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SEISMIC MICROZONATION STUDIES IN JOGJA–BAWEN TOLL ROAD, MAGELANG REGENCY, INDONESIA

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ABSTRACT: Peak Ground Acceleration (PGA) is a crucial factor in infrastructure planning, particularly in the context of constructing the Jogja–Bawen Toll Road in Magelang Regency. However, there is a lack of comprehensive research on the optimal PGA value for this region. This research addressed this gap by analyzing two significant earthquake scenarios, namely the Bantul and Yogyakarta earthquakes, with magnitudes of 6.3 Mw and 7.44 Mw, respectively. Three methods were employed for this analysis, namely the Indonesian seismic code, Kanno (2006), and Fukushima (1990) attenuations, as well as microtremor measurements. The PGA value generated by the seismic code ranges from 0.348–0.380g. For the 6.3 Mw earthquake scenario, the Kanno attenuation results in a PGA range of 0.115–0.181g, the Fukushima attenuation yielded 0.082–0.114g, and the microtremor measurements indicated 0.036–0.092g. In the case of the 7.44 Mw earthquake scenario, the Kanno attenuation generated a PGA range of 0.202–0.265g, the Fukushima attenuation produced 0.052g–0.062g, and the microtremor measurements indicated 0.036g–0.088g. The result showed that the PGA value derived from the seismic code is relatively higher because it considered various earthquake models and magnitudes. Meanwhile, the PGA value obtained from microtremor measurements was smaller due to the consideration of site class and site-specific amplification factors at the study site.

Keywords: Peak ground acceleration, Microzonation, Microtremor, Attenuation, Magelang

1. INTRODUCTION

Peak Ground Acceleration (PGA) refers to the maximum acceleration of the ground during an earthquake, which is felt at the surface. The value of acceleration can vary based on factors such as local site characteristics, ground amplification, earthquake magnitude, and distance from the earthquake source [1]. PGA can be determined using historical seismic data or by studying fault conditions around the location. In areas prone to earthquakes or located near faults, additional analysis, such as microzonation, is necessary for an effective infrastructure design process.

The research focuses on Magelang Regency, a region highly susceptible to earthquakes due to its proximity to the Java Subduction and Opak Fault. The construction of the Jogja–Bawen Toll Road, estimated to cost $1 billion, is planned for this area. However, there is a lack of comprehensive research regarding the determination of Peak Ground Acceleration at this specific location. Comparative research on PGA and PGA microzonation in Indonesia has only been conducted in Yogyakarta [2]. The research reported a range of PGA values, from 0.05 g based on microtremor measurements to 0.57 g calculated using the Indonesian seismic code SNI 1726:2012. Microtremor measurements have been carried out in various locations in Indonesia, including Gunungkidul [3], Palu [4,5], Padang [6], Semarang [7], and Bengkulu [8].

Yogyakarta has experienced two significant earthquakes with devastating consequences. The first was the 1943 Yogyakarta Earthquake with a magnitude of 7.44 Mw, originating from a subduction zone at a depth of 60 km, which resulted in 213 fatalities, 2,096 injuries, and the destruction of 2,800 houses [9]. The second event was the 2006 Bantul Earthquake with a magnitude of 6.3 Mw, caused by a strike-slip mechanism along the Opak Fault at a depth of 12.5 km. The 2006 earthquake led to more than 5,700 deaths, over 37,000 injuries, and significant damage to around 156,000 houses and other structures. It also caused long-term economic losses exceeding $3 billion, leaving many people without a source of income [10].

The primary objective of this research is to determine the Peak Ground Acceleration values using multiple methods, considering two earthquake scenarios. The research methodology involves referencing past earthquakes and conducting site investigations through core drillings and microtremor measurements. The result compared the PGA values obtained and performed microzonation based on the earthquakes analyzed.

2. RESEARCH SIGNIFICANCE

The primary focus of this research is to determine the PGA values resulting from two distinct earthquake mechanisms. The findings will make a significant contribution by generating microzonation maps based on PGA obtained from various methods. PGA is a crucial parameter in the design of infrastructure, including toll roads. By conducting this comparative research, it is expected that the planned toll road in the area can be developed in a suitable and resilient manner. The outcomes of this research are anticipated to be valuable for all stakeholders, including academics and practitioners, providing them with valuable insights and guidance.

3. GEOLOGICAL CONDITION

The research area is located in Magelang Regency, west of Mount Merapi. The region primarily comprises young volcanic deposits from the formations of Mount Merapi, including undifferentiated tuff, ash, breccia, agglomerate, and lava flows [11], as shown in Fig. 1. These deposits are of Quaternary age [11], indicating that they have not undergone significant consolidation or cementation processes. As a result, the soil in the area remains loose and lacks sufficient compaction.

The earthquakes in the research area are primarily caused by two types of faults, namely megathrusts resulting from subduction in the south of Java Island and horizontal faults trending NE–SW to SE. Subduction in the southern part of Java Island frequently generates earthquakes ranging from small to large magnitudes. One significant fault in the region is the Opak Fault, which is located approximately 20–35 km away from the research area. The Opak Fault was responsible for the earthquake that triggered liquefaction indications, such as sand boil and lateral spreading in Bantul in 2006 [12].

4. METHOD

4.1 Data Gathering

One of the PGA values was determined through the microtremor data collection method, which was conducted along the centerline (CL), left (LF), and right (RF) sides of the toll road, within a maximum distance of 300 meters from the right of way. The microtremor data collection took place from March 9th to 11th, 2023. A total of 49 microtremor points were sampled along a 15.2 km section of the Jogja–Bawen toll road, as shown in Fig. 1. The data collection and processing procedures followed the guidelines of SESAME European Research [13].

4.2 Data Analysis

Raw microtremor data was processed using Geopsy version 2.9.1. to produce a Horizontal Vertical Spectral Ratio (HVSR) value, according to Nakamura [14]. The parameters used in time windowing are 30–50s, mostly 40s, with STA 1s, LTA 30s, Min STA/LTA 0.2, and Max STA/LTA 2.5. Raw data microtremors were processed using a sample rate of 100 samples per second. For the analyzed data, the parameters included the Konno & Omachi smoothing type with a smoothing constant of 40 [15] and a window cosine tape type with a width of 5%. The output frequency range for the processed data was set from 0.3 to 15 Hz.

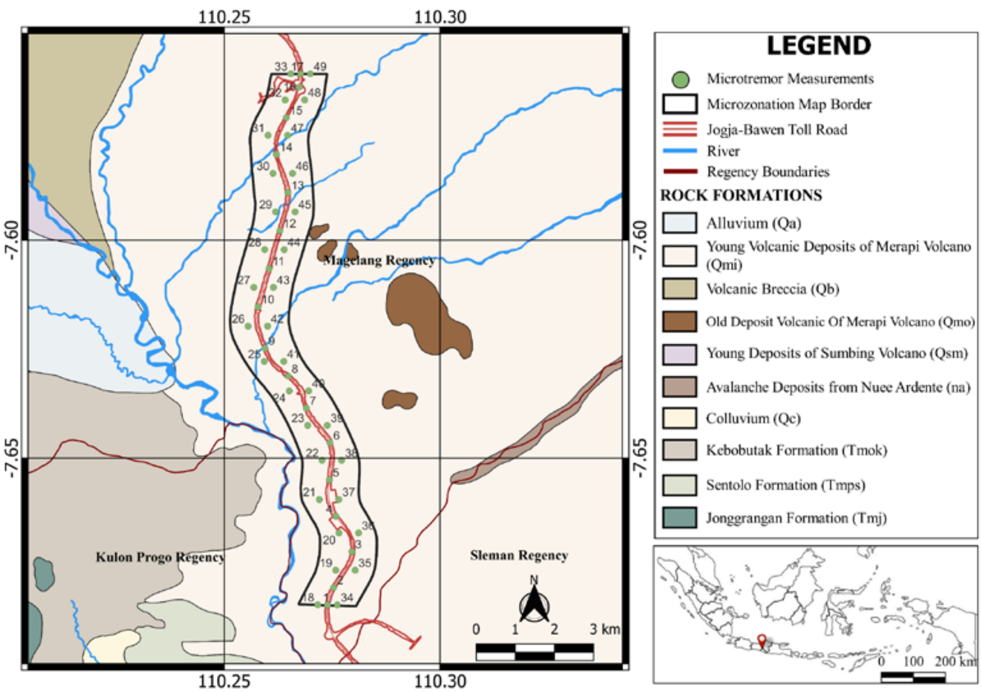

Fig.1 Geological condition and microtremor measurements in the research location

The Guideline of the SESAME European Research Project [13] was adopted to obtain precise and reliable peaks needed to estimate resonance frequency and amplification. For clear peaks, three conditions need to be fulfilled, namely the number of windows (>10s), the number of significant cycles (>200), and the level of scattering. Therefore, several windows and a low scattering level in each velocity window were taken to ensure that a minimum number of significant cycles were available in each frequency window.

5. DETERMINATION OF PEAK GROUND ACCELERATION (PGA)

In this research, the PGA values are determined using two earthquake scenarios with different mechanisms. The first scenario involved the subduction of the Indo-Australian plate, which resulted in a significant earthquake on Java Island known as the 1943 Yogyakarta earthquake, with a magnitude of 7.44 Mw. The second scenario is the 2006 Bantul earthquake, which had a magnitude of 6.3 Mw and was caused by shallow crustal activity specifically associated with the movement of the Opak fault [16]. Meanwhile, there may be variations in the epicenter locations and exact mechanisms of these earthquakes. This research used estimated values and locations provided by the USGS for consistency and comparability purposes.

5.1 PGA Determination Based on the Indonesian Seismic Code

The PGA value determines the maximum PGA value in the ground surface (*As*). Based on [17], the value of *As* for a probability of 7% in 75 years to highway and bridge design was determined by multiplying the value of PGA and the site coefficient, as shown in Eq. 1.

$$As = F_{PGA} \times PGA \tag{1}$$

Where *As* is the maximum PGA at the ground surface adapted from the site coefficient, F_{PGA} is the site coefficient for a probability of 7% in 75 years, and *PGA* is bedrock acceleration. The site class determines the site coefficient, as shown in Table 1.

Based on the geotechnical site investigation conducted by the Ministry of Public Works and Housing of the Republic of Indonesia, the research location is classified as having a medium soil (SD) site class. Therefore, according to Table 1, the site coefficient used at the research site would be selected from the SD range. The PGA at the research location was obtained from the Ministry of Public Works and Public Housing's website (https://lini.binamarga.pu.go.id/) by inputting coordinate points.

Table 1 Site coefficient [17]

Site Class	PGA≤ 0.1g	PGA= 0.2g	PGA= 0.3g	PGA= 0.4g	PGA≥ 0.5g
SA	0.8	0.8	0.8	0.8	0.8
SB	1.0	1.0	1.0	1.0	1.0
SC	1.2	1.2	1.1	1.0	1.0
SD	1.6	1.4	1.2	1.1	1.0
SE	2.5	1.7	1.2	0.9	0.9
SF	Required specific site response analysis				

5.2 PGA Determination by Using Attenuation Relationships

Empirical prediction of PGA is calculated using the empirical equations based on earthquake magnitude and hypocenter distance or active faulting that occurred in the past.

Kanno used three main parameters in modeling earthquake attenuation, namely magnitude, the shortest distance to the seismic fault plane, and focal depth. By using a comprehensive database of strong ground motion records from Japan between 1963 and 2003, Kanno developed a new standard attenuation relationship specifically for Japan. The dataset used by Kanno comprised 91,731 records from 4,967 events within Japan, as well as 788 records from 12 events in countries outside of Japan. For regression analysis, Kanno [18] selected 11,542 records from 184 events in Japan and 377 from 10 events elsewhere. Kanno's equation is shown in Eqs. 2 and 3.

$D \leq 30$ km

$$\log pre = a_1 Mw + b_1 X - \log(X + d_1 10^{0.5Mw}) + c_1 + \varepsilon_1 \tag{2}$$

$D > 30$ km

$$\log pre = a_2 Mw + b_2 X - \log(X) + c_2 + \varepsilon_2 \tag{3}$$

Where log *pre* is the logarithmic of predicted PGA (gal), *Mw* is the earthquake's magnitude, *X* is the hypocenter in kilometers, and *D* is the earthquake's depth. a_1, b_1, c_1, d_1, and ε_1 are regression coefficients for depths less than or equal to 30 km, while a_2, b_2, c_2, and ε_2 are for depths greater than 30 km can be seen in Table 2.

Table 2 Regression coefficient values for the PGA

Event Model	a	b	c	d	ε
Shallow	0.56	-0.0031	0.26	0.0055	0.37
Deep	0.41	-0.0039	1.56	-	0.40

In addition to the earthquake parameters and fault distance, Kanno incorporated site characteristics to account for site effects in validating the PGA values. Site effects are adjusted based on the average shear-wave velocity from the ground surface to a depth of 30 meters (Vs30). The Vs30 used by Kanno is approximately 300 m/s. Based on the Vs30 model generated from USGS, the value in the research area is 350–390 m/s, with an average of approximately 370 m/s. Due to the difference in the value of Vs30, a correction factor must be calculated using Eq. 4, with the corrected PGA value computed using Eq. 5.

$$G = p\log(Vs30) + q \tag{4}$$

$$\log pre_{corr} = \log pre + G \tag{5}$$

Where G is an additional correction to the value of the shear wave velocity, p = -0.55, q = 1.35, $Vs30$, is the average shear wave velocity (m/s), and $\log pre_{corr}$ is the logarithmic of corrected predicted PGA (gal).

Fukushima and Tanaka [19] developed an attenuation relationship that is applicable to near-source regions in Japan. However, this attenuation relationship can also be used over a broader range of distances, including earthquakes close to the source and those in the middle-distance region (0.1 < R < 300 km). To establish their attenuation relationship, Fukushima and Tanaka [19] used a dataset consisting of 1,372 horizontal components of peak ground acceleration from 28 earthquakes in Japan, as well as 15 earthquakes from the United States and other countries. The Fukushima equation is shown in Eq. 6.

$$\log PGA = 0.41Ms - \log\left(R + 0.03 \times 10^{0.41Ms}\right) - 0.0033R + 1.28 \tag{6}$$

The magnitude in Fukushima and Tanaka [19] used surface-wave magnitude, while the value of *Ms* was changed to *Mw* using the equation obtained from the National Center for Earthquake Studies [20]. The equation is shown in Eq. 7 and Eq. 8.

$$Mw = 0.6016Ms + 2.476 \tag{7}$$
for magnitude range $2.8<Ms<6.1$ with $R^2 = 0.8013$

$$Mw = 0.9239Ms + 0.5671 \tag{8}$$
for magnitude range $6.2<Ms<8.7$ with $R^2 = 0.8183$

5.3 PGA Determination Based on Microtremor Measurement

PGA values can be obtained using microtremor measurements, with the resulting data typically in the time domain. Fast Fourier Transformation (FFT) is used to convert the time domain into the frequency domain, which is processed using Geopsy software. The microtremor values that have become the frequency domain are processed to produce HVSR values. Nakamura [14] stated that the HVSR method compares the vertical signal components with the horizontal signal components obtained from microtremor signal measurements. The HVSR method is calculated using Eq. 9.

$$HVSR = \frac{\sqrt{F_{NSi}(\omega)^2 + F_{EWi}(\omega)^2}}{F_{UDi}(\omega)} \tag{9}$$

Where F_{NSi}, F_{EWi}, and F_{Udi} denote the Fourier amplitude of the NS, EW, and UD components of each interval, respectively, and ω is the frequency.

The parameters generated in the HVSR method are the predominant frequency (f_0), as shown in Fig. 2, and the amplification factor (A_0). The predominant frequencies can be converted into periods using Eq. 10 below:

$$f_0=1/T_0 \tag{10}$$

Where f_0 and T_0 denote the predominant frequency (Hz) and period (s).

The attenuation equation proposed by Kanai [21], can be used to determine the PGA values (gal) using predominant soil period (T_0) data from microtremor recording, earthquake magnitude (M), and the hypocenter distance (R) as shown in Eq. 11.

$$a = \frac{5}{\sqrt{T_0}} 10^{0.61M - \left(1.66 + \frac{3.6}{R}\right)\log R + 0.167 - \frac{1.83}{R}} \tag{11}$$

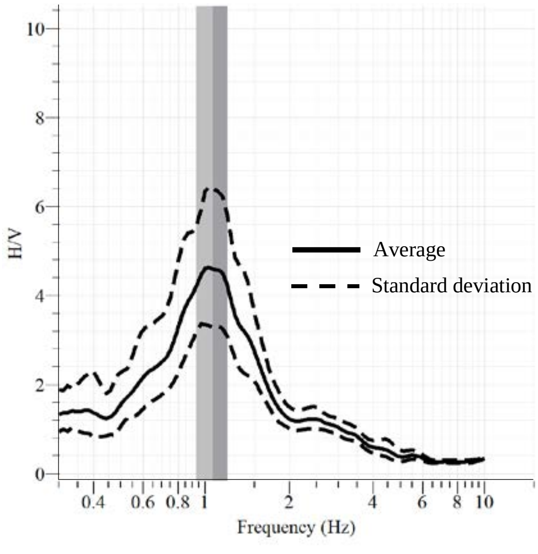

Fig.2 Example of the HVSR curve at microtremor site No.1 with a peak amplitude value of 4.599 and an f_0 value of 1.021

6. RESULTS AND DISCUSSION

6.1 Microzonation Map by Using Seismic Code

The PGA values for bedrock produced using the

Seismic Code are uniform. These values can be classified into three distinct sections, specifically 0.322g, 0.298g, and 0.288g, in a south-to-north direction across the study area. Using Site Class D, the site coefficients obtained for each PGA value in the above bedrock are 1.238, 1.204, and 1.178. Consequently, the range of PGA values obtained using the seismic code falls between 0.348g and 0.380g. A microzonation map using Indonesian seismic code is shown in Fig. 3.

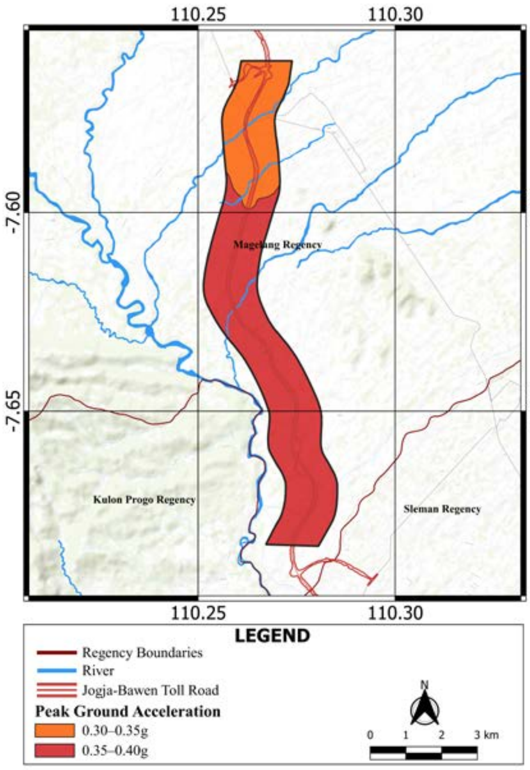

Fig.3 Microzonation of PGA value based on the seismic code

6.2 Microzonation Map by Using Attenuation Relationships

The PGA values obtained from the attenuation relationships were generated using two earthquake scenarios and two types of attenuation. When applying the Kanno attenuation, the 6.3 Mw Bantul Earthquake scenario yields a PGA range of 0.115g to 0.181g, as shown in Fig. 4. In contrast, the Yogyakarta 7.44 Mw earthquake scenario produces a PGA range of 0.202g to 0.265g, as shown in Fig. 5. With the Fukushima attenuation, based on the 6.3 Mw Bantul earthquake scenario, the PGA value ranges from 0.082–0.114g, as shown in Fig. 6. Meanwhile, for the Yogyakarta 7.44 Mw earthquake scenario, the PGA value range is 0.052g to 0.062g, as shown in Fig. 7.

6.3 Microzonation Map by Using Microtremor Measurement

The predominant frequency (f_0) value obtained from the microtremor measurement results is 0.312–1.999 Hz. Based on Kanai [21], using two earthquake scenarios, the PGA value from microtremor measurements was carried out. The value was generated using the 6.3 Mw earthquake scenario, which ranged from 0.036 to 0.095g, as shown in Fig. 8, while the 7.44 Mw earthquake scenario produced a PGA range of 0.036 to 0.088g, as shown in Fig. 9.

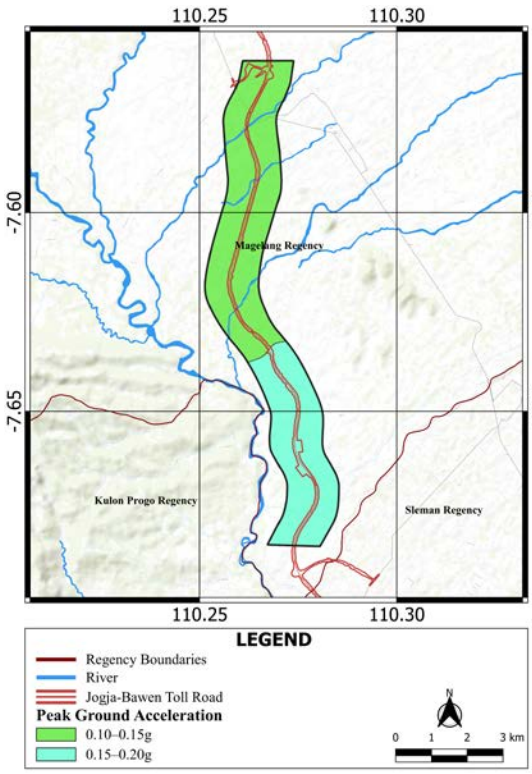

Fig.4 Microzonation of PGA value based on the Kanno's attenuation with a 6.3 Mw Bantul earthquake

6.4 Discussion

The PGA values generated using the three different methods and two earthquake scenarios have different values. A general trend observed across all methods is that the northern research area has smaller PGA values. This can be attributed to the greater distance from the earthquake source, which leads to a decrease in PGA. However, this case was not applied for PGA value from microtremor measurement. This is due to the varying site class and amplification at the measurement location.

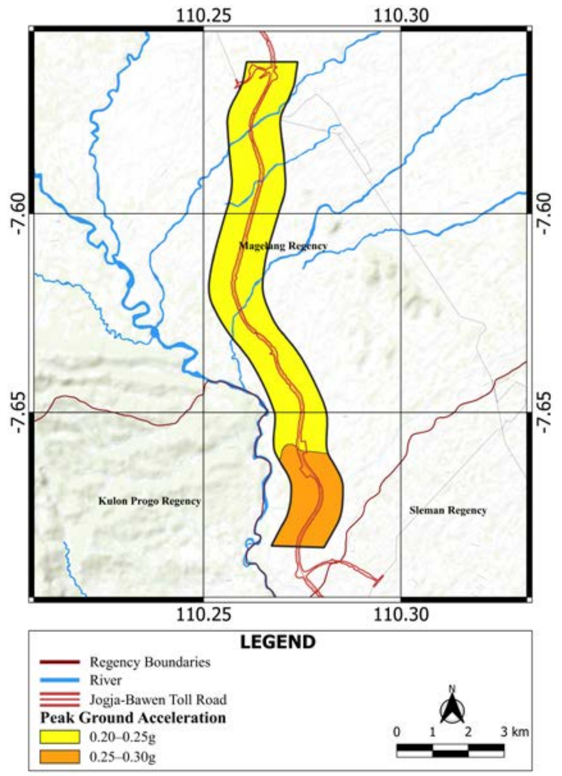

Fig.5 Microzonation of PGA value based on the Kanno's attenuation with a 7.44 Mw Yogyakarta earthquake

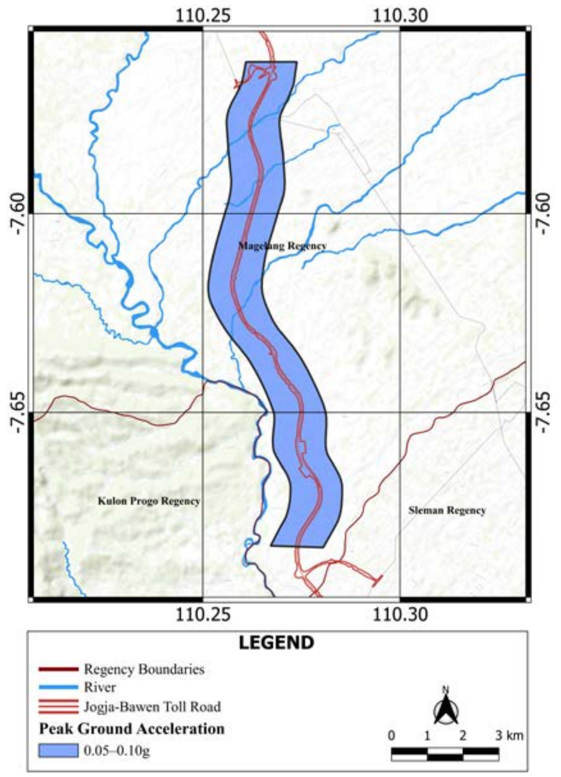

Fig.7 Microzonation of PGA value based on Fukushima's attenuation with a 7.44 Mw Yogyakarta earthquake

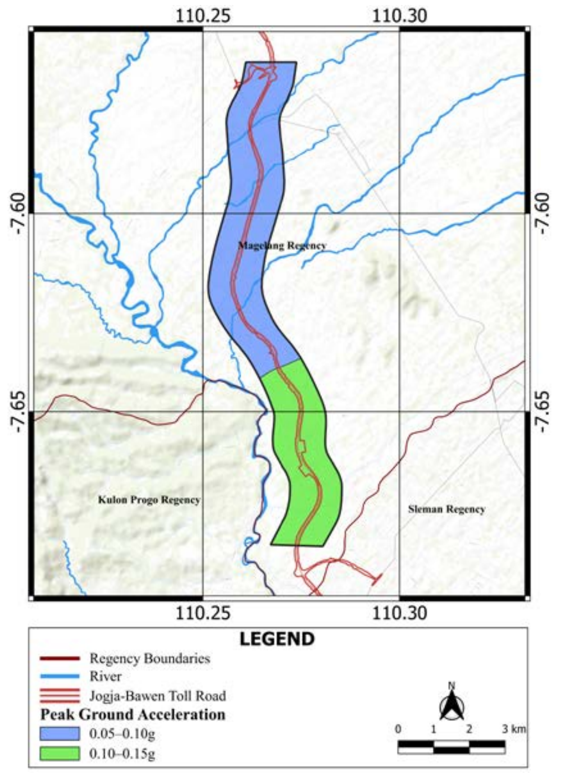

Fig.6 Microzonation of PGA value based on Fukushima's attenuation with a 6.3 Mw Bantul earthquake

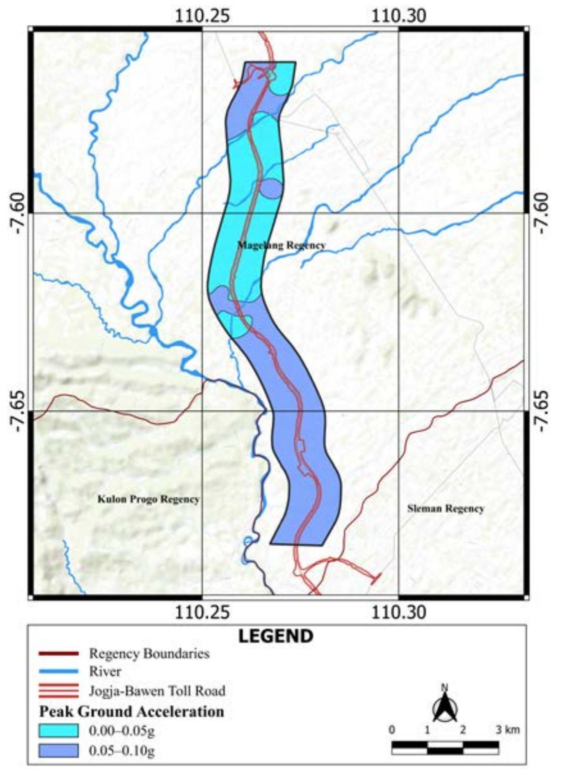

Fig.8 Microzonation of PGA value based on the microtremor measurement with a 6.3 Mw Bantul earthquake

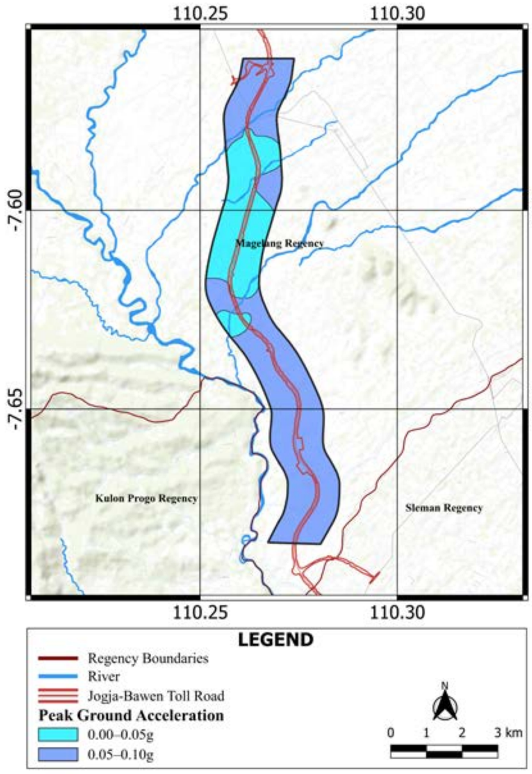

Fig.9 Microzonation of PGA value based on the microtremor measurement with a 7.44 Mw Yogyakarta earthquake

The process of determining the exact PGA value at a specific location is not straightforward. The accurate assessment of PGA requires the operation of accelerometers during earthquakes. Therefore, in practice, the PGA value is often estimated through references and comparisons with known data. In this way, the best approximation of the PGA value for a given location can be achieved. Based on the PGA map issued by the USGS, the PGA value with a scenario of 6.3 Mw and 7.44 Mw has a value of 0.05–0.10g. These values align quite closely with the PGA values obtained from microtremor measurements. In addition, the resulting PGA value from the Indonesian seismic code is relatively high because it considers the probabilities of various types of earthquake source models and magnitudes. The calculation results of PGA in the research area are shown in Table 3.

7. CONCLUSION

Peak Ground Acceleration played a vital role in infrastructure planning as it helped assess the design structures. The determination of PGA values, which was carried out with several methods using the 6.3 Mw Bantul earthquake in 2006 and the 7.44 Mw Yogyakarta earthquake in 1943, produced different values.

The highest PGA was generated from the Indonesian seismic code, ranging from 0.348–0.380g. This was followed by the PGA values obtained using the Kanno and Fukushima Attenuation, while the microtremor measurements with the lowest PGA were generated from microtremor measurements by using the Kanai Attenuation. Compared to the USGS PGA shake map from the USGS website, the PGA in this research area for both earthquakes ranged from 0.05g–0.10g. The results obtained from USGS were similar to microtremor measurements.

8. ACKNOWLEDGMENTS

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Table 3 The calculation results of PGA

<table>
<tr><th>No</th><th>Methods</th><th colspan="2">Max (g)</th><th colspan="2">Min (g)</th><th colspan="2">Avg (g)</th></tr>
<tr><td>1</td><td>Seismic code</td><td colspan="2">0.380</td><td colspan="2">0.348</td><td colspan="2">0.357</td></tr>
<tr><td></td><td rowspan="2">Methods</td><td colspan="3">2006 Earthquake (6.3 Mw)</td><td colspan="3">1943 Earthquake (7.44 Mw)</td></tr>
<tr><td></td><td>Max (g)</td><td>Min (g)</td><td>Avg (g)</td><td>Max (g)</td><td>Min (g)</td><td>Avg (g)</td></tr>
<tr><td>2</td><td>Attenuation Relationship</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>- Kanno's attenuation</td><td>0.181</td><td>0.115</td><td>0.145</td><td>0.265</td><td>0.202</td><td>0.233</td></tr>
<tr><td></td><td>- Fukushima's attenuation</td><td>0.114</td><td>0.082</td><td>0.096</td><td>0.062</td><td>0.052</td><td>0.057</td></tr>
<tr><td>3</td><td>Microctremor measurement</td><td>0.092</td><td>0.036</td><td>0.058</td><td>0.088</td><td>0.036</td><td>0.057</td></tr>
<tr><td>4</td><td>USGS Shakemap</td><td>0.100</td><td>0.050</td><td>0.075</td><td>0.100</td><td>0.050</td><td>0.075</td></tr>
</table>

9. REFERENCES

[1] Campbell, K. W., and Y. Bozorgnia. Updated Near-source Ground Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra. Bulletin of the Seismological Society of America, Vol. 94, No 1, 2003, pp. 314–331.

[2] Fathani, T. F., and Wilopo, W., Seismic Microzonation Studies Considering Local Site Effects for Yogyakarta City, Indonesia. International Journal of GEOMATE, Vol. 12, Issue 32, 2017, pp. 152–160.

[3] Wijayanto, Mardianto, D., Daryono, Nehren, U., Marfai, M.A., and Pramono, S., Spatial Distribution of Vs 30 based on MASW and Microtremor Inversion in Gunungkidul, Yogyakarta, Indonesia, International Journal of GEOMATE, Vol. 22, Issue 94, 2022, pp. 29–38.

[4] Putra, R. R., Kiyono, J., Yoshimoto, Y., Ono, Y., and Syahril., Determined Soil Characteristic of Palu in Indonesia by Using Microtremor Observation, International J. GEOMATE, 10, Issue 2, 2016, pp.1737–1742.

[5] Yulianur, A., Saidi, T., Setiawan, B., Sugianto, S., Rusdi, M., and Affan, M., Microtremor Datasets at Liquefaction Site of Petobo, Central Sulawesi-Indonesia, International Journal of Data in Brief, Vol 30, 2020.

[6] Rusnadi, R., Kiyono, J., Estimation of Earthquake Ground Motion in Padang, Indonesia, International Journal of GEOMATE, Vol. 1, Issue 1, 2011, pp. 71–77.

[7] Partono, W., Irsyam, M., Nazir, R., Kistiani, F., and Sari, U. C., Development of Site Factor for Surface Spectral Acceleration Calculation at the Alluvial Soils, International Journal of GEOMATE, Vol. 23, Issue 98, 2022, pp.24–30.

[8] Farid, M., and Mase, L. Z., Implementation of Seismic Hazard Mitigation on the Basis of Ground Shear Strain Indicator for Spatial Plan of Bengkulu City, Indonesia, International Journal GEOMATE, Vol. 18, Issue 69, 2020, pp.199–207.

[9] Ministry of Energy and Mineral Resources, 10 Years Yogyakarta Earthquake, 2, No. 2, 2016.

[10] Ministry of National Development Planning/National Development Planning Agency, Preliminary Damage and Loss Assessment, Yogyakarta and Central Java Natural Disaster, 2006.

[11] Rahardjo, W. Sukandarrumidi, and H. Rosidi Geologic Map of the Yogyakarta Quadrangle, Java, scale 1:100.000, Geol. Surv. of Indonesia, Ministry of Mines, Jakarta, 1977.

[12] Mase, L. Z., Shaking Table Test of Soil Liquefaction in Southern Yogyakarta. International Journal of Technology, Vol. 8, Issue. 4, 2017, pp. 747–760.

[13] SESAME European Research Project, WP12 – Deliverable D23.12 European Commission– Research General Directorate, 2004 Project No. EVG1-CT-200-00026.

[14] Nakamura, Y., A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremors on the Ground Surface, Railway Technical Research Institute, Quarterly Reports, Vol. 30, Issue 1, 1989, pp. 25–33.

[15] Konno, K., and Ohmachi, T., Ground-Motion Characteristics Estimated from Spectral Ratio Between Horizontal and Vertical Components of Microtremor, Bulletin of the Seismological Society of America, Vol. 88, No. 1, 1998, pp. 228–241.

[16] Budiman, R., Sahara, D. P., and Nugraha, A. D. Determining Source Model and Aftershocks of 2006 Yogyakarta Earthquake, Indonesia using Coulomb Stress Change, Proc. of 2nd Southeast Asian Conference on Geophysics, 2019.

[17] Indonesian Standard Code, Earthquake Resistance Design for Road and Bridge (SNI 2833:2016), National Standardization Agency, 2016.

[18] Kanno, T., Narita, A., Morikawa, N., Fujiwara, H., and Fukushima, Y., A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data, Bulletin of the Seismological Society of America, Vol. 96, No. 3, 2006, pp. 879–897.

[19] Fukushima, Y., and Tanaka, T., A New Attenuation Relation for Peak Horizontal Acceleration for Strong Earthquake Ground Motion In Japan. Bulletin of the Seismological Society of America, Vol. 80, No. 4, 1990, pp. 757–783.

[20] National Center for Earthquake Studies: Indonesian Seismic Sources and Seismic Hazard Maps, Center for Research and Development of Housing and Resettlement. Ministry of Public Works and Human Settlements, 2017.

[21] Kanai, K., Improved Empirical Formula for Characteristics of Strong Earthquake Motions, in Proc. Proc. of Japan Earthquake Engineering Symposium, Tokyo, 1966, pp. 1–4.