Seismic Hazard characterization study using an earthquake source with Probabilistic Seismic Hazard Analysis (PSHA) method in the Northern of Sumatra

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Abstract
Sumatra region is one of the earthquake-prone areas in Indonesia because it lies on an active tectonic zone. In 2004 there was an earthquake with a moment magnitude of 9.2 located on the coast with the distance 160 km in the west of Nanggroe Aceh Darussalam and triggered a tsunami. These events took a lot of casualties and material losses, especially in the Province of Nanggroe Aceh Darussalam and North Sumatra. To minimize the impact of the earthquake disaster, a fundamental assessment of the earthquake hazard in the region is needed.

Stages of research include the study of literature, collection and processing of seismic data, seismic source characterization and analysis of earthquake hazard by probabilistic methods (PSHA) used earthquake catalog from 1907 through 2014. The earthquake hazard represented by the value of Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) in the period of 0.2 and 1 second on bedrock that is presented in the form of a map with a return period of 2475 years and the earthquake hazard curves for the city of Medan and Banda Aceh.

1. Introduction
Indonesia has a complex and tectonic conditions because it lies on three tectonic plates, including the Indo-Australia plate moves relative to the North, the Eurasian plate is relatively moved to the South and the Pacific plate moves relative to the West. Movements and meetings between the plates forming the collision and causing subduction zones contained in several regions in Indonesia [1]

![Figure 1: Map of tectonic Indonesia [1]](image-url)

With this tectonic system, Indonesia is a disaster-prone areas because of potential earthquakes particularly in the northern part of Sumatra. In 2004 there was an earthquake with a moment magnitude of 9.2 scale, centered offshore at 160 km in West of Nanggroe Aceh Darussalam and triggered a tsunami [2]. These events took a lot of casualties and material losses, especially in the Province of Nanggroe Aceh Darussalam and North Sumatra. Associated with tectonic conditions in Sumatra that is so active...
and causing earthquakes that have a damage in material or fatalities. Therefore it is necessary to carried out an assessment of the potential regional earthquake with earthquake hazard analysis which can be used as a basis of reference mitigation and planning earthquake-resistant buildings in the research area.

The purpose of the implementation of this research is to gain an earthquake hazard that may occur in the research area based on seismic source characterization by PSHA method. While The purpose of the study is:

1. Make a seismic hazard map (seismic hazard) which is described by the value of vibration acceleration in the bedrock at the 2475 year return period earthquake in research area using PSHA method.
2. Make probabilistic curve hazard in Banda Aceh and Medan in order to determine the contribution of the source of the earthquake hazard affecting.

2. Basic Theory

Sumatra subduction zone spread from the northern part of the Sunda Strait to the Andaman Sea. Sumatran subduction zone in the segments affected by the meeting of the Indo-Australian Plate and Plate Micro Burma as part of the Eurasian plate. The Eurasian plate subduction urges under the Indian Ocean to the northwest of Sumatra to the north of Java by varying the speed of movement. The second direction of the plate subduction path forming an acute angle thereby creating a fault zone on the island of Sumatra, which is dominated by horizontal fault. Sumatra fault line or fault stretches along 1,900 km stretching from Aceh to the Sunda Strait (Figure 2). The fracture splitting into two parts of Sumatra island stretching. Sumatra fault is divided into segments amounted to 19 sections with a length of each segment ranges from 60 to 200 kilometers. The segments fault Sumatra is a segment of the Sunda, Segment Semangko, segment Kumering, segments, Manna, segment Musi, segment Ketaun, Segment Dikit, Segment Siulak, segment Sulii, segment Semani, segment Sianok, Segment Barumun, segment Angkola, segment Toru, segment Renun, Tripa segment, segment segment Seulimeum Aceh and [3].

![Figure 2 Map tectonic Sumatra Island [3]](image_url)

3. Method

3.1. Data collection

This study use compile catalog of institutions domestically and internationally, such as the Badan Meteorologi Klimatologi dan Geofisika (BMKG), Engdahl van der hilst and Bulland (EHB) Bulletin, and United States Geological Survey (USGS) from 1907 to 2014 with a maximum depth 300 km by 700 km radius of the outermost point of the study area. In addition the data used focal mechanism of the International seismological Center (ISC).
3.2. Earthquake Data Processing
Magnitude in the catalog that are used are not uniform, then the magnitude is converted to a moment magnitude (Mw) by using empirical correlation by [4]. To calculate the $b$-value and rate recurrence mainshock only the data that is used, so the earthquake followup (foreshock and aftershock) is removed using a program Zmap [5] with the criteria Gardner & Knopoff (1974). Analysis completeness of data [6] is used to remove the data mainshock incomplete. Mainshock at intervals of $5-6$ Mw complete during the interval of the last 51 years, the magnitude of Mw $6-7$ complete during the last 51 years and the magnitude of more than 7 Mw complete over 107 year.

3.3. Earthquake Source Modeling
In this study the seismic source model used is the subduction zone and shallow crust. Characterization model is based on the seismotectonic conditions, regional geology and spatial data. For subduction zone, it is using three-dimensional models. Model subduction zone is divided into two mechanisms: megathrust with a depth of $0-50$ km and Benioff at a depth of $50-300$ km. For geometry modeling megathrust zones and using catalogs Benioff EHB bulletin for this catalog has been relocated. Do manufacture cross section as a basis for making seismic data to generate profiles hypocenter (Figure 4)

![Figure 4. Cross section for geometry modeling of subduction](image)

The hypocenter profile then overlaid with tomogram created from the data of the P wave velocity deviation ($DVP$) extracted from LLNL-G3Dv3 [7] to generated cross sections as shown in Figure 5. While the interpretation of the geometry of the subduction zone re shown in Figure 6. Referring to the research by [4] subduction zones used in the study were divided into three segments.
For *shallow* crustal *earthquake* source is divided into two: the source of the earthquake source seismic faults that are modeled in 3-dimensions and for a zone that contained the seismic activity but have not yet identified the source accommodated with *shallow* earthquake source *background* is modeled two-dimensional or *area source*.

For fault earthquake source models it is used data from the research results by [4] and then in the re-use map SRTM90m *trace*. Used as many as 14 segments of the fault in this study. Visualize the source of the earthquake fault is shown in Figure 7.

![Figure 7](image)

**Figure 5** Hypocenter and tomogram Sectional profile extracted from LLNL-Earth3D [7]

*Background shallow* earthquake data with seismic source area is modeled after *the focal mechanism* of ISC is used as a weighting on the basis of the mechanism of the earthquake that will be used for the analysis of *seismic hazard*. The weighting value given to the mechanism of earthquake dominant in these areas. While the area is not accommodated *focal mechanism*, given the weighting of 0.4 for the *reverse-slip* mechanism, *strike-slip* to 0.4 and 0.2 for *normal-slip* mechanism.
Figure 6. Results of the interpretation of the geometry of subduction

Figure 7. Map of the fault segment that is used in research

Figure 8. Model shallow earthquake source background
3.3. b-value and rate Earthquake
Analysis of seismic hazard parameters required recurrence relationship that is b-value and the rate of earthquake. Determination of these parameters obtained from seismic data clustering by source and type of mechanism is then used two methods, they are Least Square [8] and Maximum likelihood [9]. From both methods obtained the value of a and b-value which is used to search earthquake rate for each source.

![Image of recurrence relationship curves]

**Figure 9.** Curve recurrence relationship each seismic source

3.4. Maximum magnitude, Slip-rate and Attenuation Function
The maximum magnitude of the earthquake as well as slip-rate subduction earthquake sources megathrust and fault using the research results of [4]. The magnitude of the earthquake fault is determined by an empirical formula by [10]:

\[ M_{\text{max}} = 5.08 + \log L 1.16 \]  

with:
- \( M_{\text{max}} \): maximum magnitude that can occur (M)
- \( L \): Long fault segment (km)

| Source quake          | Function attenuation                  |
|-----------------------|---------------------------------------|
| megathrust            | Youngs et al (1997)                   |
|                       | Zhao et al (2006)                     |
|                       | Atkinson-Boore, *Worldwide* (2003)    |
| Benioff               | Atkinson-Boore, *Worldwide* (2003)    |
|                       | Atkinson-Boore, Cascadia (2003)       |
| Fault & shallow       | Youngs et al (1997)                   |
| background            | Campbell-Bozorgnia, NGA (2008)       |
|                       | Boore-Atkinson, NGA (2008)            |
|                       | Chiou -Youngs, NGA (2008)             |
Because there is no attenuation function is derived specifically for the Indonesian region then used the attenuation function is derived for other regions as well as worldwide. Selection is based on the attenuation function similarity of geological and tectonic conditions of the area where the attenuation function is made.

3.5. Logic Tree

The processing using logic tree in PSHA to solve uncertainty parameter values that used during the seismic hazard analysis. Using logic tree provide a more appropriate framework to in this method. So the logic tree models applied to four seismic source model that has been created. Examples logic tree used in this study looked at Figure 10.

![Figure 10. Logic tree to the earthquake source fault](image)

3.6. Seismic Hazard Analysis

After obtained the parameters of the previous stage then seismic hazard analysis using EZ-Frisk program 7:52 to obtain parameters such as acceleration PGA and SA in the period spectra 0.2 and 1 second. Grid used is 0.1 ° x0.1 ° to a radius of about 50 km of the fault zone and 0.5 ° x0.5 ° outside the zone. The results of seismic acceleration at each grid was mapped using ArcGIS 9.3 program to obtain a map of seismic hazard in the northern part of Sumatra at 2475 year return period earthquake. Hazard analysis carried out on the layer of bedrock S to the value of the S wave velocity (Vs30) at 750 m/s.

4. Results and discussion

The results of the analysis of seismic hazard in this study is the acceleration of earthquake hazard maps for the bedrock in northern Sumatra region covering the provinces of Nanggroe Aceh Darussalam and North Sumatra on condition PGA, SA 0.2 second and 1 second at 2475-year return period earthquake. The visualization can be seen in Figure 11 to Figure 13. As well as hazard curves for Banda Aceh and Medan can be seen in Figure 14 and Figure 19.
PGA in the bedrock value for the period 2475 earthquake in northern Sumatra region ranged from 0.15 to 1.3g. High acceleration values found on islands and coastal areas in the southwest and around the fault segment. From the pattern contour, *megathrust* and faults are the dominant source of the earthquake in the region.

Figure 12. Map of hazard conditions SA 0.2 seconds in the bedrock over a period of 2475 years of northern Sumatra region

Value SA 0.2 seconds in bedrock for 2475 year return period earthquake in northern Sumatra region ranged from 0.35 to 2.8 g. Contour pattern looks the same as the map of the PGA, but the value of the acceleration in 0.2 seconds SA is much higher than the PGA.

Figure 13. Map of hazard conditions SA 1 second in the bedrock over a period of 2475 years of northern Sumatra region.
Value SA 1 second on the bedrock for the 2475 year return period earthquake in northern Sumatra region ranging from 0.3 to 1.3g. In this period of acceleration values decreased significantly compared to the period of 0.2 seconds, especially in the southwest region. SA 0.2 seconds has an estimated as the highest acceleration of bedrock has relatively low natural vibrating period of less than or equal to 0.2 seconds so the response at this site tend to be younger, especially in areas that close to the earthquake source. So the content of the frequency of earthquakes at close distance is still dominant with a high frequency that makes the response of the medium with a low natural frequency or short to a maximum.

**Figure 14.** Curve hazard conditions in the bedrock PGA Banda Aceh

**Figure 15.** curve SA 0.2 seconds hazard conditions in the bedrock Banda Aceh

**Figure 16.** Curve hazard conditions SA 1 second on the bedrock of Banda Aceh

Based on the hazard curves for the city of Banda Aceh, the dominant source of the earthquake fault segment is *megathrust* in Aceh and Andaman segment. Both of these sources provide significant hazard than other seismic sources.
Based on the hazard curves for the city of Medan, the dominant source is megathrust earthquake in Nias segment. It is estimated that resources megathrust earthquake magnitude and the maximum length of the segment is relatively large so it still feels significant hazard at a considerable distance. This is also supported by the value of the slip-rate that makes a big earthquake return period to be faster.

5. Conclusion

Based on the results in the form of hazard maps by the tremor in the bedrocks, the value of PGA in northern Sumatra ranged from 0.15 to 1.3g, SA 0.2 seconds value ranges from 0.35 to 2.8 g and SA 1 sec ranging from 0.3 to 1.3g with the dominant source of the earthquake in the region and the megathrust fault.

Based on the hazard curve to Banda Aceh at 2475 year return period earthquake, equivalent to 0.0004 annual rate of exceedence, PGA value is from 0.68g, SA 0.2 seconds of 1.57g and 0.69g SA 1 second of the megathrust source. The dominant earthquake in Aceh and Andaman are the fault segments. As for the Banda Aceh and Medan the value of PGA is 0.29g, SA 0.2 seconds of 0.65g and 0.51g SA 1 second of the seismic source megathrust dominant segment of Nias.
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