Earthquake Hazard Analysis in Probolinggo Region as a Mitigation Effort Using Probabilistic Seismic Hazard Analysis Method

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ABSTRACT

Probolinggo is one of the areas traversed by an active fault, namely the Probolinggo Fault. As an area that is prone to earthquake disasters, Probolinggo needs to have an earthquake hazard modeling as a mitigation effort to minimize the impact of an earthquake that occurs in the future. Earthquake hazard modeling is a multidisciplinary science that aims to predict earthquakes, and the ground shaking they produce. One method that can be used is Probabilistic Seismic Hazard Analysis (PSHA). This study aims to analyze the earthquake hazard in Probolinggo area using the PSHA method as an effort to mitigate earthquake prone areas. The data used is historical earthquake data from the Agency for Meteorology, Climatology, and Geophysics (BMKG) for the 1973-2020 period with a magnitude of Mw ≥ 5, a depth of 0-300 km, and a radius of 300 km from the study area. The earthquake source model used includes megathrust, faults, and background earthquake sources. Three sets of Ground Motion Prediction Equation (GMPE) were used for each earthquake source. PSHA was performed for the condition of a 2% probability of being exceeded in 50 years. The average shear wave velocity to a depth of 30 m (Vs30) from the United States Geological Survey (USGS) were used to model the peak ground acceleration on the surface. The results showed that the peak ground acceleration (PGA) at bedrock ranged from 0.27 to 0.71 g. PGA at the surface (PGA_M) ranges from 0.27 to 0.83 g. The distribution of the amplification value in Probolinggo area is 1.02 to 1.12. The earthquake hazard analysis obtained shows that the northern part of the Probolinggo area has a higher earthquake hazard than the southern part. The results of the study can be used as consideration in regional development based on earthquake risk reduction.

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1. INTRODUCTION

Indonesia is a country with a high potential for earthquake occurrence because it is located between of major global tectonic plates [1]. The three major plates that affect Indonesia are the Southeast Asian Plate (Eurasia), the Indo-Australian Plate and the Pacific Plate. The three plates can be divided into smaller plates that meet at the triple junction area in Papua New Guinea, the North Moluccas Plate, the Caroline Plate and the Philippine Sea Plate [2]. These plates are actively moving, causing the formation of a series of active volcanoes, subduction zones, and faults that cause high seismicity levels in Indonesia.

Probolinggo is one of the regions in East Java province located at 112°50' – 113°30' East Longitude and 7°40' – 8°10' South Latitude [3]. The history of earthquakes that have occurred in the Probolinggo area is based on the BMKG's catalog of significant and destructive earthquakes, including earthquakes with a magnitude III MMI centered on the Situbondo area having a magnitude of 6.1 SR depth on October 10, 2018, causing damage to buildings and public facilities. The earthquake was felt on a scale of II-III MMI centered on the Malang area with a magnitude of 5.9 SR at a depth of 10 km on June 8, 2013 [4].

Probolinggo is an area with a high potential for earthquakes. This happened because Probolinggo Regency and City were near several active faults, namely Probolinggo Fault, Kendeng-Surabaya Fault, and Pasuruan Fault. Therefore, a mitigation effort is needed to minimize the impact of earthquakes. One of the efforts that can be made is to conduct an earthquake hazard analysis using the Probabilistic Seismic Hazard Analysis (PSHA) method.

PSHA is a method used to determine the degree of earthquake hazard by examining uncertainty factors. This method is based on an analysis of probability distribution functions that take into account uncertainty factors from the location, size, and time of earthquake occurrence [5]. The advantage of this PSHA method is that it can account for the possible consequences of the effects of various uncertainty factors in its analysis, in addition to integrating regional susceptibility to earthquake sources [6]. One of the results obtained from the processing of this method is the maximum ground acceleration value (PGA). From this value, it can be analyzed to determine the earthquake hazard in the Probolinggo area so that mapping can be done to minimize the impact of the earthquake.

Research on the dangers of earthquakes in the Probolinggo region is still rare. From the previous research, it is still global for the province of East Java, such as research done by [5], [7], and for all regions of Indonesia by[1]. Based on this background, this study was conducted to analyze earthquake hazards in more specific areas and is expected to be used as an effort to mitigate earthquake disasters in the Probolinggo area. This study aims to determine the level of earthquake hazard in the Probolinggo region by mapping the maximum ground acceleration values (PGA) in bed and surface rocks, and the amplification and site effect conditions in the Probolinggo region during an earthquake.

1.1 East Java Regional Tectonic Order

Based on its tectonic conditions, there are several tectonic characteristics that can affect seismicity on the island of Java, namely the subduction of the Sunda Arc, faults, and normal faults in the Java sea. The tectonic activity of the island of Java is controlled by the subduction of the Indo-Australian plate to the Eurasian plate that forms the Sunda Arc system in the offshore zone (offshore) including the Java ridge, Java trough, and forearc basin. Factors that can affect the magnitude and frequency of earthquake occurrence include the age, composition and speed of the plate during subduction. This Javanese tectonic condition caused the areas along the Sundanese arc such as Java Island, NTB, and Bali to become areas with high earthquake resistance [8]

Earthquake activity in East Java is not only affected by subduction zones located south of Java, but also affected by local fault activity. Until now, there are still many local cesars in East Java that have not been identified. Based on the fault map obtained from the Geological Agency, there are several faults under investigation in East Java such as the Tulungagung Fault, the Tulungagung Fault, and the East Java Fault.

Tulungagung Fault, Lumajang, and Banyu Putih. All three faults are included in class B with a maximum magnitude of $Mw \geq 6.5$ to 7 with a slip rate of < 2 to 5 mm/year. The danger of earthquakes in East Java is also affected by faults outside East Java such as Opak Fault, Lasem, and Pati Fault [9]

East Java has several active faults that have been identified. the location of these faults is shown in Figure 1 ([1], [10]). The Surabaya, Blumbang, Waru and Cepu faults are the continuation of the Kendeng Fault which extends up to 300 km. All four faults are of the reserve fault type. The Surabaya fault has a dip of 45S, a slip rate of 0.1 mm/year, is about 25 km long, and runs north-southeast. The Cepu fault has dip 45S, slip rate 0.5 mm/year, length about 100 km long, and north-southeast trending. The Blumbang fault is an east-north trending fault with a length of about 31 km and a slip rate of 0.1 mm/year. The Waru fault is a west-north trending fault with a length of about 64 km and a movement of 0.5 mm/year. The Probolinggo fault is a strike-slip type fault that is visible from a fault line that extends in a southwest-northeast direction, and cuts the Pleistocene-age Mount Argopuro sedimentary formation. The Blumbang fault is an east-north trending strike-slip fault and has a movement of 0.2 mm/year. The Pasuruan fault is a normal fault with a length of about 13 km in a west-east direction and a movement of 0.2 mm/year. This fault can be seen by the presence of fault scarps and cuts the volcanoclastic deposits of the Rabano Formation. This fault is younger than the Pleistocene. In the last 4000 years the fault has moved actively 6 times. The Wonorejo fault is a normal fault with a slip rate of 0.3 mm/year [1].

2. METHODS

The data used in this study are secondary data, namely earthquake data, Vs30, fault locations, and subduction. Earthquake data is obtained from the Meteorology, Climatology, Geophysics Agency [4] catalog, where the data contains coordinate information on the location of the earthquake occurrence, the time of occurrence, the magnitude, and depth of the earthquake. Vs30 data were obtained from the United States Geological Survey [11]. Administrative boundary data in the .shp format is obtained from the Geospatial Information Agency [12].

2.1 Earthquake Declustering

The earthquake decluster was intended to separate the main earthquake from the aftershock and foreshock so as not to overestimate the earthquake hazard calculation. The ZMAP ver.7 program [13] was used in the decluster stage of the earthquake. The program can be run using Matlab R2018a. The earthquake decluster method used was the Gardner & Knopoff method (1974) [14].

2.2 Modelling and Characterizing Earthquake Sources

An earthquake source model is a zone in which there are earthquake occurrences, where at each point of the earthquake may experience a recurrence of future earthquakes. This model will illustrate the epicenter of historical earthquakes, slip rates, and frequency of earthquakes from a source. The earthquake model is needed as a correlation between the calculation model and the earthquake data used to determine the degree of earthquake hazard [15]. The earthquake source models used are classified into three megathrust zones, fault zones, and background zones.

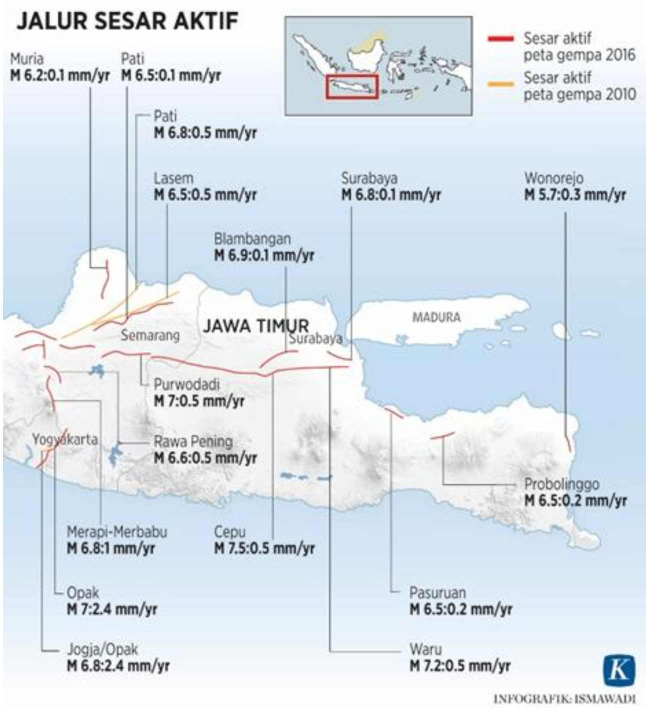

Figure 1. Active fault lines in and around East Java [1]

The modeling of earthquake sources used in this study was limited to a 300 km radius of the study area. The depth of the earthquake is less than 300 km, and the selected Ground Motion Prediction Equation (GMPE) is considered in accordance with the model in the Indonesian region. Characterization of sources in earthquake hazard analysis requires several parameters: a-b value, slip rate, recurrence rate, and maximum magnitude [16]. The Gutenberg–Richter and Char models were used to characterize the source of the earthquake. Gutenberg-Richter will be used in subduction zone and background models. Char is used in fault zone models.

2.3 GMPE Model

GMPE research on Indonesian territory is still rare. Therefore, to conduct earthquake hazard analysis, publications from other regions are used that bear similarities to Indonesia's tectonic conditions. The determination of this GMPE should be based on the location where it is categorized into subduction zones, shallow crustal zones, and background zones, as well as the mechanism of earthquake occurrence from the area to be investigated [17]. In this study GMPE was classified by the mechanisms of earthquake sources: megatrhust zone, fault zone, and background earthquake source zone. The GMPE determination used refers to the 2017 PusGeN.

2.4 Logic Tree

Logic tree methods are used with the aim of weighting each of the uncertainty parameters in data processing for earthquake hazard analysis. The sum of the uncertainty weighting of all branches in each node must be equal to 1 [15]. The logic tree model used in this study was adapted to the earthquake source model used. In this study the parameters for uncertainty weighting will be maximum magnitude and GMPE model.

2.5 An Analysis of Earthquake Hazards

The PSHA method assumes earthquakes of magnitude M and distance R as continuous independent random variables. The general form of total probability theory can be proposed as follows.

$$P[I \geq i] = \iint rm \; P[I \geq i|m \; dan \; r] f_M(m) f_R(r) dmdr \tag{1}$$

Where f_M is the function of the magnitude distribution, f_R is hypocenter distance distribution function, and $P[I \geq i]$ is the probability of intensity I [9].

In this study, PSHA processing was carried out with R-CRISIS software [18]. The output of this PSHA includes maximum ground acceleration (PGA) in the bedrock and maximum ground acceleration on the surface (PGAM) for probability conditions exceeding 2% in 50 years, or equivalent to an earthquake recurrence period of 2500 years.

3. RESULTS AND DISCUSSION

The PSHA method calculates a wide range of uncertainties to obtain earthquake hazard maps. Ouput is the maximum ground acceleration (PGA) value in bedrock and maximum ground acceleration on the surface (PGAM). An earthquake hazard analysis is performed for a probability of exceeding 2% in 50 years, or a recurrence period of 2500 years.

3.1 An Analysis of Earthquake Hazards in Baselines

The PSHA results show that the PGA value in the bedrock of the Probolinggo region ranges from 0.27 to 0.71 g (Figure 2). The area adjacent to the earthquake source has a higher PGA value than the area far from the earthquake source. In the Probolinggo region, the most important sources of earthquakes are the Probolinggo Fault and Pasuruan Fault. The area around the fault experienced an increase in ground acceleration. Regions relatively close to Probolinggo Sesar include Gading, Krucil, Tiris, Pakungan, Besuk, Krejengan, Maron, Banyu Anyar and Tegal Siwalan District, and areas close to Pasuruan Sesar in the northwest which Tongas District experienced an increase in land acceleration value. The results of the study were then compared with the PGA map in SNI 1726:19 [19]. Figure 2 is the PGA map of the research results, while Figure 3 is the PGA map in SNI 1726:19 2019. There is a difference in PGA values, where the PGA value in SNI ranges from 0.3 to 0.4 g, while the research results have a value range of 0.27–0.71 g. This difference is due to differences in the characterization of earthquake sources, as well as differences in the use of background earthquake source data.

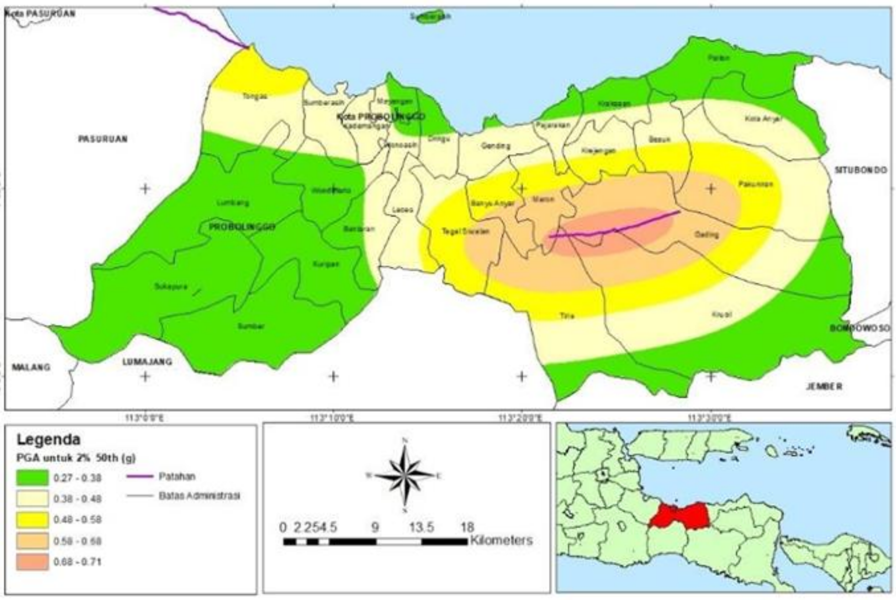

Figure 2. The PGA Map in the Bedrock of the study results

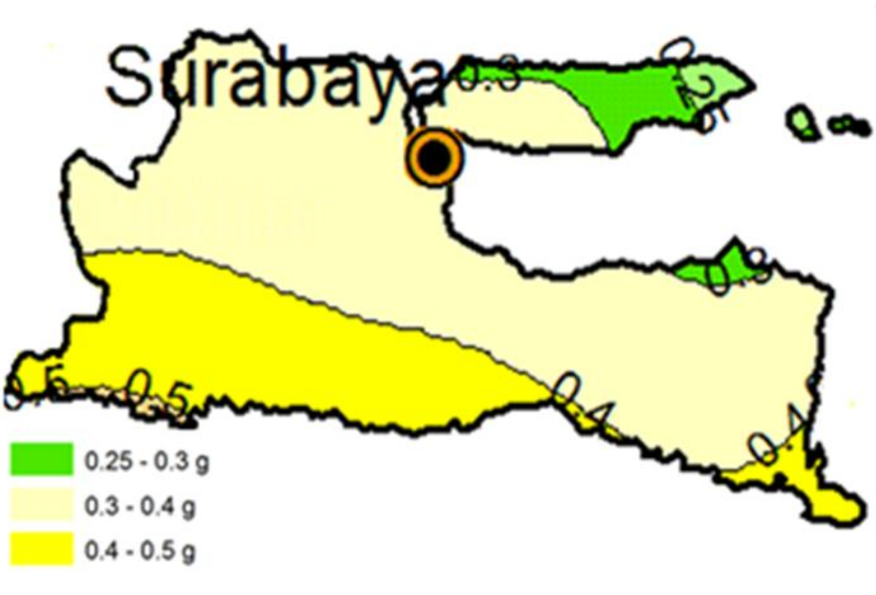

Figure 3. The PGA Map in SNI 1726:19

3.2 Analysis Vs30

The value Vs30 represents the average shear wave velocity up to a depth of 30 m. In this study, the value of Vs30 was used to obtain the maximum surface acceleration (PGAM) value. The distribution of Vs 30 values in the Probolinggo region is shown in Figure 4. It can be seen that the northern Probolinggo region has a relatively lower Vs30 value and begins to rise southward. From the value of Vs30 it can be categorized as soil type based on the value of shear wave velocity (SNI 1726:19). The area of Probolinggo can be mapped into three types of soil: medium soil, hard soil or soft rock, and rock as shown in Figure 5.

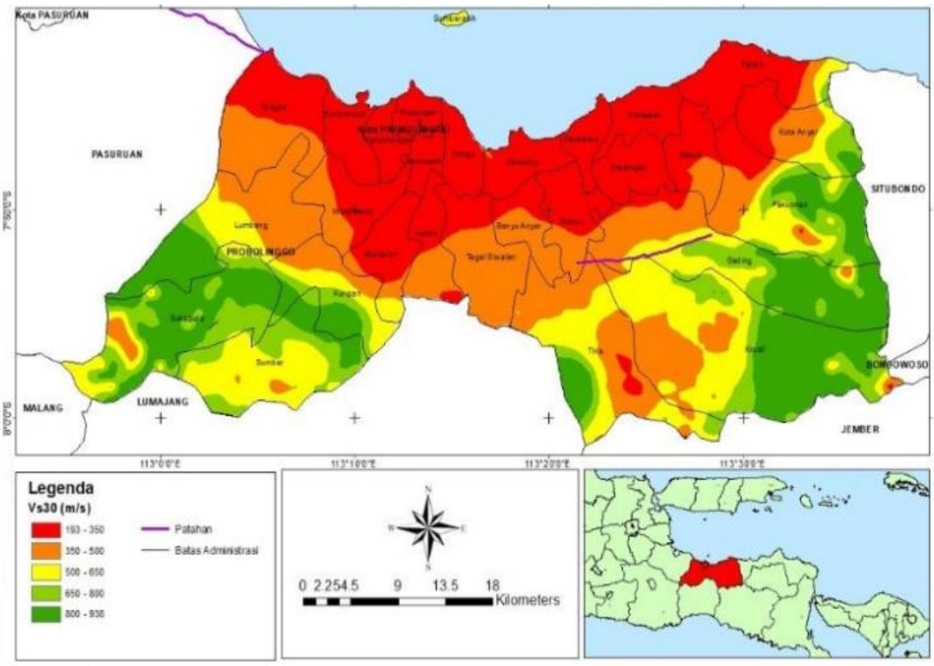

Figure 4. Map of distribution of Vs30 values in the Probolinggo region

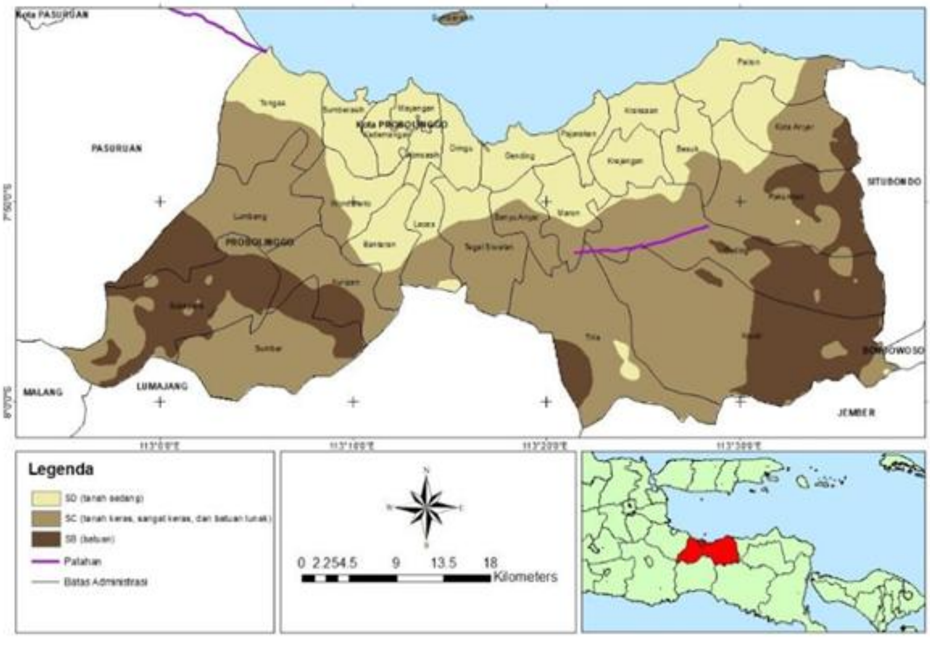

Figure 5. Classification of Soil Types based on Vs30 values

3.3 An Analysis of Surface Earthquake Hazards

The distribution of surface maximum ground acceleration values (PGAM) of the Probolinggo region is shown in Figure 6. PGAM values range from 0.27 to 0.83 g. The area adjacent to the earthquake source has a higher acceleration value than the area far from the earthquake source. In the Probolinggo region, the most important sources of earthquakes are the Probolinggo Fault and Pasuruan Fault. The area around the fault experienced a relatively high increase in ground acceleration values. The areas near Probolinggo Sesar, such as Gading, Krucil, Tiris, Pakungan, Besuk, Krejengan, Maron, Banyu Anyar and Tegal Siwalan sub-district and the areas close to Pasuruan Sesar in the northwest are Tongas sub-district experiencing an increase in land acceleration value.

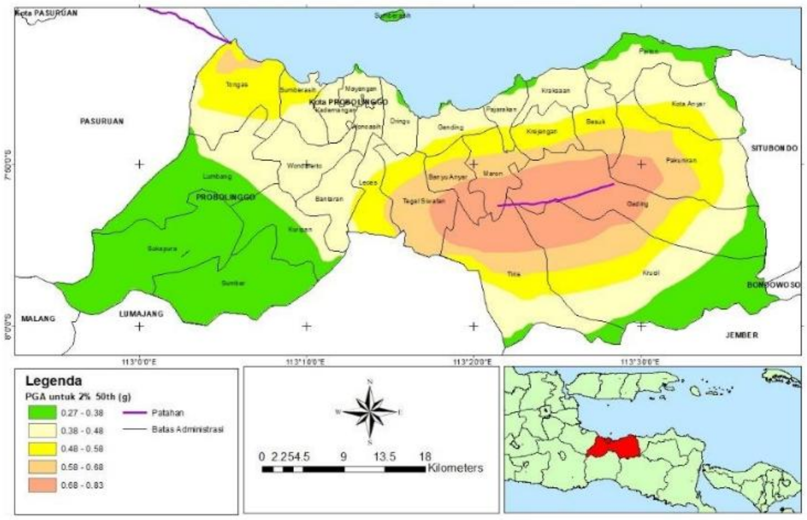

Figure 6. Surface Maximum Ground Acceleration Map (PGAM) in the Probolinggo Region

3.4 Amplification Analyze and Site Effect

The site effect related analysis is performed by correlating the Vs30 value with the ground acceleration amplification value. The amplification value is the value obtained by comparing the acceleration value of the soil on the surface with the acceleration of the soil on the bedrock. The results of the amplification mapping are shown in Figure 7. The distribution of amplification values in the Probolinggo region is 1.02–1.2. The location with the highest amplification is in the northern Probolinggo area. Amplification represents the change in the acceleration of waves vibrating through the soil layer from the bedrock to the ground surface due to differences in shear wave velocity (Vs) in the bedrock and sediment. The gradually decreasing shear wave velocity (Vs) value causes the damping factor and shear modulus value to be smaller, resulting in greater acceleration of ground vibration [20]. Therefore, the local soil condition factor has an effect on the amplification value.

Amplification factors correlate with the frequency and thickness of sediment. Low amplification values can represent that a region has a thin or rigid sedimentary layer, with a high dominant frequency and otherwise high-value amplification can represent a region with a thick or soft layer thickness, and has a small dominant frequency value.

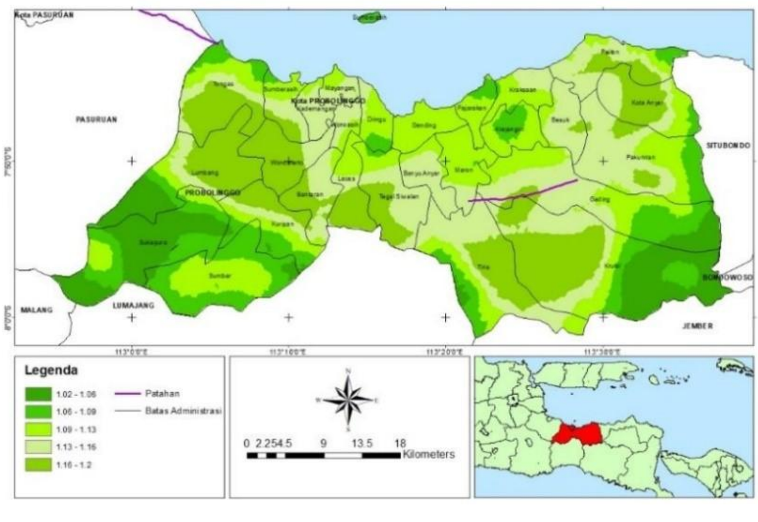

Figure 7. Soil Acceleration Amplification Map in the Probolinggo Area

When associated with the geological conditions of the research area, the northern Probolinggo region is composed of young and soft alluvial deposits, causing relatively high amplification. The southern regions have relatively low amplification values because geological conditions are composed of fairly dense rocks.

4. CONCLUSION

The results of an earthquake hazard analysis using the PSHA method for probabilities exceeding 2% in 50 years show the maximum ground acceleration (PGA) value in the bedrock of the Probolinggo region ranges from 0.27 to 0.71 g. The maximum surface soil acceleration (PGAM) value ranges from 0.27 to 0.83 g. Amplification values in the Probolinggo region range 1.02–1.2. The northern Probolinggo region, composed of young and soft alluvial deposits, has a higher earthquake susceptibility than the southern part.

DECLARATION

Author Contribution

Conceptualization, Muhammad Taufiq Akbar Al Ghifari; methodology, Muhammad Taufiq Akbar Al Ghifari. and Bambang Sunardi; software, Bambang Sunardi; validation, Dwi Budi Susanti and Wuri Handayani; formal analysis, Muhammad Taufiq Akbar Al Ghifari; investigation, Dwi Budi Susanti; resources, Bambang Sunardi; data curation, Wuri Handayani; writing—original draft preparation, Muhammad Taufiq Akbar Al Ghifari; writing—review and editing, Dwi Budi Susanti and Bambang Sunardi; supervision, Wuri Handayani; project administration, Wuri Handayani. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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