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Analysis of Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) Scale using PSHA Method in Lampung Province

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ABSTRACT

Earthquakes are inevitable natural disasters that are difficult to predict. Nevertheless, the mitigation process must still be carried out. Lampung Province as one of the regions in Indonesia with geological conditions influenced by the Sumatra Fault System (SFS) and the subduction tectonic activity of the Indo-Australian plate and the Eurasian plate makes the area have high tectonic activity. The geography of Lampung Province, which is the main gateway to Sumatra Island, also plays a very important role. Considering the above, a study is needed to analyze the earthquake hazard in Lampung Province using a method that combines Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) values on a micro scale. The PSHA method identifies earthquake microzonations and generates PGA values that are then converted to the MMI scale to determine the intensity of earthquake strength. The mapping of Lampung Province identified five zones with different levels of earthquake hazard, ranging from VII to XI MMI with varying PGA values. The first zone, on the VII MMI scale, has a PGA ranging from 0.20 to 0.25g. The second zone, in the VIII MMI scale category with PGA ranging from 0.20 to 0.40g. The third zone, falls within the IX MMI scale category with PGA ranging from 0.40 to 0.70 g. The fourth zone is categorized as X MMI scale with PGA values ranging from 0.70 to 1.00g. And finally, the fifth zone, has a scale of XI MMI with a range of PGA values between 1.00 and 2.50 g. Zones with a higher earthquake intensity scale indicate the potential for heavier damage.

1. Introduction

Earthquakes are one of the unavoidable natural disasters, but the impact of damage and casualties can be minimized with proper preparedness. Earthquakes are listed as one of the most dangerous and destructive natural disasters [1][2]. In Indonesia, earthquakes cause the most damage and losses among other natural disasters such as floods, landslides, forest fires, tornadoes and others [3][4]. Evidenced by data from the Ministry of Finance of the Republic of Indonesia [5] and the National Board for Disaster Management [6] noted that from 2000 to 2016, earthquake disasters caused the largest loss of 7.56 trillion rupiah and claimed the second highest number of lives after tsunamis. This can be minimized with a well-thought-out mitigation process and adequate public understanding of earthquake hazard risks. In accordance with Article 1 Paragraph 6 of Government Regulation No. 21/2008 [7] about disaster mitigation is a series of efforts to reduce disaster risk, both through physical development as well as awareness and capacity building to deal with disaster threats.

The damage caused by an earthquake is highly dependent on the geology and geography of a region. In Indonesia, the regions with the highest earthquake vulnerability in order are Maluku-Banda Island, Sulawesi, Sumatra, Papua, East Nusa Tenggara, Java, then Kalimantan. Although Sumatra is not one of the most earthquake-prone regions, large magnitude earthquakes can occur [8][9].

Based on geological and geophysical studies, the Lampung Province area shows an active seismic activity

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[10][11]. The geological conditions of Lampung Province are still influenced by the *Sumatra Fault System* (SFS) and the subduction tectonic activity of the Indo-Australian plate against the Eurasian plate which causes earthquake shocks generated by these two geological phenomena. In addition, according to earthquake source data from USGS and PUSGEN 2017, there are several earthquake source points with a radius of 500 km in the area around Lampung Province consisting of 26 fault earthquake sources, 4 subduction earthquake sources (megathrust), and background earthquake sources.

Geographically, Lampung Province is an area that is the main gateway to the island of Sumatra so that it has a very important role in mobility, transportation, distribution, and so on from Java to the island of Sumatra and vice versa [11][12]. Lampung Province has an area of 33.575 km^2 or occupies 7,2% of the total area of the entire island of Sumatra [13]. Even so, Lampung Province is the province with the second largest population on the island of Sumatra with 9,176,546 people in 2022 and projected population growth of 1.25 million people in 2035 [14].

According to Afnimar [15], Natural events in the form of earthquakes that produce ground motion can cause damage on the earth's surface, which can be called earthquake hazards [16][17]. By looking at the geological conditions of Lampung Province, the potential earthquake hazard can be said to be high. Given that Lampung Province is the second most populous province on the island of Sumatra and the high earthquake hazard potential there, an understanding of the earthquake hazard risk is needed, such as the lack of microzonation division of earthquake hazard risk in the Lampung Province area. Microzoning is a tool that can be used as a reference for development and mitigation of future earthquake disasters [18][19]. Another problem is that there is a lack of public understanding of the risks of earthquake hazards. Disaster education in Indonesia is still very minimal [20][21]. Therefore, it is necessary to map the microzonation of earthquake hazard risk and increase understanding of earthquake hazard risk in Lampung Province to facilitate the mitigation process and earthquake management can be done in advance.

PSHA studies that focus on Lampung Province are still limited, even though this region has the potential for significant seismic activity. This research aims to delineate the microzonation of seismic hazard risk in Lampung Province through the application of Probabilistic Seismic Hazard Analysis (PSHA). The PSHA methodology primarily involves the assessment of potential earthquake sources along with an analysis of historical seismicity data [22][23] The choice of PSHA is justified by its ability to forecast long-term seismic events, identify microzonations, and derive critical metrics such as Peak Ground Acceleration (PGA). The PGA serves as a vital indicator for understanding potential earthquake impacts within a specific region [24][25]. A higher PGA value correlates with increased seismic risk and danger, thereby underscoring the significance of this metric in hazard assessment [26][27]. To facilitate public understanding of hazard risk, it is necessary to calculate the MMI Scale based on PGA conversion. There is also a lack of long-term analysis to predict earthquakes, so the understanding of future seismic risk is not comprehensive. This gap emphasizes the need for more accurate and relevant earthquake risk microzoning research for Lampung.

In addition to creating a microzoning mapping of the risk of earthquake hazards in Lampung Province, another thing that is no less important is to create safety guidelines that can facilitate the community to be able to understand the dangers of earthquake risk. Namely by using the *Modified Mercalli Intensity* (MMI the MMI scale is a parameter that shows the intensity of an earthquake that indicates the level of damage due to shaking, having a scale of I MMI to XII MMI [28][29]. A higher MMI scale indicates the potential for more severe damage, so that people can be more alert. The MMI scale can also be used as a reference for safety measures with recommendations for safety measures in accordance with the level of the MMI scale. For example, at low MMI levels, actions such as taking shelter under a table can be recommended. While at higher MMI levels, evacuation from buildings may be a safer course of action. Therefore, creating safety guidelines based on the MMI scale will make it easier for the public to understand the risks of earthquake hazards.

Disaster mitigation is important because it involves public safety [30]. Therefore, this study aims to determine the distribution of earthquake hazard risk microzonation and efforts to increase public understanding of earthquake hazard risk in Lampung Province as a disaster mitigation effort.

2. Methods

2.1 Research Location

The research location is in the Lampung Province area. Lampung Province is an area that holds an important function in economic and industrial activities on the island of Sumatra. This is because Lampung is the entrance gate for land and sea transportation routes from Java to Sumatra or vice versa. With a population of 9,176,546 million people, it is the third most populous province on the island of Sumatra [31][32].

Geographically, Lampung Province is located at the coordinates of 6° 45′ - 3° 45′ N and 108° 48′ - 105° 45′ LU. The earthquake source data used in this study are earthquake source data obtained from USGS [33] and PUSGEN 2017 [34] for the Lampung Province area for 2500 years with the criteria of earthquake source distance to the location under review as far as 500 km. The scale of risk analysis parameters is sourced from literature studies of previous research journals [35][36].

2.2 Earthquake Sources

In the Seismic Hazard Analysis, three earthquake sources will be analyzed, namely faults, subduction (megathrust) earthquake sources, and background earthquake sources. Fault is a fracture in the rock where the parts separated by the fracture will move against each other. A fault plane is a tectonic plane between two tectonic blocks that are separated due to the [37][38]. The fault earthquake source model parameters for probability analysis are fault trace, movement mechanism, slip-rate, dip, fault length and width. Fault earthquake source data for Lampung province can be seen in Table 1. Then the input code used in data processing is filtrate.v2, continued using the HazFXnga7c code with two inputs, flt.char and flt.gr, then run all using hazAll.v2.

Then the earthquake source that has a significant influence on earthquake events is the subduction zone or megathrust. Megathrust occurs because the relative density of the oceanic lithosphere is greater and the character of the atenosphere is relatively weak, causing the oceanic lithosphere to experience a movement towards the land lithosphere [39][40]. The megathrust earthquake source model parameters used are the subduction location (latitude and longitude), rate and a-b value, and the depth limit of the subduction area, the megathrust earthquake source parameter data can be seen in Table 2. For subduction earthquake sources, the data processing only uses the hazSUBXnga code. Furthermore, to calculate the overall probability of the combination of the three earthquake sources above is done using the hazallXL input code [34].

The background zone is an earthquake source that is not yet clearly known, but in that place, there are several earthquake events (earthquake events with unknown faults). The background earthquake source uses parameters such as subduction location (latitude and longitude) and the depth limit of the subduction area. The depth analysis is divided into six intervals, namely shallow background source (0-25 km), and (25-50 km) for deep background source (50-100 km), (100-150 km), (150-200 km), and (200-300 km). The background earthquake source processing mechanism is by using the agridMLsm.v2 input code for all depths, continued using the hazgridXnga2 code, then run all using hazAll.v2 to find out the analysis results.

Figure 1. Regional map of Lampung Province

Table 1. Data and Parameters of Fault Earthquake Sources for Lampung Province

Name	Slip-Rate (mm/yr)	Sense Mechanism	Dip	Top	Bottom	L (km)	M max
Siulak	14.0	Strike-slip	90	3	20	70	7.2
Dikit	12.0	Strike-Slip	90	3	20	60	7.1
Ketaun	12.0	Strike-Slip	90	3	20	85	7.3
Musi	13.5	Strike-Slip	90	3	20	70	7.2
Manna	13.5	Strike-Slip	90	3	20	85	7.3
Kumering North	12.5	Strike-Slip	90	3	20	111	7.5
Kumering Sourth	12.5	Strike-Slip	90	3	20	60	7.1
Semangko Barat A	8.0	Strike-Slip	90	3	20	90	7.4
Semangko Barat B	8.0	Strike-Slip	90	3	20	80	7.3
Semangko Timur A	5.0	Strike-Slip	90	3	20	12	6.5
Semangko Timur B	3.0	Strike-Slip	90	3	20	35	6.9
Semangko Graben	8.0	Normal	90	3	20	50	6.5
Ujung Kulon A	10.0	Strike-Slip	90	3	20	80	7.3
Mentawai	5.0	Reverse-slip	45W	3	20	560	8.2
Enggano	5.0	Reverse-Slip	45W	3	20	160	7.6
Ciremai	0.1	Strike-Slip	90	3	18	20	6.5
Ajibarang	0.1	Strike-Slip	90	3	18	20	6.5
Tegal	0.1	Reverse-Slip	45S	3	18	16	6.5
Brebes	0.1	Reverse-Slip	45S	3	18	22	8.5
Cirebon	0.1	Reverse-Slip	45S	3	18	15	6.5
Cirebon-2	0.1	Reverse-Slip	45S	3	18	18	6.5
Subang	0.1	Reverse-Slip	45S	3	18	33	6.5
Lembang	2.0	Strike-Slip	90	3	18	29,5	6.8
Rajamandala	0.1	Strike-Slip	90	3	18	45	6.6
Nyalindung Cibeber	0.40	Reverse-slip	45S	3	18	30	6.5
Cimandiri	0.55	Reverse-Slip	45S	3	18	23	6.7

Table 2. Data and Parameters for subduction earthquakes in Indonesia for the Province

Index	Structure	Segment	Max Magnitude	a value	b value
M5	Sumatran Megathrust	Mentawai Pagai	8.9	3.02	0.63
M6	Sumatran Megathrust	Enggano	8.4	5.57	1.05
M7	Sunda Strait Megathrust	Selat Sunda Banten	8.7	5.99	1.15
M9	Java Megathrust	West- Central Java	87	5.55	1.08

From Table 1, there are 25 fault earthquake sources affecting Lampung province with three types of faults, namely one normal fault, eight reverse faults and 16 strike slips.

There are four megathrust earthquake sources that affect the earthquake in Lampung Province, namely Mentawai Pagai, Enggano, Banten Sunda Strait, and West Central Java. In the PSHA analysis process, earthquake source parameters are required as input such as maximum magnitude, a and b values and rate. These parameters will be processed using ArcGis software.

2.3 Probabilistic Seismic Hazard Analysis (PSHA)

In analyzing seismic sources, one method that can be used is Probabilistic Seismic Hazard Analysis (PSHA). This method is often used to create regional seismic hazard maps. The PSHA method identifies earthquake microzonations and produces the highest ground vibration acceleration or maximum ground acceleration in units of gravitational acceleration (gal or cm/s2). The PGA value is the largest ground acceleration experienced by an area due to earthquake shaking. PSHA maps provide explicit space to account for epistemic uncertainty and deviation from potential shaking [34][41].

PSHA estimates seismic hazard as the probability of exceeding a certain intensity of ground motion at a given location during a given time interval (or alternatively, return period; for example, 10% in 50 years, equivalent to a return period of 475 years). The frequency of seismic events corresponds to the annual rate of exceedance of a certain intensity level. Ground motion acceleration can be measured in the form of peak ground acceleration (PGA), peak ground velocity, peak ground displacement, or response spectral acceleration. The PSHA approach achieves maximum acceleration values of ground motion in bedrock to estimate earthquake events within a 2500-year return period for a 50-year building period. The use of this return period was chosen because it can predict the potential for large earthquakes to occur compared to other periods, the longer the period of earthquake data obtained the more so that the possibility of earthquake occurrence in the study area will be higher. In this paper we will always use PGA. [42][43].

In calculating the acceleration of ground motion on bedrock with the PSHA approach, there are four attenuation function models or GMPE (Ground Motion Prediction Equation) used, namely shallow crustal fault, shallow background, megathrust subduction and Benioff subduction. The selection of the GMPE equation is based on previous research, the GMPE used for the shallow crustal fault earthquake source model is the same as the shallow background model, namely Boore and Atkinson [44], Campbell & Bozorgnia [49] and Chiou & Youngs [45]. GMPEs for megathrust subduction earthquake source models are Abrahamson et al. [46], Zhao et al. [47] and Atkinson & Boore [44].

To minimize the risk of earthquakes, information on the maximum ground acceleration (PGA) value is needed. From this parameter, the level of risk in a region can be known, where the greater the PGA value, the higher the risk experienced by the region. The equation used in analyzing the level of earthquake threat with the probabilistic method is as follows [50], [51].

$$Px(x) = v \int_{M}^{R} \int_{R}^{M} P[X > x|m,r] f_M(m) f_R(r) dr dm \quad (1)$$

Where $Px\ (x)$ for the total probability of an earthquake producing a peak acceleration of $X > x$, magnitude M, distance R during the time span under review. f_M for magnitude probability function. f_R for distance probability function. $P[X > x|m,r]$ is the probability of an earthquake of magnitude m at a distance r giving a maximum acceleration X at a location higher than x. In addition to PGA, the calculation of MMI scale risk can also help analyze risks with different damage intensity characteristics.

2.4 Risk Intensity in MMI Scale

Intensity is a measure that indicates the strength of an earthquake based on how severe the damage is in the affected area. The scale used to analyze the risk level of earthquake intensity is the MMI (Modified Mercalli Intensity) scale. Giuseppe Mercalli, an Italian volcanologist, created this scale in 1902. This scale is used if there is no seismometer equipment to measure the strength of an earthquake around the event. The following is the level of earthquake risk based on the MMI scale according to the Meteorology Climatology Geophysics Agency [52][53] shown in Table 3.

Table 3. Parameters with MMI scale

MMI Scale	Short Description	Long Description
I-II	Not Felt	Not felt or perceived by some people except under certain circumstances but recorded by equipment.
III-V	Felt	Vibration can be felt but does not cause damage. Small hanging objects swayed.
VI	Slight Damage	Non-structural parts of buildings were damaged, such as cracks in the walls and roofs of houses that shifted or some fell.
VII-VIII	Moderate Damage	Many cracks in the walls of simple buildings, some collapsed, broken glass, loose wall plaster, and falling roofs. Building structures suffered minor to moderate damage.
IX-XII	Heavy Damage	Walls in permanent buildings collapsed, building structures may shift, railroad tracks bent, and waves appear on the ground.

There is a relationship between PGA and the MMI (Modified Mercalli Intensity) scale [54], [55]. The PGA data obtained will be used to classify the level of earthquake vulnerability based on the MMI scale. The equation used to convert the PGA value into the MMI Scale for the worldwide area [56] is:

$$MMI = 2{,}27 + 1{,}647 \times \log PGA \quad (2)$$
$$For\ \log PGA \leq 1{,}6$$

$$MMI = -1{,}361 + 1{,}647 \times \log PGA \quad (3)$$
$$For\ \log PGA > 1{,}6$$ [57]

The Mercalli scale can be used to measure the strength of an earthquake, so that the level of risk in the event of an earthquake in the region can be known as an initial disaster mitigation effort. The MMI scale is divided into 12 levels (I, II, II, IV, V, VI, VII, VIII, IX, X, XI, XII) with an explanation of the characteristics of different levels of damage. The MMI scale as an earthquake parameter is subjective while the parameter with the maximum acceleration value (PGA) is more objective. However, the conversion of this parameter was chosen because it allows ordinary people to better understand the level of danger in the area, because not all people understand the concept of earthquake hazard risk data in the maximum acceleration value (PGA) diagram.

2.5 Research Flow Chart

In making the map, ArcGis software was used with the Probabilistic Seismic Hazard Analysis (PSHA) method. The earthquake sources used are divided into three, namely Megathrust, Fault and Background. USGS data for each earthquake source is run using Command Prompt then the output is displayed using ArcGis Map. The flow chart in this research is as Figure 2.

Based on Figure 2 the process began by studying the relevant literature to understand the latest methodologies, research findings and relevant data sources. Data on earthquakes was obtained from the United States Geological Survey (USGS), which provides information on earthquakes around the world. The data obtained was entered into software to evaluate the potential earthquake hazard in the Lampung Province area. The output of the hazard program is the PGA model, which describes the potential intensity of earthquakes at various points in the Lampung province area. The PGA model is executed or run using GIS (Geographic Information System) software such as ArcGIS to visualize the data spatially. This process produced a map showing the spatial distribution of potential earthquake hazards based on the PGA model. Subsequently, the PGA model was converted to the MMI scale, which reflects the impact of earthquake vibrations on humans and building structures. The converted data was then re-run using ArcGIS to produce an earthquake source map with the MMI scale. This resulted in a final map showing the level of earthquake intensity on the MMI scale, which can be used to understand the potential impact on people and infrastructure in the area studied.

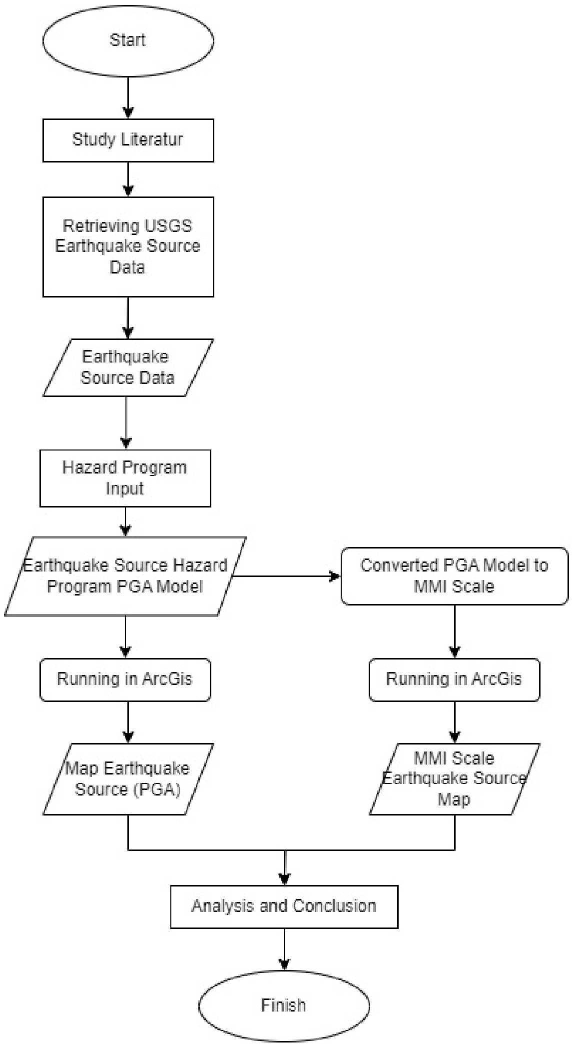

Figure 2. Research flow chart

3. Result and Discussion

PSHA analysis using the USGS PSHA software has been conducted in this study. Based on simulations with the earthquake methods and data discussed in the previous chapter, the results are presented in Figure 3.

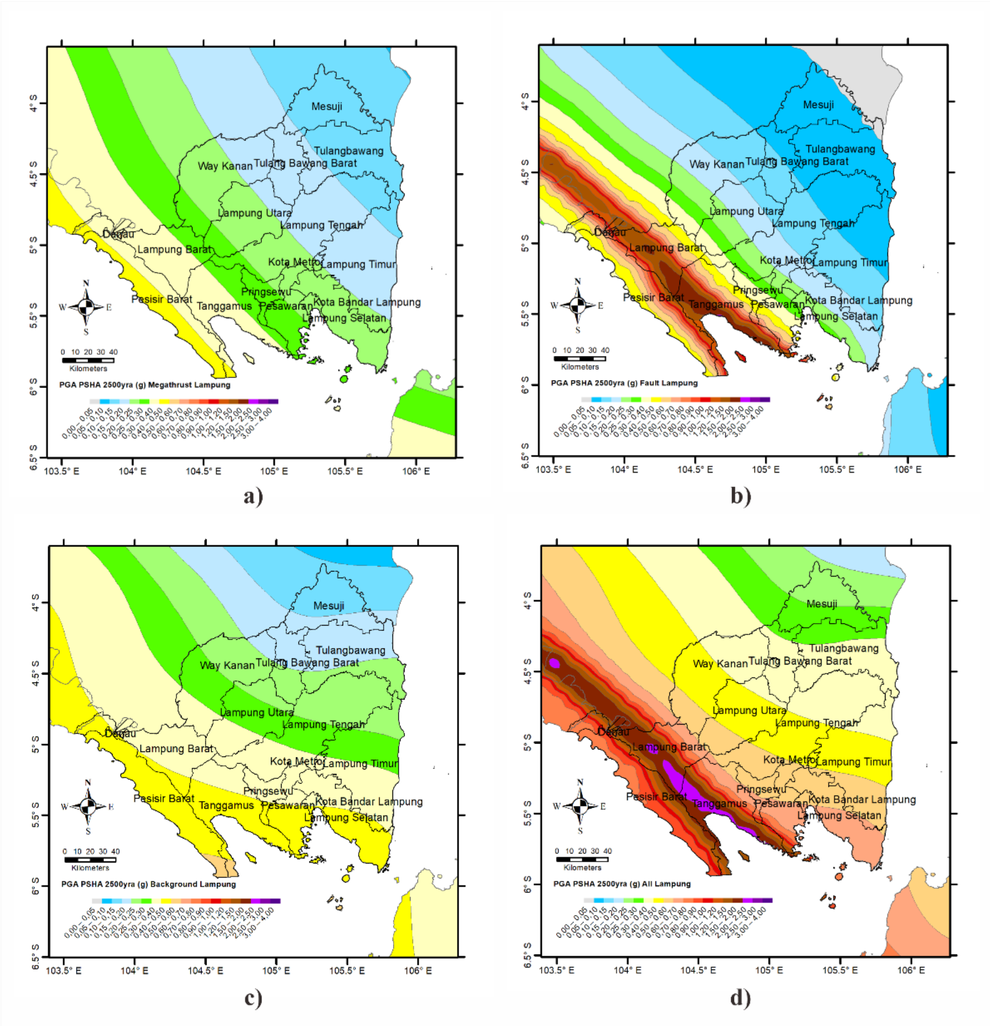

Figure 3. The bedrock PGA map of Lampung Province for the 2500-year return period using the PSHA method with earthquake sources a) subduction (megathrust), b) fault, c) background (shallow & deep) and d) combined all earthquake sources (all).

In the results of the subduction (megathrust) earthquake source map, the maximum acceleration caused is around 0.10- 0.50 g (Figure 3a). Areas that are vulnerable to earthquake sources are the western part of Lampung province, namely the Pesisir Barat and surrounding areas with a PGA of 0.30-0.50. The closer the earthquake source, the more vulnerable the region is to earthquakes.

Based on the PGA Map in the Bedrock of Lampung Province for fault earthquake sources, the PGA value caused by these fault earthquake sources is around 0.05-2.00 g (Figure 3b). Areas that have sufficient PGA values are those that are close to or on the path of the fault earthquake source such as Tanggamus, West Lampung and several areas in Pesisir Barat as well as surrounding areas with PGAs of 0.50-2.00g.

In the results of the background earthquake source map, the resulting PGA value range is around 0.10-0.60 g (Figure 3c). Just like the previous earthquake source, the areas that have sufficient PGA values are those in the western region such as Pesisir Barat, Tanggamus, and surrounding areas with a PGA of 0.40- 0.50 g. The PGA value of the background earthquake is 0.10-0.60 g (Figure 3c).

From the results of the distribution of the map, the areas that have high enough earthquake acceleration are areas close to faults and subduction (megathrust) earthquake sources (Figure 3d). Seismic hazard analysis obtained PGA values at several large locations in Lampung Province, the highest of which are Tanggamus and West Lampung with acceleration values of 0.5-2.5 g, West Coast with acceleration values around 0.70-2.00 g. This is in accordance with the earthquake catalog map. This is in accordance with the earthquake catalog map for Lampung Province for the period 2010-2024 based on earthquake data from the USGS (Figure 4) which shows high earthquake activity in the region.

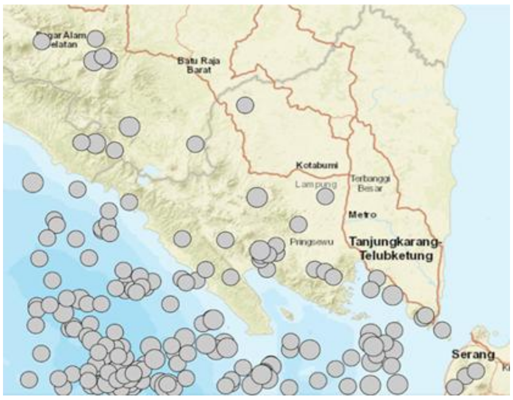

Figure 4. Earthquake catalog map for Lampung Province for the period 2010-2014 based on USGS data [33].

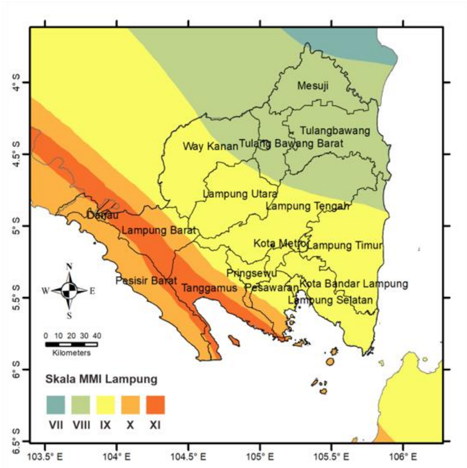

Figure 5. MMI scale Lampung Province

As a result of combining the three earthquake sources, based on the Modified Mercalli Intensity (MMI) scale, the Lampung region was divided into five zones according to the intensity of the damage caused on the surface (Figure 5). The first zone with a scale of VII MMI for a small part of Mesuji District. The second zone with a scale of VIII MMI in Mesuji, Tulangbawang. West Tulangbawang, parts of Way Kanan and Central Lampung, and a small part of East Lampung with a range of ground acceleration values of 0.20-0.40 g and moderate damage risk intensity. The third zone with a scale of IX MMI in West Way Kanan Regency, North Lampung, most of Central Lampung, East Lampung, Pesawaran, and Pringsewu, a small part of West Lampung Regency and Tanggamus, as well as in Metro City, Bandar Lampung City and East Lampung with a range of ground acceleration of 0.40-0.70 g. Then the fourth zone with a scale of X MMI. Then the fourth zone with a scale of X MMI for the Pesisir Barat region, as well as parts of West Lampung Regency, Tanggamus and Pesawaran with a ground acceleration range of 0.70-1.00g. The fifth zone is the XI MMI scale for most of West Lampung and Tanggamus with a range of ground acceleration values of 1.00-2.50g. The intensity of damage for the IX-XI MMI scale falls into the category of heavy damage. From the results of the analysis that has been carried out, the area close to the fault and subduction (megathrust), the level of intensity of the risk of damage is higher and the possibility of damage is also greater.

4. Conclusion

A study has been conducted to analyze the maximum ground acceleration (PGA) value and damage intensity with the MMI scale using the PSHA method. There are three earthquake sources, namely fault, subduction (megathrust), and background. The results of the analysis based on the PGA map can be concluded that Lampung Province has a moderate to high level of earthquake disaster risk. Compared to the eastern region, districts in the western region have higher PGA values such as in Tanggamus and West Lampung with a PGA range of 0.60-2.50 g. The high level of risk is because the region is traversed by several fault earthquake sources and the influence of the subduction activity of the Indo-Australian plate or megathrust zone.

The results of converting the PGA value to the MMI scale in Lampung Province are divided into five zones from VII to XI MMI. The first zone, with a scale of VII MMI is in the Mesuji Regency area with a very small location coverage. The second zone, categorized as the VIII MMI scale with a PGA of 0.20-0.40 g. The third zone, categorized as IX MMI scale with PGA 0.40- 0.70 g. The fourth zone, included in the X MMI scale category with a PGA value of 0.70-1.00 g. Finally, the fifth zone, with a scale of XI MMI has a range of PGA values of 1.00-2.50 g. The zones with X and XI scales have a heavy intensity of damage risk because they are close to the earthquake source. With this MMI scale map, it can help the community to know the risk of earthquake hazards in their area easily as an initial disaster mitigation effort.

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