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Mapping Ground Acceleration in the Purworejo Region Using the Probabilistic Seismic Hazard Analysis (PSHA) Method with Seismic Data from 1900 to 2024

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ABSTRACT

Purworejo Regency is located in southern Java, directly facing the subduction zone. Its formation is alluvial, making the area vulnerable to seismic hazards. This study aims to map the Peak Ground Acceleration (PGA), Spectral Acceleration (SA), and amplification values in the southern part of Purworejo. PGA values were obtained using the Probabilistic Seismic Hazard Analysis (PSHA) method, while SA was calculated at periods T = 0.2 s and T = 1 s at a 2% exceedance probability over 50 years in both bedrock and surface layers. The data used were earthquake catalog data from the United States Geological Survey (USGS) from 1900 to 2024 with a minimum magnitude of M ≥ 5.0 and a depth of ≤ 300 km. The results show that for bedrock, the PGA value for the Purworejo region is 0.37–0.43 g, SA at T = 0.2 s is 0.79–1.0 g, and SA at T = 1 s is 0.55–0.63 g. The PGA value at the surface is 0.37–0.45 g, the SA at T = 0.2 s is 0.81–1.0 g, and the SA at T = 1 s is 0.55–0.73 g. The calculated amplification values are 1.0–1.03 for PGA and 1.0–1.09 for SA at T = 0.2 s, and 1.0–1.17 for SA at T = 1 s. Among the southern regions of Purworejo showing high PGA, SA, and amplification values are Purwodadi and Ngombol districts. These two areas have higher vulnerability to earthquake hazards compared to surrounding areas.

Keywords : earthquake mitigation; PGA, PSHA; amplification; Purworejo

ABSTRAK

Kabupaten Purworejo terletak di Pulau Jawa bagian selatan berhadapan langsung dengan zona subduksi. Formasinya berupa aluvial sehingga memiliki kerentanan wilayah terhadap bahaya seismik. Penelitian ini bertujuan untuk memetakan nilai Peak Ground Acceleration (PGA), Spectral Acceleration (SA), dan nilai amplifikasi batuan di wilayah Purworejo bagian selatan. Nilai PGA diperoleh dengan metode Probabilistic Seismic Hazard Analysis (PSHA), sedangkan SA dihitung pada periode T = 0,2 s dan periode T = 1 s pada probabilitas terlampaui 2% dalam 50 tahun di batuan dasar dan permukaan. Data yang digunakan berupa data katalog gempa dari United States Geological Survey (USGS) pada tahun 1900-2024 dengan nilai magnitudo minimum M ≥ 5,0 dan kedalaman ≤ 300 km. Hasil menunjukkan bahwa pada batuan dasar nilai PGA Wilayah Purworejo adalah 0,37 – 0,43 g, SA saat T=0,2 s adalah 0,79 – 1,0 g, dan SA untuk T=1 s adalah 0,55 – 0,63 g. Nilai PGA di permukaan yaitu 0,37 – 0,45 g, untuk SA pada saat T = 0,2 s 0,81 – 1,0 g, dan SA pada saat T = 1 s adalah 0,55 – 0,73 g. Nilai amplifikasi yang terhitung adalah 1,0 – 1,03 untuk PGA dan 1,0 – 1,09 untuk SA pada saat T = 0,2 s, dan 1,0 – 1,17 untuk SA pada saat T = 1 s. Di antara wilayah Purworejo bagian selatan yang menunjukkan nilai PGA, SA, dan amplifikasi yang tinggi adalah Kecamatan Purwodadi dan Ngombol. Kedua daerah ini memiliki kerentanan yang lebih tinggi terhadap bahaya gempa bumi dibandingkan wilayah sekitarnya.

Kata Kunci : mitigasi gempa bumi; PGA; PSHA; amplifikasi; Purworejo

1. INTRODUCTION

The Purworejo region is located in southern Central Java, an area prone to earthquakes. Purworejo is situated between active fault lines and the megathrust zone in southern Java, making it vulnerable to serious threats from potential earthquakes. Central Java is classified as a high-risk earthquake zone. This is due to Central Java's location at the junction of the Indo-Australian Plate and the Eurasian Plate (Prabowo et al., 2019). The megathrust zone can trigger major earthquakes and increase the risk of local earthquakes along active fault lines in Central Java, including in Purworejo. Based on historical data from June 30, 2023, the southern part of Purworejo was affected by the Bantul earthquake with a magnitude of 6.3 M, causing moderate damage to buildings (BNPB, 2023). From a geological perspective, the southern part of Purworejo is dominated by soft rocks that can amplify earthquake shaking (Bronto, 2007).

One effort to identify and reduce earthquake hazards is by determining the Peak Ground Acceleration (PGA) value. The PGA value indicates the ground acceleration caused by an earthquake, which affects structural damage and the potential for casualties (Bustari & Wibowo, 2023). The Probabilistic Seismic Hazard Analysis (PSHA) method can be used to identify high-risk zones and predict possible PGA values (Kumala & Wahyudi, 2016). The PSHA method defines earthquake hazards based on the distribution of ground motion values, which are expressed in terms of Peak Ground Acceleration (PGA), or the maximum ground acceleration, as key parameters for developing seismic hazard maps (Susanti et al., 2020). PSHA displays the relative contributions to seismic hazard from various random components of the problem, particularly earthquake magnitude (M) and source-to-site distance (R), through a process known as deaggregation (Setiawan et al., 2017). This study aims to map the distribution of ground acceleration values in bedrock and surface rock, which can be used as a mitigation effort.

2. METHOD

2.1. Data collection

The PSHA method is carried out in several stages. This study utilizes an earthquake catalog from 1900 to 2014 obtained from the USGS with coordinate limits of 3° 2’ - 12° 24’ S and 105° 17’ - 114° 38’ E, depth limits up to 300 km, and a minimum magnitude of $M \geq 5.0$. The data obtained has a variety of magnitude scales, so it must be converted to moment magnitude (Mw). Standardizing the magnitude type to the Mw scale is crucial for calculating seismic hazard and crustal deformation (Scordilis, 2006). In this study, only mainshock earthquake data is used, so the data obtained requires a declustering process. Declustering involves separating mainshocks from aftershocks and foreshocks using the Reasenberg criterion with ZMAP Ver.7 software.

2.2. Modeling and Characterization of Earthquake Sources

In PSHA processing, one important component is the modeling of the earthquake source used. In this study, the earthquake source zone is classified into three types of models, namely subduction (megathrust), fault, and background earthquake sources.

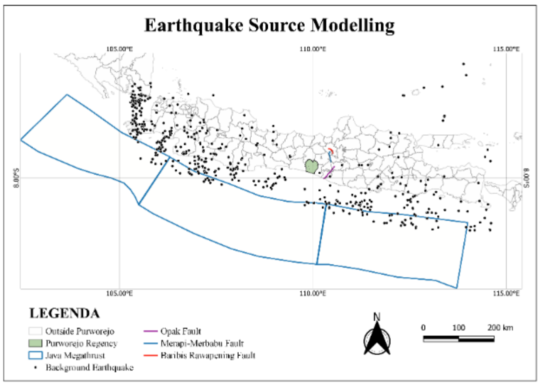

Figure 1. Earthquake Source Modeling

The modeled earthquake sources were then characterized, including parameters such as a, b values, slip velocity, and maximum magnitude. This study analyzes earthquake source characterization in the Purworejo region using a seismicity model, focusing on fault, subduction, and background earthquake sources. The seismicity model applied includes the Gutenberg-Richter model for analyzing subduction and background earthquake sources, as well as a characteristic model specifically used for fault earthquake sources.

2.3. Probabilistic Seismic Hazard Analysis

The Probabilistic Seismic Hazard Analysis (PSHA) method is used to estimate and analyze the distribution of potential seismic hazards by taking into account various factors, including the location and frequency of earthquake occurrences (Oktaviani et al., 2023).The seismic hazard analysis in this study used a probabilistic approach with R-CRISIS Ver 20.0.3 software. Earthquake source parameters, such as maximum magnitude and slip rate, are essential in the PSHA process (Sulistio et al., 2024). In the PSHA method, calculations are performed to determine the probability of exceedance over a specific time period or earthquake return period, making the results applicable for various purposes (Ridwan et al., 2024).

The mathematical equation for the PSHA method is a probability theorem expressed in the following equation.

$$\lambda(IM > im) = \lambda(EQ) \iint_{RM} P(IM > im\,|m, r) f_M(m_i) f_R(r_i)\, dmdr \quad (1)$$

During the processing, the research area grid, earthquake source, characteristic model, and attenuation function were inputted. The attenuation function can be used to predict the intensity of ground motion at a location based on the magnitude and distance from the earthquake source (Sa'adah et al., 2015). Specific attenuation refers to a localized reduction in seismic wave energy, taking into account the geographical location, the earthquake generation mechanism, soil types, and tectonic activity in the area (Zera et al., 2021).

To determine the actual conditions on the surface, corrections are made to the geological conditions using the V_{s30} value. The equation used is as follows.

$$AF = \phi_1 . min\left(ln\left(\frac{V_{s30j}}{1130}\right), 0\right) + \phi_2 . \left\{e^{\phi_3(min(V_{s30IJ},1130)-360)} - e^{\phi_3(11360-360)}\right\} . ln\left(\frac{y_{ref}+\phi_4}{\phi_4}\right) \quad (2)$$

The final results of the seismic hazard analysis are the Peak Ground Acceleration (PGA) values and acceleration spectra at the bedrock and surface with a 2% probability of exceedance over a 50-year period. The acceleration spectra generated are for short periods T = 0.2 s and long periods T = 1 s. The amplification values are obtained from the comparison of PGA values at the surface with PGA values in bedrock. After obtaining these values, earthquake hazard mapping is carried out based on the known values using QGIS software.

3. RESULT AND DISCUSSION

3.1. Ground Acceleration in Bedrock

The calculation of PGA values involves the contribution of each earthquake source. The analysis results show that the PGA values in the bedrock of the Purworejo region at a 2% exceedance probability over 50 years range from 0.37 to 0.43 g. Figure 3 shows that the southern part of the Purworejo region, including Ngombol District, Purwodadi District, Bagelen District, and Grabag District, has relatively high PGA values up to 0.43 g, indicated by the color red.

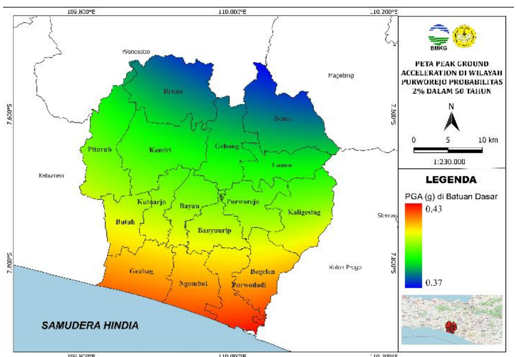

Figure 2. PGA value map on bedrock for a 2% probability of exceedance in 50 years in the Purworejo Region

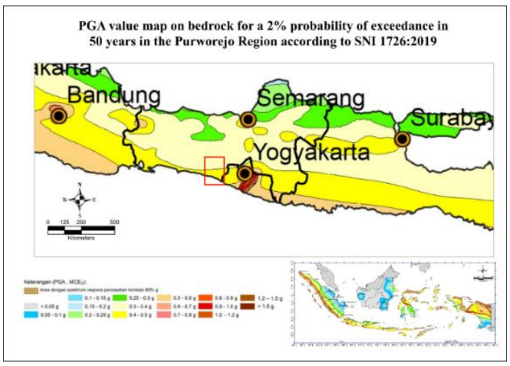

Figure 3. PGA value map on bedrock for a 2% probability of exceedance in 50 years for the Purworejo Region according to SNI 1726:2019

The results of the study, when compared with the map according to SNI 1726:2019, show slight differences in the range of values. However, there is a similarity in the PGA value pattern, namely that the southern part has higher values than the northern part (BSN, 2019).

3.1.1. Ground Acceleration under Spectral Acceleration Conditions T = 0.2 s

The acceleration spectrum value (SA) represents the level of earthquake hazard that can be felt by building structures. In this study, the SA values (T=0.2 s) ranged from 0.79 to 1.1 g. The southern part of Purworejo, bordering the Indian Ocean, showed high SA values (T=0.2 s) up to 1.1 g in Purwodadi District. This distribution indicates that the southern region needs to consider earthquake hazard levels in infrastructure development. The SA values with T = 0.2 s are higher than the PGA values in bedrock. This difference occurs due to resonance between earthquake vibrations and the natural vibration period of building structures at that period.

The map according to SNI 1726:2019 shows that the SA value ranges from 0.8 to 1 g. Based on the results of the SNI 1726:2019 analysis and this study, Purwodadi Subdistrict has the maximum SA value among the regions in Purworejo. This reflects that the earthquake source model and attenuation function used in this study are capable of providing accurate seismic hazard analysis.

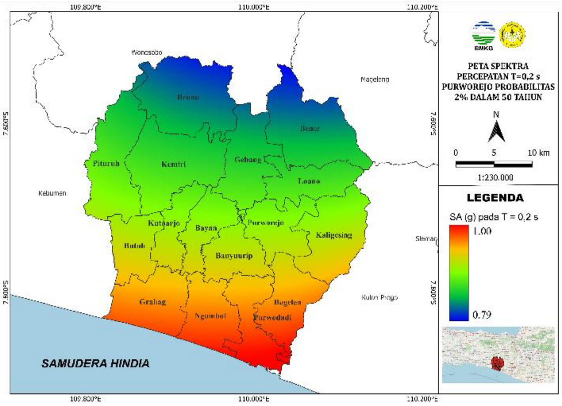

Figure 4. SA value map at T = 0.2 s in bedrock for a 2% probability of exceedance in 50 years for the Purworejo Region

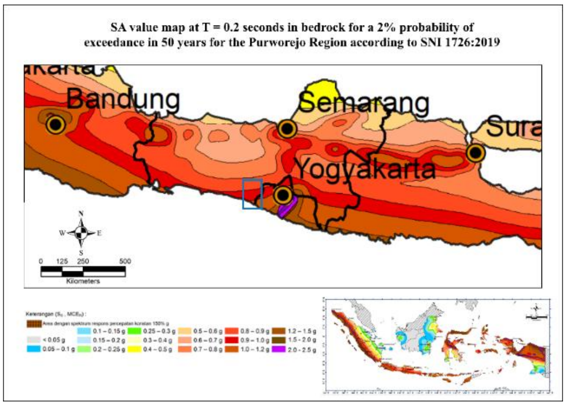

Figure 5. SA value map at T = 0.2 seconds in bedrock for a 2% probability of exceedance in 50 years for the Purworejo Region according to SNI 1726:2019

3.1.2. Ground Acceleration under Spectral Acceleration Conditions T = 0.2 s

The spectral acceleration (SA) distribution with a period of T = 1 second in the bedrock of the Purworejo region shows a range of 0.55 g to 0.63 g. Southern regions such as Ngombol District and Purwodadi District have relatively high SA values (T = 1 s) of 0.63 g. Tall buildings are more affected by earthquakes with long periods (T = 1 s) compared to earthquakes with short periods, such as T = 0.2 s or T = 0 s.

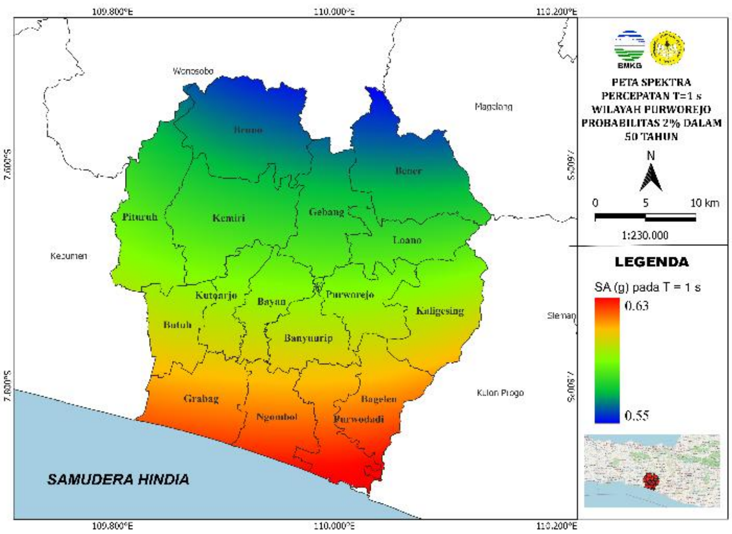

Figure 6. SA value map at T = 1 second in bedrock for a 2% probability of exceedance in 50 years for the Purworejo Region

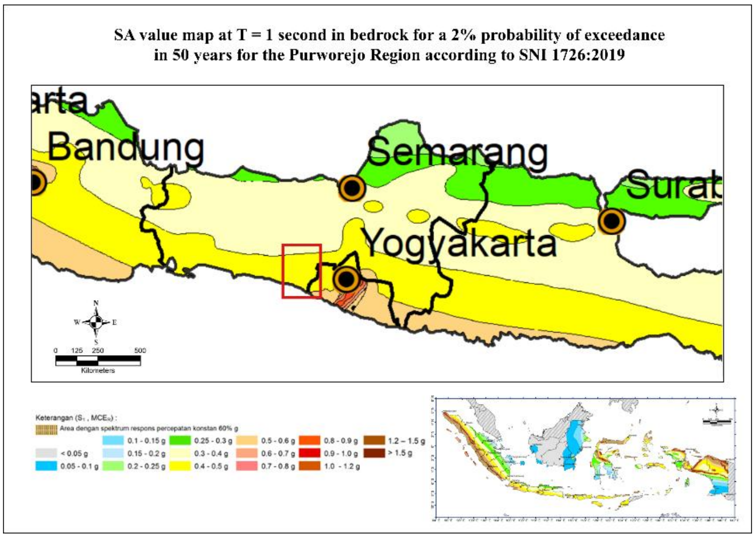

Figure 7. SA value map at T = 1 second in bedrock for a 2% probability of exceedance in 50 years for the Purworejo Region according to SNI 1726:2019

Based on Figure 7, the SA value at T = 1 s in the study results is higher than the results in SNI 1726:2019. The SA value (T = 1 s) in this study ranges from 0.55 g to 0.63 g, while according to SNI 1726:2019, the SA value (T = 1 s) for the Purworejo region ranges from 0.3 g to 0.4 g. The difference in SA values may be due to the use of earthquake source models and attenuation functions in the study.

3.2. Surface Ground Acceleration

Surface earthquake hazard analysis was conducted by combining the Vs30 values in the Purworejo region with the PGA results in the bedrock. This approach accounts for variations in surface soil conditions, which significantly influence soil response to earthquakes, thereby providing more accurate vulnerability estimates for each location (Ginting et al., 2020). Surface PGA values in the Purworejo region vary from 0.37 g to 0.45 g. Higher PGA values indicate greater vulnerability to earthquakes. (Sefiyanti et al., 2024).

The highest PGA value of 0.45 g is located in Purwodadi District. This value, when converted to the MMI scale, ranges from VII to VIII with strong shaking (Muzli et al., 2016). The southern part of Purworejo is generally located on alluvial rocks and coastal deposits with low Vs30 values. Alluvial rock types are highly susceptible to shaking, resulting in relatively high PGA values (Hadi et al., 2021). In a study conducted by (Muryani et al., 2024) on earthquake risk assessment in Purworejo, the seismic hazard level in the southern part of Purworejo was found to be higher than in the northern part. Lower PGA values combined with low population density indicate a lower seismic risk, whereas higher values significantly increase the potential impact of earthquake disasters (Supriyadi et al., 2024).

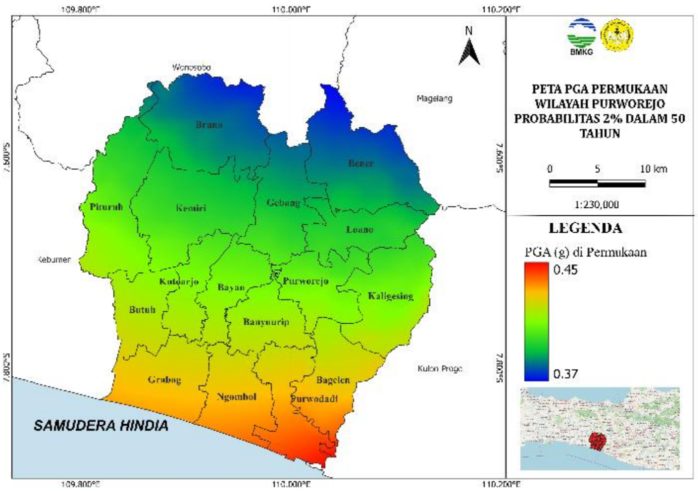

Figure 8. Map of maximum ground acceleration (PGA) values on the surface for a 2% probability of exceedance in 50% of the Purworejo region

3.2.1. Ground Acceleration under Spectral Acceleration Conditions T = 0.2 s on the Surface

The spectral acceleration (SA) values at a period of T = 0.2 s in the Purworejo region show varying values ranging from 0.81 g to 1 g. In the southern part, including the districts of Grabag, Ngombol, Purwodadi, and Bagelen, most of the area shows high SA (T = 0.2 s) values of 1.0 g, depicted in red. The high SA values in the southern part are due to its proximity to the megathrust earthquake source, resulting in greater structural impact on buildings. Geologically, the area is located on alluvial rocks and coastal deposits. The soil characteristics in this region have low Vs30 values and are classified as medium to soft soil.

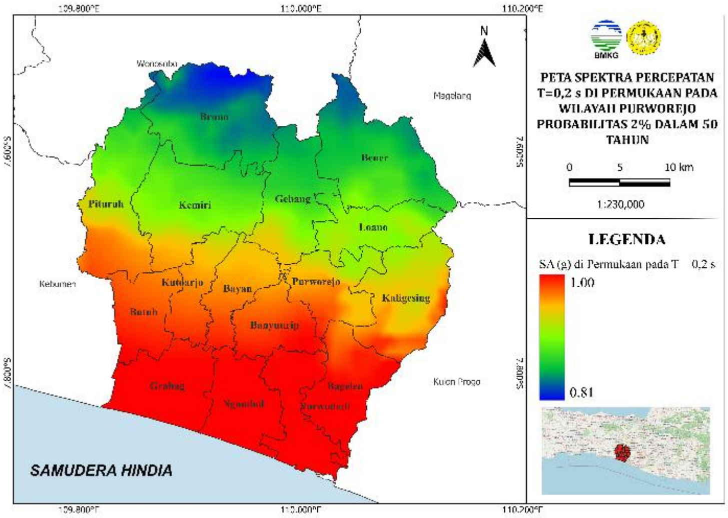

Figure 9. SA value map at T = 0.2 seconds on the surface for a 2% probability of exceedance in 50 years for the Purworejo Region

In the northern part of Purworejo, such as Bruno, Kemiri, Gebang, and Bener subdistricts, the SA value (T=0.2 s) is lower, ranging from 0.81 g. These areas have harder soil characteristics with high Vs30 values, making them stable against earthquake shocks.

3.2.2. Soil Acceleration under Spectral Acceleration Conditions T = 1 s on the Surface

The soil acceleration spectrum (SA) map at a long period of T = 1 second shows that the SA value (T=1 s) in the Purworejo region varies from 0.55 g to 0.73 g. Figure 10 shows the highest SA value (T=1 s) of 0.71 g, located in Ngombol and Purwodadi districts. These areas are located on alluvial rock with low Vs30 values. The northern part of Purworejo, such as Bruno District, Bener District, and part of Gebang District, shows lower SA values (T=1 s) ranging from 0.55 g. The northern part is located in the Kebo Butak and Peniron Formations, which consist of breccia with high Vs30 values.

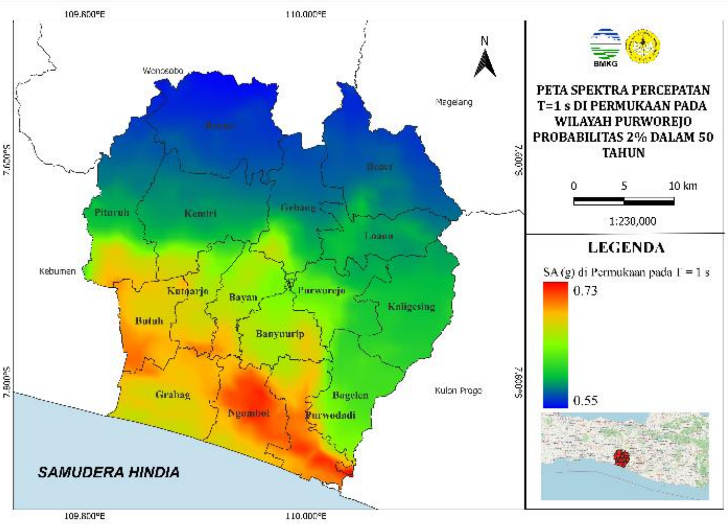

Figure 10. SA value map at T = 1 second on the surface for a probability of exceeding 2% in 50 years for the Purworejo Region

3.3. Amplication Value

Amplification is the change (increase) in ground vibration acceleration from the bedrock layer to the surface, influenced by soil characteristics, including the Vs30 value. In hazard analysis, the amplification value is obtained from the comparison of the PGA value at the surface with the PGA value at the bedrock (Azhar et al., 2020). Based on data processing, the Peak Ground Acceleration (PGA) amplification value in the Purworejo region ranges from 1 to 1.03, with a higher concentration of values in the southern part.

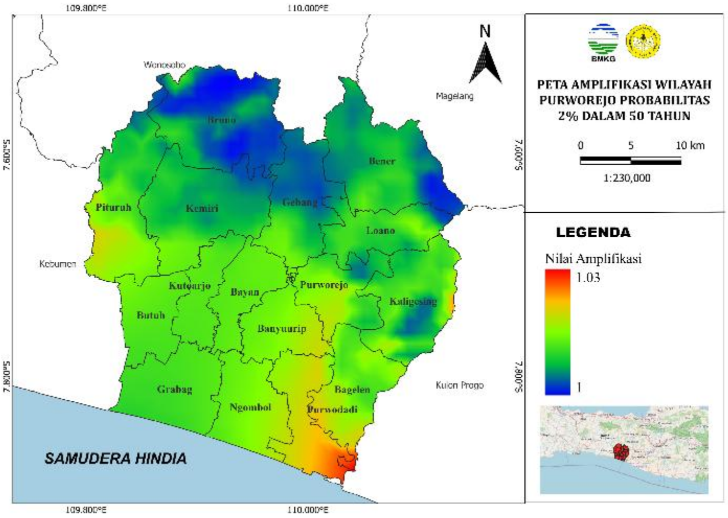

Figure 11. Amplification Map of Purworejo Region

3.3.1. Amplification Value under Spectral Acceleration Conditions T = 0.2 s on the Surface

The SA amplification value at a period of T = 0.2 seconds is obtained by comparing the SA value at T = 0.2 seconds at the surface with the bedrock. In Figure 12, the amplification values range from 1 to 1.09, with areas having higher amplification values depicted in red to orange. Areas with high amplification include Purworejo, Kutoarjo, Butuh, Bayan, and Banyuurip districts. These areas are located on alluvial rock and have low VS30 values, which amplify earthquake waves. Low amplification values are found in Bruno and Bener districts, which have more stable soil, indicated by blue and green colors.

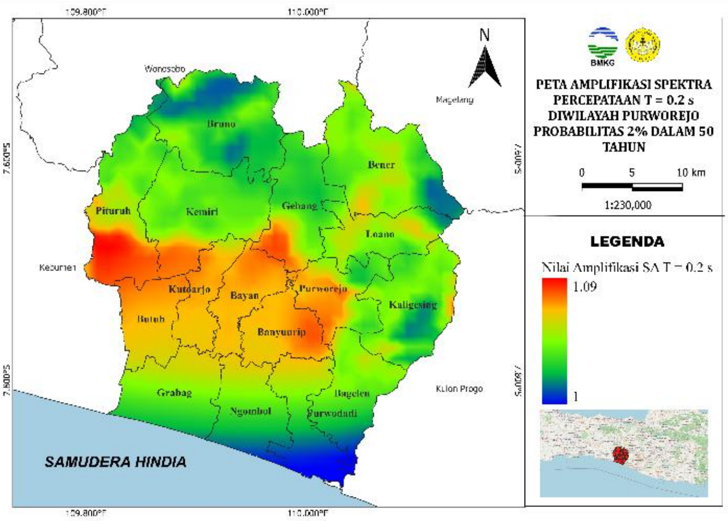

Figure 12. SA amplification map at T = 0.2 seconds for a 2% probability of exceedance in 50 years for the Purworejo Region

3.3.2. Amplification Values under Spectral Acceleration Conditions T = 1 s at the Surface

Amplification values at a period of T = 1 second indicate the soil's response to longer-period earthquake vibrations that affect tall building structures. The amplification value at SA period T = 1 second ranges from 1 to 1.17. Areas such as Ngombol, Purwodadi, and Grabag subdistricts have high earthquake amplification potential, indicated by red and orange colors. The soft soil conditions and low Vs30 values in these areas cause wave amplification.

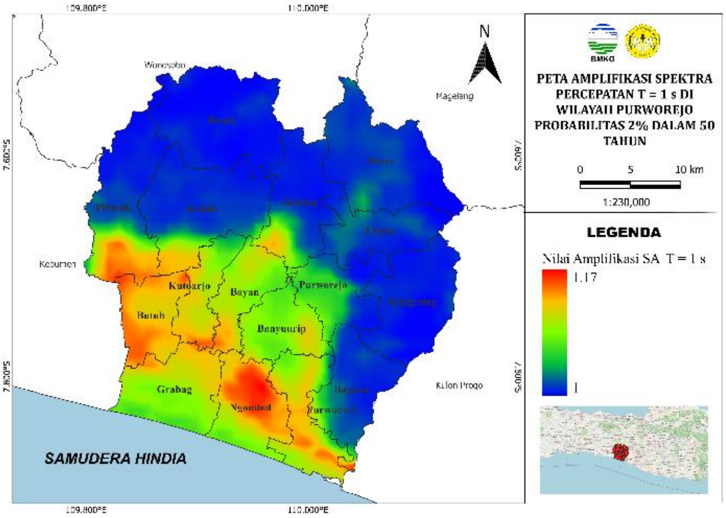

Figure 13. SA amplification map at T = 1 second for a 2% probability of exceedance in 50 years for the Purworejo Region

4. CONCLUSION AND RECOMMENDATION

Based on the results of research and analysis of earthquake hazards in Purworejo with a probability of exceeding 2% in 50 years using the Probabilistic Seismic Hazard Analysis method, it can be concluded that the PGA value in the Purworejo region has an increasing pattern from north to south. The PGA values in bedrock range from 0.37 to 0.43 g, while the PGA values at the surface range from 0.37 to 0.45 g. The highest PGA values are found in Purwodadi and Ngombol districts. The distribution of amplification values ranges from 1 to 1.3, with high amplification values in Purwodadi District. Based on these results, the southern part of the Purworejo region, particularly Purwodadi District, requires greater attention regarding earthquake disaster mitigation efforts. To improve the precision of seismic hazard analysis in the Purworejo region, it is advisable to use the actual Vs30 values from the study.

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