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Estimation Of Maximum Ground Acceleration Value Based on Mentawai Earthquake Scenario Using Atkinson Boore and Zhao

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Abstract: We have estimated the value and intensity of maximum ground acceleration in West Sumatra based on the Mentawai earthquake scenario by using the formulation of Atkinson Boore (2003) and Zhao (2006). This study aims to determine the PGA value of an area as the level of activity and intensity of the earthquake in West Sumatra region from the Mentawai earthquake scenario as a measure of damage caused by the earthquake and analyze its distribution. This study uses earthquake information data for the period 1900-2023 with magnitude > 7 SR and depth < 100 km and shear wave velocity model at a depth of 30 meters (Vs 30) sourced from the National Earthquakes Information Center US Geological Survey (NEIC/USGS) catalog. After that, calculations are carried out so that the estimated maximum ground acceleration value is obtained using the Atkinson Boore (2003) and Zhao (2006) formulas. The maximum ground acceleration and earthquake intensity values for each city/regency in West Sumatra were calculated with a 0.1° grid. The estimation results show that the largest values for each scenario are in Mentawai Islands and South Pesisir because those areas are close to the subduction zone. In addition, it is also influenced by the epicenter, magnitude and soil type in the region. So that the maximum ground acceleration value in West Sumatra ranges from 0.007 g - 2.117 g with earthquake intensity ranging from I - X+ MMI. This indicates that the area is vulnerable to damage if an earthquake occurs.

Keywords: Earthquakes, Atkinson Boore, Zhao, PGA, Intensity

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Introduction

Indonesia is the most active and complex tectonic region because it is located in the meeting zone of three earth plates, namely the Indo-Australian, Eurasian and Pacific plates [1] [2]. The Indo-Australian plate moves underneath the Eurasian plate which produces a subduction zone along the west of Sumatra Island to the south of Nusa Tenggara. While the Eurasian plate pushes under the Pacific plate which forms a subduction zone along the north of Sulawesi and the Maluku Islands. Sumatra Island is located in a tectonically active zone, namely in the subduction zone, the Sumatran fault and the Mentawai fault [3] [4] [5]. One of the areas on the island of Sumatra is West Sumatra, which is tectonically prone to earthquakes because it is located in the 3 zones.

The Mentawai Islands are one of the areas in West Sumatra that often experience earthquakes because they are located in the Eurasian and Indo-Australian plate regions. This zone is formed because the Indo-Australian plate subducts under the Eurasian plate and moves against each other at a very slow speed and the plate bends to form a subduction angle [6]. Topographically, the geographical condition of the Mentawai Islands varies between plains, rivers and hills. Geographically, the Mentawai Islands are directly adjacent to the Indian Ocean. On April 25, 2023, an

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earthquake with a magnitude of 6.9 occurred offshore, 177 kilometers northwest of the Mentawai Islands at a depth of 23 km. The tremor was felt in Siberut with an intensity of VI on the MMI scale. In contrast, the earthquake was experienced at intensity V MMI in West Pasaman, Padang Pariaman, Agam, and Padang. BMKG had issued a tsunami early warning and ended aftershocks with the largest magnitude of M 5 [7]. Therefore, it is necessary to see how much impact the earthquake whose epicenter was in the Mentawai Islands region had on West Sumatra Province. According to [8] and [9], the Mentawai Islands, located on Siberut Island, still store the potential earthquake energy of 8.9 SR that has been stored since 1797. Although there have been earthquakes in the Mentawai Islands, the energy released is less than a third of the total energy that has been accumulated since 1797. When the seismic waves from this earthquake reach the surface, the ground they travel through will experience a level of acceleration known as maximum ground acceleration.

An earthquake is a sudden discharge of seismic wave energy caused by deformation or shifting of tectonic plates in the Earth's crust [10] [11]. This energy release process is in the form of elastic waves, namely seismic or earthquake waves that reach the earth's surface and cause vibrations to cause damage to objects or buildings on the earth's surface. The extent of the damage can be influenced by the maximum ground acceleration [12].

Peak Ground Acceleration (PGA) is one of the factors that determine the magnitude of the strongest ground shaking that occurs in an area due to earthquake waves [13]. This level of ground shaking reflects the earthquake risk in the area and needs to be considered as an important aspect of earthquake-resistant building planning [14]. The PGA value generated by an earthquake is related to the intensity of the earthquake. The higher the PGA value of an area, the stronger the earthquake is felt [15]. PGA values are determined either by direct measurements with an accelerograph or through calculations based on empirical formulas applied to earthquake data [16]. This formula is used to determine the PGA value in West Sumatra using the attenuation formula.

The methods used to estimate the maximum ground acceleration in an area include, first, the formulation of [17] [18]. This formulation is the attenuation relationship of earthquake-resistant ground motions that occur in subduction zones in various parts of the world. This formula is defined in the Cascadia region in the form of an Equation (1).

$$logY = c_1 + c_2M + c_3h + c_4R - g\log R + c_5\,slS_C + c_6\,slS_D + c_7\,slS_E \quad (1)$$

Where Y is maximum ground acceleration value, M is moment magnitude, R is epicenter distance, h is depth of earthquake source (km) and g is gravity.

The second, using the formulation of [18] [19]. Zhao's formula applies to earthquake sources located in subduction areas. This equation was developed from observations of 4,518 earthquake records that occurred in Japan, 1,508 of which were subduction interface earthquakes, determining a maximum depth for the interface of up to 50 km. The form of this attenuation function is Equation (2).

$$Log_e(y) = aM_w + bx - log_e(r) + e(h - h_e)\delta_h + F_R + S_l + S_s + S_{SL}log_e(x) + C_k + \xi + \eta \quad (2)$$

Where Y is maximum ground acceleration value, Mw is moment magnitude, x is distance from source to location (km), r is hypocentral distance (km), h is depth of focus (km), Fr is reverse fault parameter, Sl is interface parameter coefficient, Ss is subduction parameter coefficient, and Ssl is intraslab path modification coefficient.

The conversion of maximum ground acceleration (PGA) values can be classified into categories of intensity, maximum ground acceleration, perceived vibration, and destructive capability as shown in Table 1.

Table 1. Grouping Earthquake Intensity Values Based on The Level of Damage

Intensity (MMI)	PGA (g)	Perceived shaking	Potensial demage
I	< 0.0017	Not felt	None
II - III	0.0017 – 0.014	Weak	None
IV	0.014 – 0.039	Light	None
V	0.039 – 0.092	Moderate	Very light
VI	0.092 – 0.18	Strong	Light
VII	0.18 – 0.34	Very strong	Moderate
VIII	0.34 – 0.65	Severe	Moderate to heavy
IX	0.65– 1.24	Violent	Heavy
X+	>1.24	Extreme	Very heavy

(Source: Ref [20])

Data used in this study consists of earthquake scenarios from the years 1900 to 2023. This analysis aims to evaluate the impact of earthquakes originating in the Mentawai Islands on PGA values and earthquake intensity across 19 cities and regencies in West Sumatra. The epicenter of these earthquakes is located in the Mentawai Islands region, which is influenced by the subduction zone.

A key innovation of this research is the application of the Atkinson-Boore and Zhao formulations to earthquake scenarios specific to the Mentawai Islands from 1900 to 2023. This approach evaluates how earthquakes in this region affect PGA values and intensity, using 336 calculation points derived from a 0.1° grid across the 19 cities/regencies in West Sumatra.

Mapping and analyzing maximum ground acceleration and earthquake intensity are crucial for earthquake disaster mitigation, as they provide insights into local tectonic conditions. This information is valuable for assessing seismic risk and planning infrastructure development in affected areas.

Method

This research is quantitative research using the formulation of Atkinson Boore (2003) and Zhao (2006) to determine the Peak Ground Acceleration (PGA) value of the Mentawai earthquake. The researcher used two variables, namely independent variables and dependent variables. The independent variable consists of longitude, latitude, depth, and magnitude and the dependent variable is Peak Ground Acceleration (PGA).

This research uses data from the National Earthquakes Information Center U.S. Geological Survey (NEIC/USGS) catalog in the period 1900-2023 with magnitude M>7 SR and depth <100 km. The earthquake parameters used consist of longitude, latitude, hypocenter, magnitude, and origin time. Shear wave velocity (Vs30) was determined by taking USGS data, namely VS30 in the West Sumatra region from Earthquake USGS.

The approach used in this study involved multiple steps, starting with calculating the distance between the epicenter coordinates of the earthquake and the coordinates of the calculation points using the following Equation (3).

$$D^2 = (x2 - x1)^2 + (y2 - y1)^2 \quad (3)$$

Where D is the distance of the earthquake epicenter to the calculation point, x1 and y1 are the latitude and longitude coordinates of the earthquake, and x2 and y2 are the latitude and longitude coordinates of the calculation point. Initially, the epicenter distance was converted using the conversion factor of 1° = 111 km.

Calculate the hypocenter distance of the earthquake using the Equation (4).

$$R^2 = D^2 + H^2 \quad (4)$$

Where R is the hypocenter distance, D is the epicenter distance, and H is the depth of the earthquake.

After obtaining these parameters, the values are then substituted into the form of Equations (1) and (2). One method that can be used to estimate the peak value of ground acceleration is the statistical analysis method, such as the formulation of Atkinson Boore and Zhao.

PGA values obtained from equations 1 and 2 are converted into the modified Mercalli intensity (MMI) scale to show the intensity scale with Murphy & o'brien's empirical formula in Equation (5).

$$MMI = 2{,}86 \log(PGA) + 1{,}24 \quad (5)$$

Prior to calculating the maximum ground acceleration value, the study area is divided into grids spaced 0.1 degrees apart, as illustrated in Figure 1. This procedure ensures the precision of the maximum ground acceleration values obtained. In total, 336 calculation points are utilized to determine the maximum ground acceleration in West Sumatra.

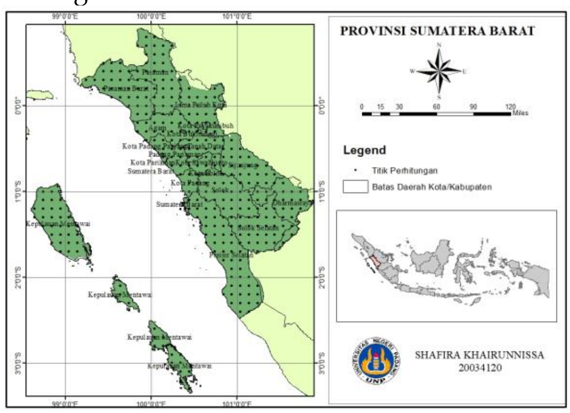


Figure 1. Calculation point map

Based on the Figure 1, there are 336 distribution of safe calculation points at each point, the value of PGA and earthquake intensity in the period 1900-2023 with magnitude> 7 SR and depth < 100 km. after that, analysis and map making of the distribution of estimated maximum ground acceleration values and earthquake intensity in the West Sumatra region based on the calculation results.

Result and Discussion

The results of this study consist of PGA values and earthquake intensity, derived from secondary data processing of earthquakes originating in the Mentawai Islands region within the subduction zone. Earthquake data was obtained from the USGS website and obtained 4 earthquake events in the period 1900-2023. Earthquake data can be seen in Table 2.

Table 2. Scenario of Earthquake Parameters

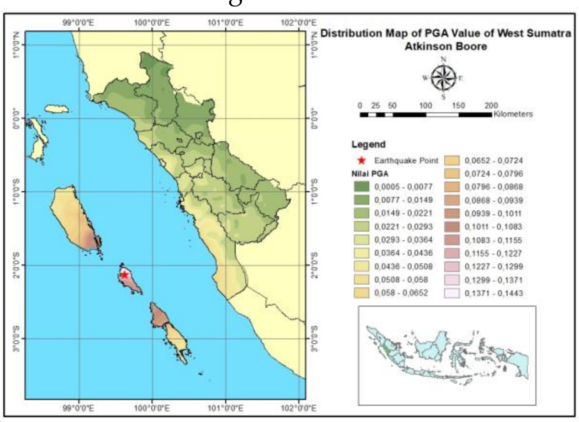
No	*Time*	*Latitude*	*Longitude*	*Depth*	*Mag*
1	2007-09-13T03:35:28.720Z	-2.13	99.627	22	7
2	2008-02-25T08:36:33.030Z	-2.486	99.972	25	7.2
3	2007-09-12T23:49:03.720Z	-2.625	100.841	35	7.9
4	2010-10-25T14:42:22.460Z	-3.487	100.082	20.1	7.8

(Source: USGS)

The area to be studied is the area of 19 cities / regencies in West Sumatra with an earthquake scenario in the Mentawai region. The earthquake parameters used are longitude, latitude, depth, epicenter distance, and magnitude.

Based on the calculation of ground acceleration values obtained using the attenuation function, the resulting maps of the distribution of maximum ground acceleration and intensity for earthquake scenarios with epicenters in the subduction zone can be seen in Figure 2 to Figure 5.

First, the results of data processing of maximum ground acceleration values using the Atkinson Boore formula with magnitudes 7 Mw, 7.2 Mw, 7.9 Mw and 7.8 Mw can be seen in Figure 2.



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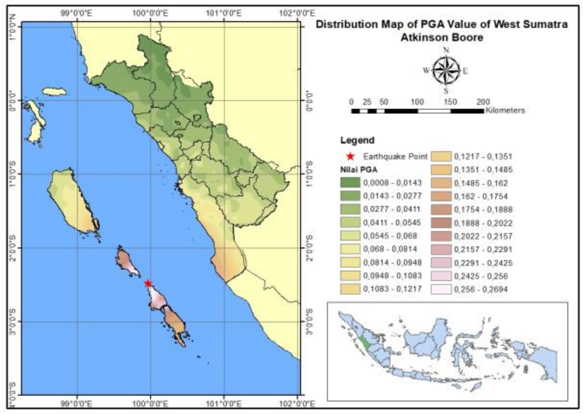

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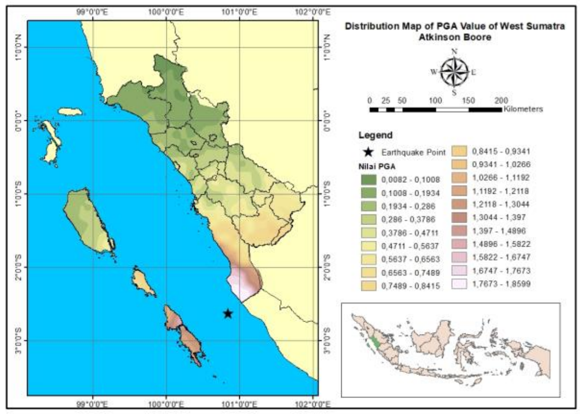

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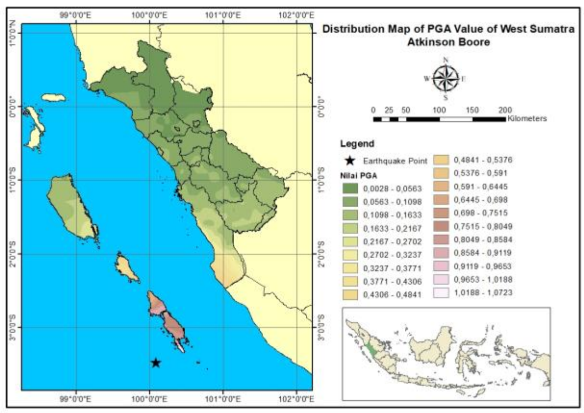
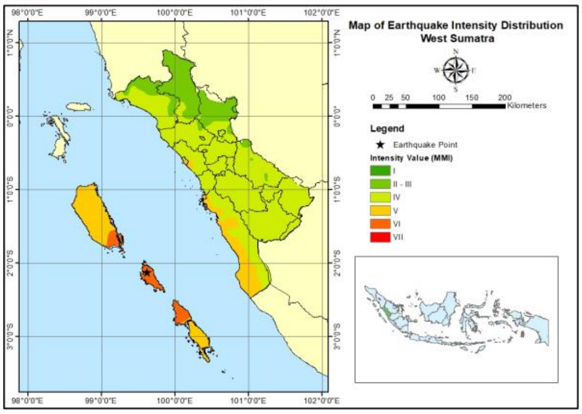


(d)

Figure 2. Distribution map of maximum ground acceleration values using Atkinson Boore formula for earthquake magnitude a) Mw 7, b) Mw 7,2, c) Mw 7,9, d) Mw 7,8

Based on Figure 2, it can be seen the value of the distribution of maximum ground acceleration with the Atkinson Boore formula which is marked with a change in color. The largest maximum ground acceleration value is in the Mentawai Islands region with a value of 0.0486 g - 1.844 g which is marked in pink. The smallest maximum ground acceleration value is in the Pasaman Regency region with 0.007 g - 0.180 g. Based on Figure 2a, the largest ground acceleration value is in the Mentawai Islands region with 0.0486 g - 0.144 g which is marked with white pink color. The smallest maximum ground acceleration value is in the Pasaman region with 0.007 g - 0.017 g marked in green. Based on Figure 2b, the largest maximum ground acceleration value is in the Mentawai Islands with 0.056 g - 0.250 g marked in pink. The smallest ground acceleration value is in the Pasaman region with 0.011 g - 0.027 g which is marked in dark green. Based on Figure 2c, the largest maximum ground acceleration value is in the Mentawai Islands and South Coast region with 0.202 g - 1.844 g market in white and pink. The smallest ground acceleration value is in Pasaman region with 0.062 g - 0.180 g which is marked in dark green. Based on Figure 2d, the largest maximum ground acceleration value is in the Mentawai Islands region with 0.102 g - 1.075 g marked in pink. The smallest maximum ground acceleration value is in Pasaman region with 0.027 g - 0.059 g which is marked in dark green.

Second, the results of data processing of the intensity value of the West Sumatra earthquake with magnitudes 7 Mw, 7.2 Mw, 7.9 Mw and 7.8 Mw can be seen in Figure 3.



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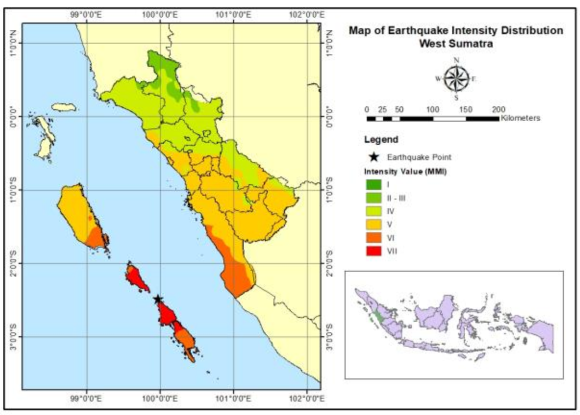

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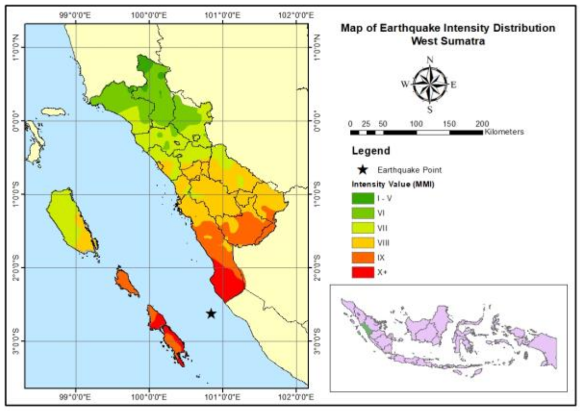

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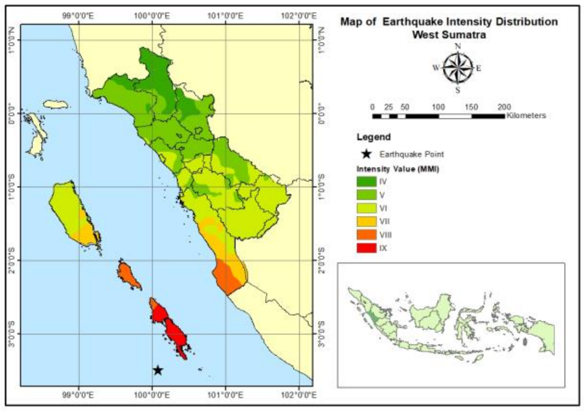


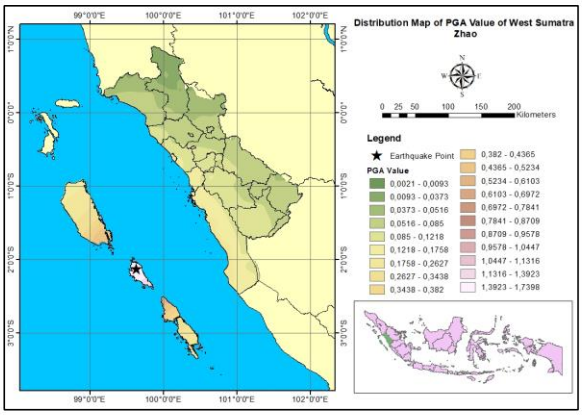
(d)

Figure 3. Map of earthquake intensity distribution using the Atkinson Boore formula for earthquake magnitude

a) Mw 7, b) Mw 7,2, c) Mw 7,9, d) Mw 7,8

Based on Figure 3, it can be seen that the highest earthquake intensity is in the Mentawai Regency and the south coast with V - X + MMI marked in red. The lowest intensity value is in the Pasaman Regency area with I - III MMI marked in dark green. Based on Figure 3a, the largest intensity value is in the Mentawai Islands region with V-VI MMI which is marked with orange color. The smallest intensity value is in the Pasaman Regency region with I - III MMI which is marked with dark green color. Based on Figure 3b, the largest earthquake intensity value is in the Mentawai Islands region with V-VII MMI which is marked with orange color. and the smallest intensity value is in the Pasaman Regency, West Pasaman Regency, and Regency 50 Kota with I - IV MMI which is marked with dark green color. Based on Figure 3c, the largest earthquake intensity value is in the Mentawai Islands and South Coastal District with VII - X + MMI marked in red. The smallest intensity value is in the Pasaman region with V-VI MMI marked in green. Based on Figure 2d, the largest intensity value is in the Mentawai Islands region with VI - IX MMI marked in red. The smallest intensity value is in the Pasaman district area with IV - V MMI marked in dark green.

Third, the results of data processing of maximum ground acceleration values using the Zhao formula with magnitudes 7 Mw, 7.2 Mw, 7.9 Mw and 7.8 Mw can be seen in Figure 4.



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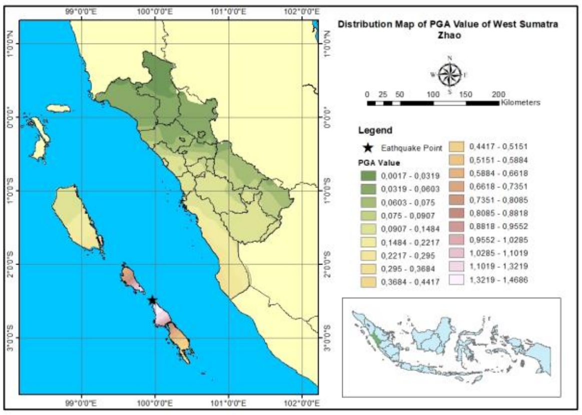

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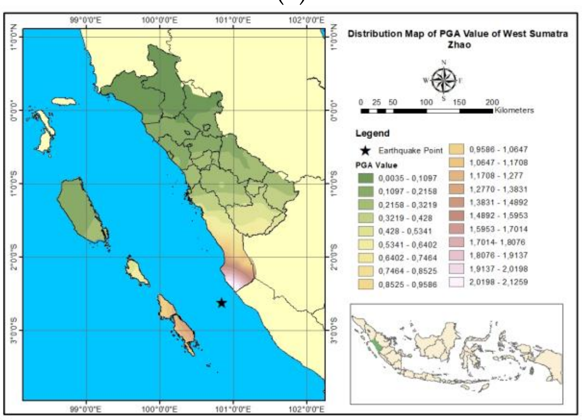

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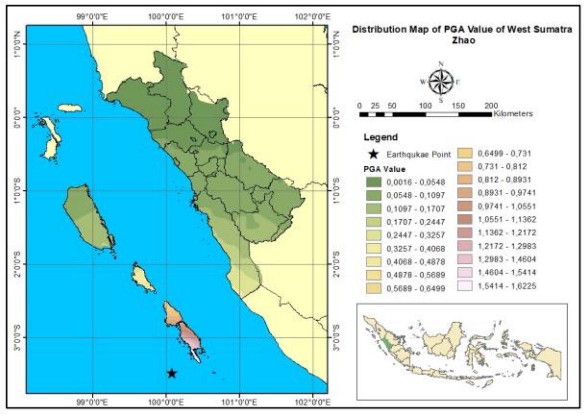
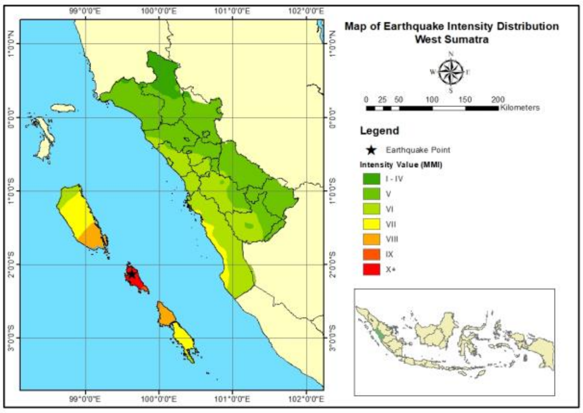


(d)

Figure 4. Distribution map of maximum ground acceleration values using Zhao formula for earthquakes magnitude, a)Mw 7, b) Mw 7,2, c) Mw 7,9, d) Mw 7,8

Based on Figure 4a, the largest maximum ground acceleration value based on Zhao's formulation is in the Mentawai Islands region with 0.152 g - 1.743 g which is marked in pink. The lowest ground acceleration value is in the Pasaman region with 0.023 g - 0.071 g which is marked in dark green. Based on Figure 4b, the largest ground acceleration value is in the Mentawai Islands region with 0.094 g - 1.487 g which is marked in white and pink. The lowest ground acceleration value is in the Pasaman region with 0.019 g - 0.058 g which is marked in dark green. . Based on Figure 4c, the largest ground acceleration value is in the Mentawai Islands and South Coastal Regency with 0.121 g - 2.117 g which is marked in white and pink. while the lowest ground acceleration value is in the Pasaman region with a value of 0.042 g - 0.125 g which is marked in dark green. Based on Figure 4d, the largest ground acceleration value is in the Mentawai Islands region with 0.076 g - 1.571 g which is marked in pink. the lowest maximum ground acceleration value is in the Pasaman region with 0.016 g - 0.045 g which is marked in dark green.

Next, the results of data processing of the intensity value of the West Sumatra earthquake with magnitudes 7 Mw, 7.2 Mw, 7.9 Mw and 7.8 Mw can be seen in Figure 3.



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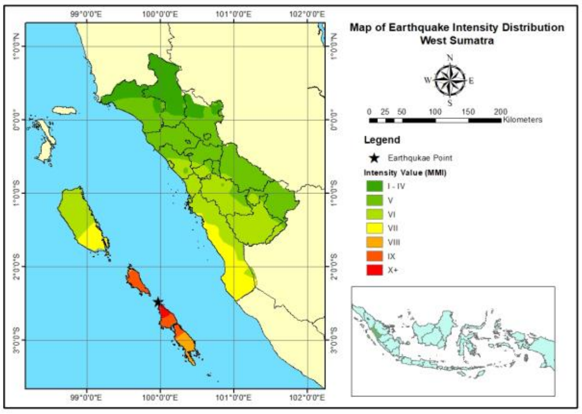

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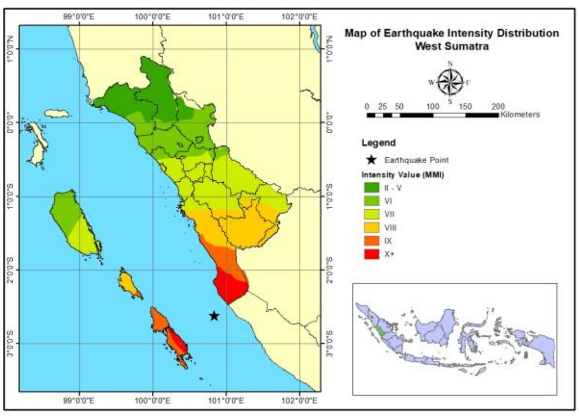

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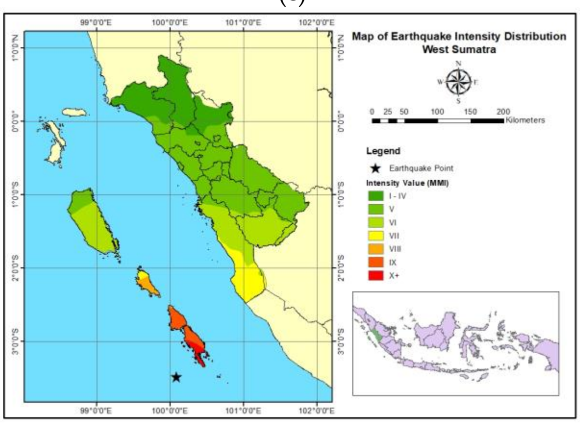

(d)

Figure 5. Map of earthquake intensity distribution with Zhao formula for earthquakes magnitude a) Mw 7, b) Mw 7,2, c) Mw 7,9, d) Mw 7,8

Based on Figure 5a, the largest earthquake intensity value is in the Mentawai Islands with VI- X+ MMI which is marked in red. The lowest intensity value is in Pasaman Regency with I-IV MMI which is marked in dark green. Based on Figure 5b, the largest earthquake intensity value is in the Mentawai Islands with VI-X+ MMI which is marked in red. The smallest intensity value is in the Pasaman Regency area with I-IV MMI marked in green. Based on Figure 5c, the largest earthquake intensity value is in the Mentawai Islands and South Peissir Regency with VI-X+ MMI marked in red. The smallest intensity value is in Pasaman Regency with I-V MMI marked in dark green. Based on Figure 5d, the largest earthquake intensity value is in the Mentawai Islands with V-X + MMI marked in red. The smallest intensity value is in the Pasaman district with I-IV MMI marked in dark green.

The results of the Vs 30 value of the West Sumatra region based on USGS data can be seen in Figure 6.

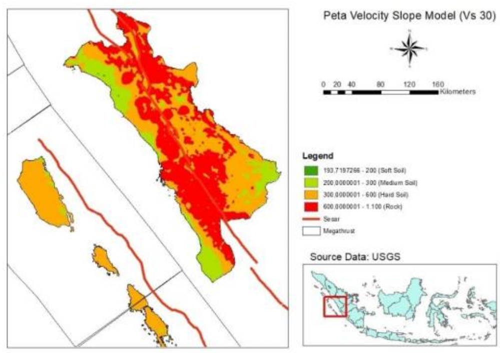

Figure 6. Shear wave velocity model distribution map at 30 meters depth (Vs 30) in West Sumatra from USGS.

Based on Figure 6, relatively high Vs 30 values in the West Sumatra region range from 300m/s to 600m/s and 600 m/s to 900 m/s, marked with orange and red colors on the map. This is influenced by topographic conditions in the form of hills dominated by hard soil and rocks, resulting in a low amplification process and fairly weak ground movement.

This happens because the Mentawai Islands region is close to the epicenter of the earthquake so the maximum ground acceleration value that occurs will be even greater. The maximum ground acceleration value will increase if the distance of each city/regency is closer to the epicenter so that the vibrations that occur will be more pronounced and can cause damage [13]. In addition to epicenter distance, earthquake strength also affects the maximum ground acceleration value, the greater the earthquake energy, the greater the maximum ground acceleration value. In addition, the soil type in the region is classified as medium soil., where based on research [21], the thicker the sediment layer, the higher the peak value of ground acceleration.

The value of maximum ground acceleration and intensity of earthquakes that occur in West Sumatra based on earthquake data originating from the Mentawai Islands subduction zone can be important information in spatial planning and better regional development planning in West Sumatra. The Mentawai Islands region based on the research has a high value of maximum ground acceleration and intensity. This maximum ground acceleration is the main factor that affects building construction. Therefore, the Mentawai Islands region should have met the requirements of earthquake-resistant buildings, because it has a high maximum ground acceleration value.

Conclusion

The maximum ground acceleration (PGA) and earthquake intensity (MMI) values in West Sumatra, resulting from earthquakes in the Mentawai Islands region between 1900 and 2023 with magnitudes greater than 7 SR and depths less than 100 km, were calculated using the Atkinson-Boore (2003) and Zhao (2006) formulations. The highest values, ranging from 0.007 g to 2.117 g, are found in the Mentawai Islands and Pesisir Selatan Regency, due to the region being close to the earthquake epicenters. Conversely, the lowest PGA and intensity values are observed in District 50 and Pasaman Regency. The distribution map shows that the maximum values are located in the Mentawai Islands Regency, close to the epicenter, while the lowest values are in Pasaman Regency, which is farther from the epicenter in the Mentawai subduction zone and thus experiences less impact. Additionally, the estimated values are influenced by the magnitude and depth of each earthquake. The West Sumatra region based on the soil classification of the 30-meter wave propagation velocity (Vs30) value is dominated by medium soil, hard soil, and rock. Where the Mentawai Islands region with the largest PGA value is dominated by medium soil types.

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