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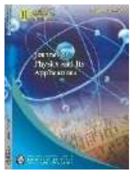

Probabilistic Analysis of Hazard Soil Movement Based on Maximum Ground Acceleration Spectrum Patterns Due to the Malang Raya Earthquake

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ABSTRACT

Earthquakes occur when tectonic plates beneath the earth's surface shift due to pressure accumulated in rocks, releasing kinetic energy and causing earthquake waves. This study analyzes the potential risk of earthquake hazards using the Probabilistic Seismic Hazard Analysis (PSHA) method which is based on the calculation of the probability of earthquake occurrence and vibration intensity using data from 3 sources of subduction earthquakes, faults and background earthquake sources in the Malang Raya research area which is geographically located in the Indonesian archipelago with an active collision zone of the Indo-Australian plate with the Eurasian plate. Research processing uses Zmap and R Crisis software. The results of the study show that peak ground acceleration has a value on the bedrock ranging from 0.169 g to 0.255 g. The ground acceleration spectrum at T = 0.2 seconds ranges from 0.288 g to 0.464 g, while at T = 1 second ranges from 0.150 g to 0.275 g. The distribution of PGAm values on the surface ranges from 0.174 g to 0.273 g, and the ground acceleration spectrum at T = 0.2 seconds ranges from 0.302g to 0.551g, while at T = 1 second it ranges from 0.151 g to 0.284 g. The area that shows the highest earthquake vulnerability value is around the southern coast of Malang Raya because it is close to the earthquake source. The northern region experiences an increase in the acceleration spectrum value due to its proximity to the source of the fault earthquake and several other geophysical factors.

1. Introduction

Earthquakes are one of the natural disasters that often occur in Indonesia in other natural events such as volcanic eruptions and floods. The elastic rebound theory explains it as a natural phenomenon that arises due to the buildup of potential energy during periods of strain in rocks that experience significant deformation changes in the lithospheric layers triggering earthquake wave vibrations that propagate to the surface [1]. Indonesia is geographically located in the equatorial region with a complex tectonic framework regarding seismic activity. Java Island is one of the islands in Indonesia that has a high level of earthquake activity. This phenomenon is caused by tectonic dynamics on the island of Java which is triggered by the movement of the Indo-Australian plate which moves north and collides with the Eurasian plate. The interaction between these two plates is the cause of frequent earthquakes in the Greater Malang area.

Malang Raya is one of the metropolitan cities of East Java which is known as a leading tourism destination in Indonesia because it has Geotourism potential with beauty that attracts tourists from inside and outside the region and even foreign tourists. Population growth and infrastructure development are very significant every year. Tectonic activity in the southern region is very significant resulting in the potential for earthquakes to occur frequently and have an impact on damage to public facilities and especially residential buildings in the Sumbermanjing Wetan area and Malang City due to natural disasters which are very detrimental to the community [2]. Earthquakes occur as a result of the manifestation of seismic waves propagating through layers until they reach the earth's surface, causing shocks or vibrations in the surrounding environment that can be felt by humans and interact with building structures. Structural durability and safety are the main factors that determine the structural response of buildings to earthquakes to minimize the risk of damage and protect human life.

The research will investigate the relationship between rock elasticity and the acceleration characteristics of seismic waves and provide a better understanding of the response of soil to earthquakes and their impact on the surface. The study of ground acceleration in periods of 0.2 and 1 second is important because these periods cover the frequency range relevant to the response of infrastructure structures to seismic waves, which is influenced by the elasticity of each rock passed through [3]. This information can be a reference in structural planning and earthquake disaster risk mitigation to ensure the safety of buildings and infrastructure in areas that are vulnerable to earthquake vibrations and can understand how soil and rock will respond to earthquake vibrations within that period.

Earthquakes occur due to seismic waves propagating through the earth's layers until they reach the surface. Seismic waves are elastic waves that propagate through the earth's interior and pass through the earth's surface, causing rock layers to break. The propagation properties of seismic waves depend on the elasticity of the rock through which they pass.

The Probabilistic Seismic Hazard Analysis (PSHA) method is used to evaluate the potential danger of seismic ground movement in an area by considering all possibilities of an earthquake using historical seismic data, regional seismic models, and other parameters in the area to assess the risk of an earthquake disaster. PSHA presents a complex mathematical model that considers several factors to evaluate and understand the potential for earthquake hazard in an area using a probability approach, including earthquake source characteristics, tectonic plate movements, and local geological characteristics. The Probabilistic Seismic Hazard Analysis (PSHA) method has many advantages because it is able to accommodate various uncertainty factors in its analysis. This method continues to be developed and becomes one of the popular approaches in analyzing earthquake hazards, based on the concept of total probability theory, which was first introduced through mathematical equations by Cornell [4]:

$$P[I \geq i] = \int_r \int_m P[I \geq i \mid \text{m and r}] \cdot f_m(m) \cdot f_r(r)\, dm\, dr \qquad (1)$$

with:

f_m = Density function from magnitude M

f_r = Density function from hypocenter distance

$P[I \geq i \mid \text{m and r}]$ = Condition of random probability of intensity (I) exceeding value (i) in the study area for earthquake events with magnitude (m) and distance from the hypocenter (r).

PGA (Peak Ground Acceleration) is the highest maximum value of ground acceleration that occurs during an earthquake at a location on the ground acceleration curve against time. PGA can be determined as a graphical representation of the ground acceleration spectrum point of the structural response to earthquake waves at various frequencies of earthquake wave vibrations. PGAM (Peak Ground Acceleration on the Surface) is the maximum value of acceleration on the ground surface that can provide a more detailed picture of the intensity of vibrations felt directly by the structure and foundation of the building [5]. The main objective of this article is to describe the peak acceleration of the earth's surface (PGAM) and spectral acceleration in the Malang Raya area using a probabilistic approach. Research related to PGAM and spectral acceleration is expected to contribute to efforts to plan the construction of earthquake-resistant buildings and infrastructure in Malang Raya.

2. Methods

The research documented in the article will review the acceleration of seismic waves with a focus on maximum acceleration in bedrock and surface and acceleration spectra for periods T = 0.2 and T = 1 second. The research area is located in Greater Malang (Malang Metropolitan Area) covering Malang Regency, Malang City and Batu City. Located at coordinates 7°48”- 8°30” South Latitude and 112°20”-112°55” East Longitude.

This research began with creating a strong motion database consisting of earthquake types and parameters, site conditions, and seismicity observation values. The steps were carried out by taking USGS earthquake catalog data that was relocated in 1910 – 2022 at an epicenter 300 km from the research area. Earthquake data in research functions as the primary parameter with the aim of several stages of research analysis.

Earthquake data processing begins by converting the magnitude scale into Mw (Magnitude Moment) using the following equation: [6]

$$\boldsymbol{M_w} = 0.143\ (M_S)^2 - 1.051\ (M_S) + 7.285$$

$$\boldsymbol{M_w} = 0.114\ (M_B)^2 - 0.556\ (M_B) + 5.560$$

$$\boldsymbol{M_w} = 0.787\ (M_E)^2 - 1.537$$

$$\boldsymbol{M_B} = 0.125\ (M_L)^2 - 0.389\ (M_l) + 3.513\ (2)$$

Magnitude moment is the global standard for measuring earthquake energy precisely. Mw measures the total energy released by an earthquake based on the surface area of the fault and the magnitude of the seismic displacement that occurs using a magnitude scale limit starting from M=5 [7]. The earthquake data declustering process is intended to separate the main earthquake (Mainshock) from its predecessor earthquakes and aftershocks (Foreshock and Aftershock) so that overestimation does not occur in the calculations. Declustered earthquake data was analyzed using the Gutenberg-Richter model which displays results in the form of FMD (Frequency Magnitude Distribution) graphs complete with information on a-values, b-values, and MC (Magnitude of Completeness) values. This process uses Zmap software which helps map distribution and identify patterns of seismic activity to analyze spatial variations in earthquakes.

Parameter a and b are used to calculate estimates of potential earthquake hazards in certain areas based on a catalog of all historical earthquakes. The seismicity parameter or a-value is a seismic parameter whose value depends on the number of earthquake events, volume, and time window. Seismicity values can show the characteristics of seismicity level data for an area or describe its seismic activity. Tectonic parameters or b-valeu can reflect local stress accumulation. They can be seismic parameters obtained from the relative frequency of the number of large and small earthquakes in an area. The b-value determines changes in physical phenomena observed before an earthquake occursParameter a and b are used to calculate estimates of potential earthquake hazards in certain areas based on a catalog of all historical earthquakes. The seismicity parameter or a-value is a seismic parameter whose value depends on the number of earthquake events, volume, and time window. Seismicity values can show the characteristics of seismicity level data for an area or describe its seismic activity. Tectonic parameters or b-valeu can reflect local stress accumulation. They can be seismic parameters obtained from the relative frequency of the number of large and small earthquakes in an area. The b-value determines changes in physical phenomena observed before an earthquake occurs [8].

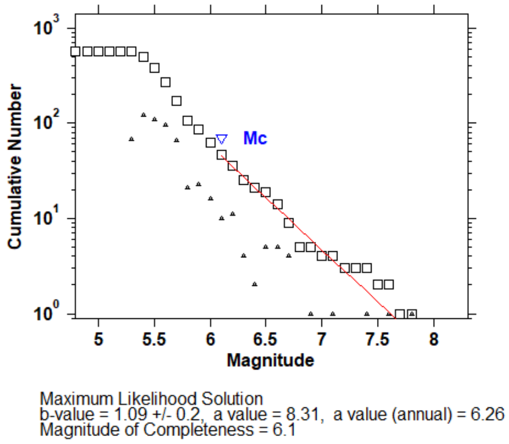

Fig. 1: Frequency Magnitude Distribution

Tectonic conditions can be calculated using the selection of Ground Motion Prediction Equations (GMPE) attenuation function calculations which are adjusted based on earthquake sources in the Greater Malang area to estimate damage due to earthquakes. The attenuation function is able to estimate ground motion parameters accurately over long periods and is useful in building engineering. The attenuation function involves the relationship between local ground motion intensity, earthquake magnitude, and distance from the earthquake source. The attenuation function used will be differentiated based on the mechanism of the earthquake. The earthquake occurred due to a shallow crustal fault, an earthquake in a subduction zone (megathrust), and obtained from analysis of other geophysical parameters so that the results are more complex.

The article uses a descriptive quantitative method using several GMPE attenuation function formulations based on the Pusgen 2022 literature.[9] The selection of Ground Motion Prediction Equations (GMPEs) must align with the type of seismic sources and the regional characteristics of the study area to ensure accurate ground motion predictions and support practical risk mitigation efforts. Malang Raya is predominantly situated within a subduction zone and is influenced by seismic activities from nearby active faults. Consequently, this study utilizes the Chiou and Youngs (2014) GMPE for fault-related seismic sources, the Campbell and Bozorgnia (2008) GMPE for background seismic sources, and the BC Hydro (2016) GMPE for megathrust subduction zones. These models were chosen due to their capability to represent ground motion characteristics specific to the regional tectonic settings of the study area.

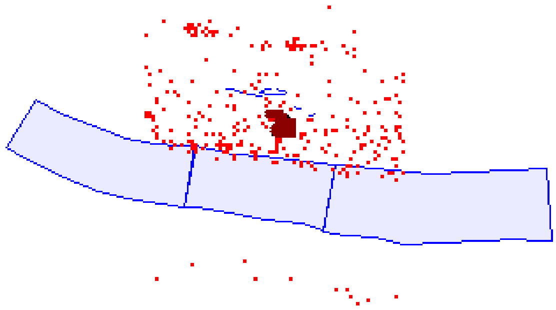

Fig. 2: Source Digitization

The tool used in this process is the R Crisis 2018 software from BMKG which helps calculate and estimate the probability of attenuation of earthquake waves. The GMPE equation of Chiou and Youngs (2014) is used for fault earthquake sources with the following formulation [10]:

$$
\begin{aligned}
\ln\left(y_{ref_{ij}}\right) = \; & C_1 + \left\{C_{1a} + \frac{C_{ic}}{\cosh(2\max(M_i - 4.5,0))}\right\} F_{RVi} \\
& + \left\{C_{1b} + \frac{C_{1d}}{\cosh(2\max(M_i - 4.5,0))}\right\} F_{NMi} \\
& + \left\{C_7 + \frac{C_{7b}}{\cosh(2\max(M_i - 4.5,0))}\right\} \Delta Z_{TORi} \\
& + \left\{C_{11} + \frac{C_{11b}}{\cosh(2\max(M_i - 4.5,0))}\right\} (cos\delta_i)^2 \\
& + C_2(M_i - 6) + \frac{C_2 - C_3}{C_n} \ln\left(1 + e^{C_n(C_M - M_I)}\right) \\
& + C_4 \ln\left(R_{RUPij} + C_5 \cosh(C_6 \max(M_I - C_{HM}, 0))\right) \\
& + (C_{4a} - C_4) \ln\left(\sqrt{R_{RUPij}^2 + C_{RB}^2}\right) + \{C_{Y1} \\
& + \frac{C_{Y2}}{\cosh\left(max(M_i - C_{Y3}, 0\right)}\} \cdot R_{RUP_{ij}} \\
& + C_8 \max\left(\frac{\max\left(R_{RUP_{ij}} - 40,0\right)}{30}\right) \min \\
& \left(\frac{\max\left(R_{RUP_{ij}} - 5.0,0\right)}{0.8}\right), 1) e^{C_{8a}(M_i - C_{8b})} \Delta DPP_{ij} \\
& + C_9 . F_{HW_{ij}} cos\delta_i . \{C_{9a} \\
& + (1 \\
& - C_{9a}) \tanh\left(\frac{R_{RUP_{ij}}}{2}\right)\} \left\{1 \right. \\
& \left. + \frac{\sqrt{R_{JB_{ij}}^2 + Z_{TOR_i}^2}}{R_{RUP_{ij}} + 1} \right\}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\ln\left(y_{ref_{ij}}\right) = \; & \ln\left(y_{ref_{if}}\right) \\
& + \phi_1 . \min\left(\ln\left(\frac{V_{s30_j}}{1130}\right), 0\right) \\
& + \phi_2 . \{e^{\phi_3(\min(V_{s30IJ}, 1130) - 360)} \\
& - e^{\phi_3(1130 - 360)}\} . \ln\left(\frac{y_{ref_{ij}} e^{ni} + \phi_4}{\phi_4}\right) \\
& + \phi_5 . \left\{1 - e^{\frac{-\Delta Z_{1.0_j}}{\phi_6}}\right\} + \eta_i \qquad (4)
\end{aligned} \tag{4}
$$

Background earthquake sources can be used with GMPE Campbell Bozorgnia with the following main formula [11]:

$$\ln(Y) = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} \tag{5}$$

The GMPE BC Hdyro (2012) equation is used for subduction earthquake sources with the formula sound can be written as follows [12]:

$$\ln(Sa_{interface}) = \theta_1 + \theta_4\Delta C_1 + (\theta_2 + \theta_3(M - 7.8))\ln(R_{rup} + C_4 \exp(\theta_9(M - 6))) + \theta_6 R_{rup} + f_{mag}(M) + f_{FABA}(R_{rup}) + f_{site}(PGA_{1000}, V_{S30}) \quad (5)$$

$$\ln(Sa_{interslab}) = \theta_1 + \theta_4\Delta C_1 + (\theta_2 + \theta_{14}F_{event} + \theta_3(M - 7.8))\ln(R_{hypo} + C_4 \exp(\theta_9(M - 6))) + \theta_6 R_{hypo} + \theta_{10}F_{event} + f_{mag}(M) + f_{depth}(Z_h) + f_{FABA}(R_{hypo}) + f_{site}(PGA_{1000}, V_{S30}) \quad (6)$$

The attenuation function is included in the earthquake source processing and has gone through the earthquake source digitization process so that it can be analyzed and calculated to assess how the intensity of the earthquake vibration amplitude decreases with distance from the earthquake source. This process involves applying mathematical equations and other seismic data to calculate the reduction in vibration amplitude. The results of attenuation analysis are able to provide information in earthquake risk assessment and disaster mitigation planning for areas affected by earthquakes.

The acceleration value on the surface can be determined by adding the average value of the shear wave velocity Vs30 to a depth of 30m from the ground surface. The Vs30 value is integrated into the mathematical model through the GMPE formula to calculate soil amplification in seismic analysis. The Vs30 value is entered into the software as a parameter in the data processing process data obtained from the USGS [13]. The primary purpose of this integration is to calculate the soil response to the earthquake so that the results of the bedrock PGA can be obtained from the surface PGA value. Low Vs30 values tend to experience seismic wave amplification or can be interpreted as seismic waves can experience an increase in amplitude. The classification of Vs30 location values can be seen based on the SNI 1726:2019 map in Table 1 [14].

Table 1: Site Classification SNI 1726:2019 [14]

Site Class	Vs (m/sec)
SA (Hard Rock)	>1500
SB (Rock)	750 - 1500
SC (Very Dense Soil and Soft Rock)	350 - 750
SD (Stiff Soil)	175 - 350
SE (Soft Soil)	< 175

3. Result and Discussion

Based on PSHA analysis processing, the maximum ground acceleration in bedrock has the unit "g" (gravity). This research uses a probability of 2% in 50 years because it follows applicable building standards using that value. The selection of a particular period (T) in PSHA analysis is essential because that period represents the dynamic characteristics of different building structures and infrastructure. There are two periods used, T = 0.2 seconds, which are relevant, with a short vibration period referring to low-rise buildings (2-story buildings) and an extended period, T = 1 second, for high-rise buildings up to 10 floors. There are differences in soil types in each region causing each region to have different characteristics and characteristics of vulnerability so this value can be a reference for designing buildings and infrastructure that are more earthquake-resistant to reduce the risk of damage and loss of life.

PSHA processing results show PGA values in bedrock in the area (Malang Raya) with a value range between 0.169 - 0.225 g as seen in Fig. 3. The southern region of Malang Raya has a higher acceleration spectral value shown by the red indicator. The higher acceleration is caused by the subduction zone of the Indo-Australian plate which collides with the Eurasian plate not far from the study area. The results of research in the eastern region of the research location also show an increase in ground acceleration values are influenced by the Kendeng Fault which is located approximately 90 km from the research area.

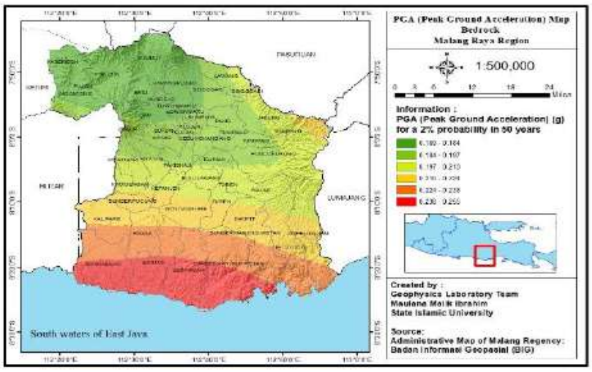

Fig. 3: PGA map in bedrock with a 2% probability of exceedance in 50 years for the Malang Raya area

Fig. 4 shows the results of the acceleration spectra values in the bedrock for a short period of T = 0.2 seconds with acceleration spectra values between 0.288 to 0.464 g. The long period T = 1 is shown by the information in Fig. 5 hat the acceleration spectrum value is between 0.150 to 0.275 g. The areas with the highest level of vulnerability include the Donomulyo, Bantur, Gedangan and Sumbermanjing Wetan areas. Bedrock PGA is the maximum value of ground acceleration measured on bedrock and shows that the soil layer is very hard and does not have an amplification effect. Extended analysis to identify high PGA values requires steps to mitigate disaster risk by involving an in-depth understanding of soil conditions, building structures, and impacts that may occur during an earthquake.

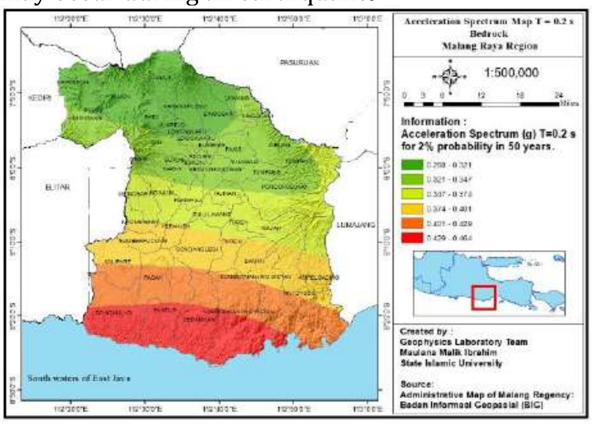

Fig. 4: Map of Ground Acceleration Spectra at T = 0.2 seconds in bedrock with a probability of exceeding 2% in 50 years for the Malang Raya area.

Differences in PGA values are influenced by earthquake source activity factors resulting from the complex interaction of some factors that influence the characteristics of earthquakes (magnitude, type of fault, ray path (wave propagation path, hypocenter distance), as well as local factors which can be geological conditions or characteristics of an area. Local factors reflect the diversity of geological traits in an area that influences the response of the soil to earthquakes. Calculating PGA values needs to be carried out using an empirical approach due to the limitations of accelerograph equipment in an area.

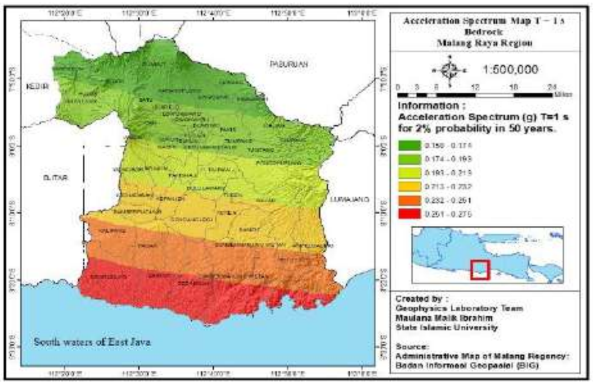

Fig. 5: Map of Ground Acceleration Spectra at T = 1 second in bedrock with a probability of exceeding 2% in 50 years for the Malang Raya area.

Further analysis of the seismic characteristics of the topsoil is fundamental in assessing the potential impact of earthquakes, considering that buildings and infrastructure are located directly on the ground surface. The PSHA process then obtains the maximum ground acceleration value at the surface [PGAm], which requires the acceleration value in the bedrock and involves VS30 data in Malang Raya. The PGAm value will be different from the value in bedrock because soil structural characteristics can influence soil acceleration. In this study, we got a PGAm value of 0.174 - 0.273 g. This information is in Fig. 6. From the results of surface analysis, parts of the Malang Raya region have high spectral values found in the Donomulyo, Bantur, Gedangan, Sumbermajingwetan, Kalipare, Pagak, Gondanglegi, Sumberpucung, Kepanjen, and Turen areas.

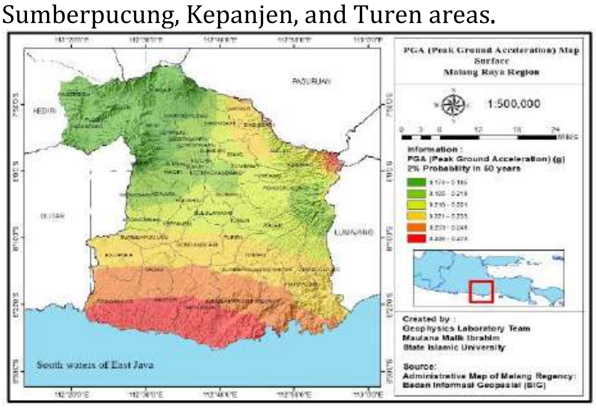

Fig. 6: PGAm Hazard Map of Earthquakes on the Surface with a probability of exceedance of 2% in 50 years.

Under short period conditions T = 0.2, values between 0.302 g and 0.511 g are obtained as shown in Figure 7. It was noted that the Greater Malang area in the south had an increase in acceleration spectra values. Analysis was carried out on the acceleration spectra on the surface with a long period T = 1 second. Data processing shows that the most considerable acceleration spectral value is between 0.151 g to 0.284 g as presented in Fig. 8. Areas with red indicators show higher values because the area is close to a subduction zone. The northern region in the processing results shows a varying range of acceleration values. The northern part has high acceleration values including parts of Lawang, Singosari, Blimbing and Tumpang.

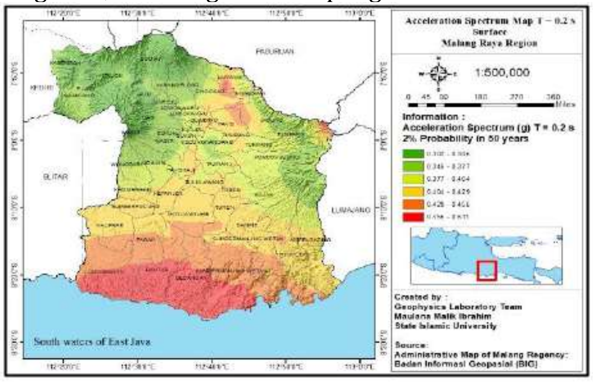

Fig. 7: Earthquake Hazard Map on the Surface under short period conditions T = 0.2 with a probability of exceedance of 2% in 50 years.

There is an increase in the acceleration spectra in the northern part of Malang Raya, triggered by the presence of active faults and there are also factors from the presence of seismic waves that propagate in various layers. Seismic waves spread in all directions on the surface due to various other geophysical factors such as the characteristics of the earthquake source, geological structure, seismic wave interference and various other factors that can trigger the upward movement of seismic waves.

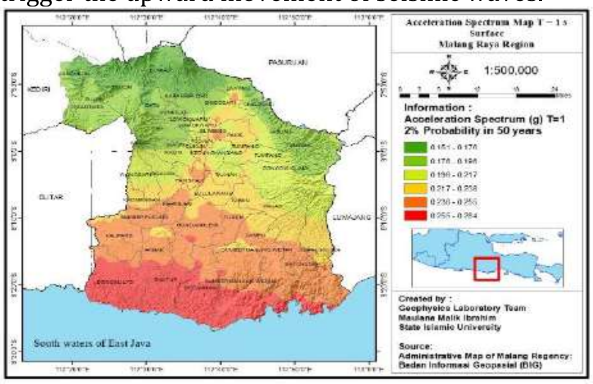

Fig. 8: Earthquake Hazard Map on the Surface under long period conditions T = 1 with a probability of exceeding 2% in 50 years

The high acceleration in the northern region can also be caused by relatively greater ground amplification. Soil amplification occurs when seismic waves experience an increase in amplitude when passing through soft soil layers or different thicknesses. Soil amplification occurs when seismic wave energy is concentrated and expansions on the ground surface at specific locations and periods. The northern region has conditions with low Vs30 values with a high possibility that the soil layer can cause greater amplification of seismic waves, resulting in higher acceleration spectra values at that location. The map for information on changes in amplification with this period is shown in Fig. 9. Soil with a high Vs30 value has a faster seismic wave velocity. These fast waves are caused by seismic waves experiencing

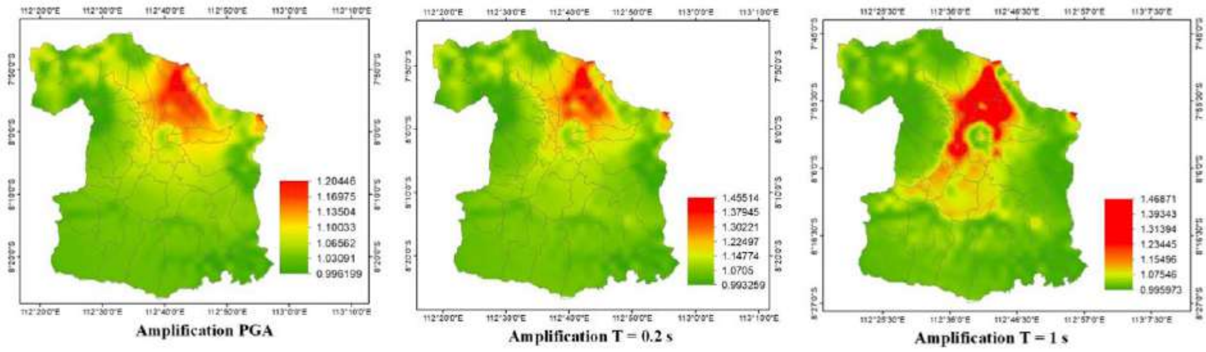

Fig. 9: Amplification Map

an increase in amplitude, describing the dynamic characteristics when passing through soft soil layers or different thicknesses.

4. Conclusions

Research conclusions that focus on Probabilistic Seismic Hazard Analysis (PSHA) contribute to identifying potential risks of earthquake hazard levels and providing information for disaster planning and mitigation. The PSHA method is described in four procedural stages, including identification and characterization of earthquake sources, source zone modeling, wave propagation path modeling, and site modeling in the form of ground movement acceleration values. Bedrock PGA values describe the complex interaction of several factors that influence earthquake characteristics. The surface PGAm value considers the effects of soil conditions in areas of potential structural damage on the earth's surface. The PGA values and acceleration spectra in bedrock for the Malang Raya area obtained a maximum acceleration value range of 0.169 - 0.255 g. The acceleration spectrum (T = 0.2 seconds) is 0.288 - 0.464 g, and for (T = 1 second), it is 0.150 - 0.275 g. The PGAm values and surface acceleration spectra for the Greater Malang area obtained a maximum acceleration value range of 0.174 - 0.273 g. The acceleration spectrum (T = 0.2 seconds) is 0.302 - 0.551 g, and for (T = 1 second) it is 0.151 - 0.284g. Distributing seismic vulnerability maps to determine how far the earthquake source affects an area is essential for understanding soil behavior in each region and developing earthquake risk mitigation strategies.

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