Analysis of peak ground acceleration (PGA) using the probabilistic seismic hazard analysis (PSHA) method for Bengkulu earthquake of 1900 – 2017 period

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Abstract. This study was aimed to find out and analyze Peak Ground Acceleration (PGA) in order to mitigate the earthquake. The PGA map resulted was an acceleration map on bedrock with a probability exceeding 10% and 2% with the Probabilistic Seismic Hazard Analysis (PSHA) method for PGA in 50 years. The software used to analyze the Probabilistic Seismic Hazard Analysis (PSHA) method is USGS-PSHA. The data used was in the form of historical earthquake data from 1900 to 2017 and a depth of 1 km to 300 km. Earthquake magnitude ≥ 4.5 Mw with a research limit of 2.53° - 7.58° SL and 96.1° - 106.1° EL from the International Seismological Center (ISC) earthquake catalog, ISC-EHB Bulletin, United States Geological Survey (USGS) and The Geophysical Climatology Meteorology Institution (BMKG), a radius of 500 km from the border of Bengkulu Province. The results show that the most earthquakes for shallow depths with a magnitude of 4.5 Mw - 5.9 Mw as much as 2805 times, while for medium depths at magnitude 4.5 Mw - 5.9 Mw as much as 642 times. The probabilistic calculations exceeding 10% are 0.24 gal - 0.86 gal and probabilistic calculation exceeding 2% is 0.36 gal - 1.35 gal. The areas exposed to the danger zone are Lebong, Rejang Lebong, Kepahiang, Mukomuko, North Bengkulu and Bengkulu City. Whereas the regions included in the medium zone are Seluma and Bengkulu Tengah. And the areas of the safe zone are Kaur and South Bengkulu.

1. Introduction
The position of Bengkulu Province is in a subduction zone between the Indo-Australian and Euro-Asian plates. This condition results Bengkulu Province being an area that is very vulnerable to earthquake disasters. According to the records of tectonic earthquakes from 1900 to 2010, about 95% of the earthquake's source is below the Indian Ocean which is directly adjacent to Bengkulu city. Therefore the coastal area is first object to suffer earthquake tremors and its implications greater than the mainland. And The number of abrasion points along the coast of Bengkulu City is apparently due to the condition of soil vulnerability caused by frequent earthquakes in the region [1].

The earthquake average that occurred around Bengkulu city from 1963 to 2011 was 25 times/year with a magnitude of 3.6 Mw - 7.9 Mw. The general assumption states that the closer an area to the
source of the earthquake, the greater the damage produced. In general, the level of damage that might occur depends on the strength and quality of the building, the geological and geotectonic conditions of the building location, as well as the magnitude of PGA and seismic vulnerability index in that areas [2].

High level seismicity of Bengkulu region should be analyzed and a mitigation is needed to minimize its impact. One of the efforts that could be done is by planning the territorial arrangement in accordance with the guidelines. This paper analyzes it using Probabilistic Seismic Hazard Analysis (PSHA) method. The PSHA method calculates the level of ground shock in a certain location probabilistically which means that calculations are carried out regarding uncertainty factors in the analysis such as size, location, and frequency of earthquake occurrences [3]. This method has four steps, namely a) identification of earthquake sources, b) earthquake source characterization, c) selection of attenuation functions, and d) calculation of earthquake hazard [4].

The analysis uses USGS-PSHA software with probabilistic exceeding 10% and 2% in 50 years, equivalent to the return period of the 2,475 years earthquake. Whereas it uses ArcGis for hazard mapping and Matlab for data processing.

2. Sumatra Tectonic Order

Figure 1. Sumatran Fault Map (National Earthquake Study Center Team, 2017)

Tectonic activity of Sumatra island is caused by collision of the Eurasian plate and the Indian-Australian plate. The meeting zone between the two plates forms a trough with a depth of 4,500 meters to 7,000 meters known as a subduction zone. As a result, a regional fault was formed, namely the Sumatran Fault and the Mentawai Fault. Sumatran Fault which consists of 19 segments stretching from Aceh to Teluk Semangko, Lampung Province [5]. The activity of the Indo-Australian and Eurasian plates at the subduction zone often causes earthquakes so that Sumatra Island is considered as one of the active tectonic regions in the world [6].
The crustal fault in Sumatra is divided into 55 segment faults based on directions from the Geological Working Group [7]. The shear rate value of each cesarean segment is calculated by the Geodetic Working Group based on observations of GPS data from the Geospatial Information Agency [8], with input in the form of velocity points of observation points and the shortest distance to a fault segment. A number of fault segments on the island of Sumatra are known as "The Great Sumatran Fault (GSF)". The term is now more familiar with the term Sumatran Fault. Sumatra Fault is a fault that moves menganan and extends along ± 1,900 km. These faults extend from Aceh to the Sunda Strait between Java and Sumatra. This horizontal fault movement is caused by the Indian-Australian Plate's oblique subduction towards the Eurasian Plate with a direction of subduction of 10° N ~ 7° S [10]. The movement of Sumatra Fault is responsible for the occurrence of destructive earthquakes on the mainland of Sumatra, e.g. the earthquake on 17 May 1892 with the epicenter around the Batang Gadis Valley and Angkola Stem, and the Kerinci Earthquake on 3 June 1903 [11]. While the Sumatra fault is segmented into 19 main segments with the length of each segment is 60 ~ 200 km [10]. Based on geological data, some of the main segments are divided into smaller segments [12].

3. Research Methodology

3.1. Data Collection from the Earthquake Catalog
Data used was the 2015 to 2017 earthquake data from the earthquake catalog of The Geophysical Climatology Meteorology Institution (BMKG), the 1900 to 2017 earthquake data from International Seismological Center (ISC), the 1960 to 2017 earthquake data from International Seismological Center (ISC-EHB Bulletin) and the 1960 to 2017 earthquake from United States of Geological Surveys (USGS). The earthquake catalog data was selected at coordinates 2.53° - 7.58° SL and 96.1° - 106.1° EL. The minimum magnitude scale used is Mw ≥ 4.5 with depths of 0 - 60 km (shallow earthquake) and depths of 60 - 300 km (medium earthquakes), and the assumption that earthquake events below 300 km (deep earthquakes) do not contribute to the PSHA analysis.

3.2. Earthquake Scale Conversion
The magnitude scale such as body magnitude (mb), local magnitude (ML), magnitude surface (MS), and moment magnitude (Mw) should be converted into the same magnitude scale before analyzing. In this study the magnitude scale used was MW. Moment magnitude is an earthquake magnitude that is consistent to indicate the magnitude of earthquake strength [13]. The conversion used refers to the correlation of several magnitudes for the Indonesian region based on Table 1 [12].

| No | Correlation Conversion | Range Mag |
|----|------------------------|-----------|
| 1  | Mw = 1.0107mb + 0.0801  | 3.7 ≤ mb ≤ 8.2 |
| 2  | Mw = 0.6016ML + 2.476   | 2.8 ≤ ML ≤ 6.1 |
| 3  | Mw = 0.9239MS + 0.5671   | 6.2 ≤ MS ≤ 8.7 |

ML into Mw is not done because the plot results show almost comparable results between the two and it is considered that the local magnitude (ML) can represent the moment magnitude (Mw).

3.3. Declustering
Declustering is a process of separation between the main earthquake (mainshock) from follow-up earthquakes or aftershocks (foreshock and aftershock). An empirical criterion for identifying major
earthquake events is based on a certain time span and distance from one large earthquake event [10]. This paper used empirical criteria proposed by Gardner and Knopoff (1974) and MatLab software with ZMAP for the separation process.

3.4. Input Parameters and Determination of Parameters a and b-values
The input parameters used for identification and modeling of earthquake sources and their mechanisms include location, dimensions, type of earthquake source mechanism and activity level based on earthquake data from catalogs and previous studies [14]. This study used three earthquake source models namely: a) background earthquake source, b) earthquake source fault, and c) subduction earthquake source. The source of the earthquake originated from the BMKG, ISC, ISC-EHB and USGS earthquake catalogs at an area of \(0.1^\circ \times 0.1^\circ\) or equivalent to 1 km in the study area.

The area was used is based on a 500 km radius from the Bengkulu province boundary with the following limitations of source zone modelling:
1. The distance of the research area reviewed is limited to a radius of up to 500 km.
2. The depth of the earthquake source used is limited to 300 km.
3. The attenuation function for each earthquake source model is considered to be in accordance with the seismic characterization and earthquake source model in the Indonesian region.

Furthermore, for the calculation of \(a\) and \(b\)-values carried out in the Gutenberg-Richter magnitude distribution model by taking historical earthquake data in the background earthquake source area, then a statistical analysis was performed with the maximum likelihood model. To determine the values of \(a\) and \(b\)-values from each earthquake source model estimated with the help of MatLab with ZMAP.

3.5. Determination of Function of Attenuation & Logic-Tree
In general, the attenuation function model is divided into three categories [15]: (1) attenuation models that are derived in subduction zones, (2) attenuation models that are derived in the fault transform zones and (3) attenuation models are derived only based on the boundary depth of earthquake focus.

In this paper, the attenuation function used is classified based on the earthquake source mechanism which is divided into several classifications. The classification used was the background earthquake source zone (which consists of shallow background earthquake source zone, deep1 background, deep2 background, deep3 background and deep4 background), earthquake source zone fault and subduction zone source zone.

The logic tree model is a nodal series (node) represented as a point which specific models and branches represent different models specified at each node. Addition value of the probability of all branches that are connected to one particular node would be equal to one [5]. Hence, Logic-Tree was used to overcome parameter uncertainty in the calculation of seismic hazard analysis. The approach using logic tree makes it possible to choose several alternative methods or models by determining a weighting factor that describes the percentage of possible relative accuracy of a model against others.

3.6. Determination of Maximum Ground Surface Acceleration Value
Maximum ground velocity acceleration value was determined with the help of USGS-PSHA software. And seismic hazard analysis was modeled for each earthquake source due to the influence of background earthquakes, faults or subduction.

In the general form, the PSHA method can be stated in Equation

\[
P_X(x) = \int \int P(X > x | m, r) f_M(m) f_R(r) dr dm
\]

The PSHA method assumes that the magnitude of earthquakes M and distance R are continuous and independent random variables [16].

The final result of this seismic hazard analysis is the maximum ground vibration acceleration map in bedrock for the study area with probability exceeding 10% and 2% in 50 years of building plan age (earthquake return period of 475 years and 2475 years) using grid spaces \(0.1^\circ \times 0.1^\circ\) or equal to 1 km at the real location.
4. Results and Discussion

The center of the research area was printed in Bengkulu Province with geographical coordinates 5.4° - 2.0° SL and 100.4° - 104° EL. To obtain the maximum ground vibration acceleration of the area center, an area of ~ 500 km is used at the geographical coordinates of 2.53° - 7.58° SL and 96.1° - 106.1° EL with a magnitude scale of ≥ 4.5 at 300 km earthquake depth.

![Bengkulu Seismicity Map From 1900 Until 2017](image)

**Figure 2.** Map of the Seismicity of the Research Area

The result shows that along the Sumatra fault there is a high seismic activity that can be divided according to three depth classifications, namely at depths less than 93 km, 186 km and 310 km. Many earthquake activities occur in depths of less than 93 km indicating that many earthquakes occurred are dominated as shallow earthquakes.

Furthermore, the existing earthquake data was declustered using Zmap software. In the decluster method used an empirical criterion proposed by Gardner and Knopoff. This criterion is used because it is in accordance with the geological and topographic conditions of study area.
The result of decluster shows that the seismic activity change from lot becomes less. This is caused by the provision or grouping of seismic activities that occur due to foreshock and aftershock earthquakes. Foreshock and aftershock earthquake will be set aside so that the earthquake data in the form of main earthquake data (mainshock).
Figure 4. The Seismicity Map (background) of the Research Area

After declustering, it will generate background earthquake data. Then \( a \)-value and \( b \)-value was calculated using Earthquake background data. The results shows that \( a \)-value of a (annual) in the background earthquake is 4.15 and \( b \)-value is 0.722 +/- 0.04 with the value of Magnitude Completeness 5.1.

Figure 5. Magnitude of Completeness
Based on the results, the maximum ground velocity acceleration values in the bedrock are influenced by background earthquake source, fault or fault source, subduction earthquake source and combination source (all earthquake sources) in the study area with a probability exceeding 10% and 2% in the 50 year old building plan in the study area. The maximum ground vibration acceleration value caused by the influence of each earthquake source will contribute to the maximum value of ground vibration acceleration in the area. The maximum vibration acceleration value will be large if the earthquake source distance is close and vice versa.

**PGA Map For Probabilistic 10% in 50 Years**

**Bengkulu Province**

The magnitude of the ground vibration acceleration value represents the level of the acceleration of the ground in the bedrock. The results of the analysis using the PSHA method show the Probabilistic Peak Ground Acceleration (PGA) value Exceeding 10% in 50 years in bedrock for Bengkulu Province has a value between 0.24 gal to 0.86 gal. The areas included in the red zone or danger are Lebong, Rejang Lebong, Kepahiang, Mukomuko, North Bengkulu and Bengkulu City. While the areas included in the medium zone are Bengkulu Tengah and Seluma. For those included in the category of safe zones are parts of the South Bengkulu area and most of the Kaur area.

The magnitude of the value of ground vibration acceleration in the bedrock for the red zone or the danger caused by the area being traversed by the number of Sumatran faults namely the Dikit, Ketaun,
Musi and Manna segments. Whereas in the Mukomuko and North Bengkulu regions it is effected by the Sumatra Mentawai segment faults.

**PGA Map For Probabilistic 2% in 50 Years**

Bengkulu Province

![ PGA Map For Probabilistic 2% in 50 Years](image)

**Figure 7.** Probabilistic PGA Map Exceeds 2%

The results of the analysis using the PSHA method show the Probabilistic Peak Ground Acceleration (PGA) value over 2% in 50 years in bedrock for Bengkulu Province has a value between 0.36 gal to 1.35 gal. The areas included in the red zone or danger are Lebong, Rejang Lebong, Kepahiang, Mukomuko, some from North Bengkulu, Bengkulu City and part of the South Bengkulu area. Whereas the regions included in the medium zone are from North Bengkulu, Bengkulu Tengah and Seluma. For those included in the category of safe zones are parts of the South Bengkulu area and most of the Kaur area.

The magnitude of ground vibration acceleration in the bedrock for the red zone or danger is still influenced by the number of Sumatran faults that resemble the area, namely the Dikit, Ketaun, Musi and Manna segments. Whereas some of the Mukomuko and North Bengkulu regions are effected by the Mentawai segment of Sumatra, the rests are effected by the Dikit, Ketaun, Musi and Manna segments.

### 5. Conclusion

- The Probabilistic Peak Ground Acceleration (PGA) value Exceeds 10% in 50 years in bedrock for Bengkulu Province has a value between 0.24 gal to 0.86 gal.
- Probabilistic Peak Ground Acceleration (PGA) value Exceeded 2% in 50 years in bedrock for Bengkulu Province has a value of 0.36 gal to 1.35 gal.
- Most of the red or hazard zones are Lebong, Rejang Lebong, Kepahiang, Mukomuko, North Bengkulu and Bengkulu City.
- The amount of PGA value for Bengkulu province is influenced by the Sumatra fault.
The segment of the Sumatran fault through the province of Bengkulu is the Dikit, Ketaun, Musi and Manna segments.

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