewon Prambanan, Sleman Regency, especially in Madu Rejo Village, Sumber Harjo Village, and Boko Harjo Village. Meanwhile, areas with low seismic vulnerability should still establish disaster-resilient spatial planning to minimise the risks of earthquakes and other natural disasters such as landslides.

3.5. Elaboration of Research and Data on Damage Caused by the 2006 Yogyakarta Earthquake

The research was elaborated based on previous studies to ensure its validity based on existing theories. The HVSR method research in Jambi City found that the dominant frequency value was low in thick sediments, i.e., more than 30 m, and was dominated by soft soil (Satria et al., 2020). Furthermore, the HVSR method study in Bandung City explained that high amplification values were found in rocks dominated by volcanic deposits. Additionally, the rocks in the study area had undergone weathering (Januarta et al., 2020). The study was also elaborated upon with research in Kapanewon Galur, Kulon Progo Regency, which was directly affected by the high seismic activity in Yogyakarta. The seismic vulnerability values in Kapanewon Galur are very high, ranging from 4.8 to 87.85 (Mita et al., 2023).

The research was also supported by data on damage that occurred during the major earthquake in Yogyakarta in 2006, especially in villages in the Merapi Muda Formation, which were prone to damage. The village of Sumber Harjo experienced liquefaction, causing sedimentary rocks to be displaced and water to emerge, accompanied by sulphur-smelling mud and sand, resulting in uneven roads and damage to residents' homes (Munawaroh et al., 2024). Additionally, Madu Rejo Village was also severely damaged, with buildings collapsing due to the loss of soil bearing capacity The earthquake also caused damage to the Prambanan Temple located in Boko Harjo Village (Addawiyah et al., 2017). The damage included cracks in the structure and the collapse of some temple ornaments. This was due to the Prambanan Temple complex being located on soft rock with thick sediment layers

4. CONCLUSION AND RECOMMENDATION

4.1. Conclusion

The results of microtremor analysis in Kapanewon Prambanan, Sleman Regency show that the dominant frequency values range from 0.98 Hz to 17 Hz. The amplification factor ranges from 1.06 to 11.61. The V_s30 values range from 114 m/s to 726 m/s, and the seismic vulnerability index values range from 0.18 to 91.32. Overall, this study indicates that the Merapi Muda Formation area has a higher seismic hazard potential and requires special attention in earthquake risk mitigation and disaster-resistant infrastructure development.

4.2. Recommendation

In future research, further analysis should be conducted on 3D modelling of subsoil sediment layers. The government and community should pay attention to the quality of building structures based on microzonation maps of seismic vulnerability values to minimise the risks associated with earthquakes.

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