Probabilistic seismic hazard map analysis for Aceh Tenggara district and microzonation for Kutacane city

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Abstract. The Aceh Tenggara (Southeast Aceh) District, especially Kutacane, is located along with the main GSF (Great Sumatra Fault) system and the Tripa segment in particular based on seismic hazard map of Indonesia 2017. Therefore, the seismic hazard map needs to be updated based on the recent seismotectonic information and the latest active fault investigations. This paper discusses the updated seismic hazard map for the Aceh Tenggara district. In seismic hazard calculation, input source definition including fault characteristics, subduction zone, and seismicity background. Ground Motion Prediction Equation (GMPE) is used by the Indonesian official seismic hazard map 2017 to compute the hazard curve of strong ground shaking. Probability exceeding 2% and 10% for 50 years is chosen to calculate PGA (Peak Ground Acceleration) map on bedrock. On the other hand, Kutacane is located on a younger alluvium basin in the Holocene epoch thus site sediment amplification effect is taken into account in the microzonation calculations (local scale). The geomorphological slope is used to estimate the Vs30 distribution map. The site amplification is calculated based on PGA value on bedrock and Vs30 value on each site location. The Probabilistic Seismic Hazard Analysis (PSHA) is applied to produce seismic hazard maps as also used since many scientists and engineers in Indonesia although for critical infrastructure Neo-Deterministic Seismic Hazard Analysis (NDSHA) is suggested to be applied. The newly updated seismic hazard map can be used for the reference of infrastructure development in order to reduce the risk of disaster.

1. Introduction

Aceh Tenggara is one of the districts in Aceh Province directly bordering with Tanah Karo district of North Sumatra. It is a region having the largest national conservation in Indonesia. This district occupies 4,165.63 km² and two-third of the area includes in Taman Nasional Leuser (TNGL). Spatially, most of this region is inhabitant, meaning that this region is not prone to earthquake damage. However, a large number of the population settled in the area of Plato Basin Qh (Quaternary Holocene) which is the Blangkejeren town as seen in figures 1a and 1b. The population density in the area is relatively higher with a population of 204,486 people based on statistics 2017 [1].
According to the geological map with the regional scale 1:250.000, Aceh Tenggara is included in the map of Medan sheet[2] and a part of it is in Tapaktuan sheet[3]. In figure 1, the rock formation of Aceh Tenggara is generally classified into Tapanuli group with the age of Paleozoic era, such as Kluet Formation (Puk) and Bahorok Formation (Pub) formed at Carboniferous period (purple color). Whereas, Alas
Formation (Ppa) and (Ppal) were formed at Permian period consisting of limestone and the younger formation is Alluvium (Qh) that was formed from clastic sediment in Cenozoic era, Neogene period and Holocene epoch. This formation composes of sediment layer filling fracture of pull-apart basin originated from Sumatra’s fault tectonic activity[4][5][6][7]. The Plato sediment or also known as Kutacane Graben is the main area settled by Aceh Tenggara District’s population.

Aceh Tenggara is the region crossed by the Great Sumatran Fault (GSF). As seen in figure 1b, GSF lies on the east side of Kutacane Graben especially Tripa segment 3 based on PuSGeN nomenclature book[8][9][10][11][12][13]. At figure 2a, it can be seen that in the northern part, Aceh Tenggara district is controlled by Tripa fault 2, Tripa 4 and Tripa 5, whereas in the southern part influenced by Renun-A and Renun-C Fault. The subduction earthquake is highly triggered by Aceh-Andaman segment and Nias segment as pointed in figure 2b. These faults are very well recognized and documented in the book of map source and earthquake hazard of Indonesia 2017 also well known the hypocenters distribution [8][14]. Nevertheless, there are still a number of faults unidentified so it needs to be studied more comprehensively. So then in this paper, we analyze the probabilistic seismic hazard map for Aceh Tenggara District and the Microzonation for Kutacane town. This work is an initial study in order to map potential hazards from locally seismic activity. This work is also the answer to the demand for seismic hazards map discussed on October 15th, 2019 in Banda Aceh where the authors participated as representatives from Aceh province and districts.

2. Methodology

Earthquake hazard assessment is an important step in predicting the potential strong ground motion in the future. Earthquakes do not kill and hurt, but earthquake-prone buildings are the ones that kill and injure humans. So that even though the complex phenomenon of earthquakes in the under earth is difficult to understand, we continue to do our best to define the level of earthquake hazard in a place by compiling existing knowledge and accommodating uncertainty in the form of statistical probabilistic analysis, so the method name is called PSHA (Probabilistic Seismic Hazard Analysis)[15][16].

In Figure 3, a block diagram of the PSHA study is shown both in the regional scale of the Aceh Tenggara Regency and the local scale (microzonation) of Kutacane. This research conducted an updated source definition that was also assisted by geomorphology study data and earthquake relocation[17][18]. PSHA calculations (shaking in bedrock) using software developed by USGS and also used by the National Earthquake Study Center (PuSGeN) team [8].

The software uses three earthquake source models with different algorithms and programs to run subduction sources, fault sources, and background sources are sorted by the complexity of the input data. Each source has different characteristics for each a-b parameter, maximum magnitude, slip rate, and attenuation function. Determination of these parameters including the logic tree requires long experience and discussion as done by PuSGeN. Therefore, some of these parameters in this calculation use the input data used by PuSGeN.

Simply, the PSHA calculation process is shown in Figure 4a. Step 1 determines the source of the earthquake. Step 2 is the determination of earthquake recurrence which usually uses the Gutenberg and Richter [19] relationship in the form of magnitude and frequency correlation $\log_{10}(N) = a-bM$ by determining the parameters a and b through statistical regression. Step 3 is to determine the strong ground motion parameter or Peak Ground Acceleration (PGA) for a certain magnitude based on empirical GMPE (Ground Motion Prediction Equation)[20][21].

Because the determination of strong ground motion values is obtained statistically, there will be many attenuation equations according to the data and equations used. Besides using GMPE, a more thorough way is to do a realistic synthetics seismogram[22][23][24] as used in the NDSHA method[25][9][26][27]. In step 3, the PGA value is in the form of probabilities from many earthquake sources which can then be expressed in terms of the hazard curve which is step 4 in Figure 4a. In Figure 4b a hazard curve is shown for the sum of all earthquake sources with one observation point 3.5N, 97.8E. To draw a map, many observation points are needed, so one probability value of Mean Annual Frequency of Exceedance must be chosen for all points to form a map in figures 5, 6, 7, 8, and 9. In most cases, 2% and 10% exceedance within 50 years are chosen. The two probabilities of exceedance are used to map the PGA in this paper.
The definition of 2% probability that is over 50 years is related to 2,475 years return period. This value is obtained by assuming the occurrence of exceedance of an acceleration of the land through a Poisson process \( P = 1 - \exp(-\gamma t) \) where the frequency \( \gamma \) of occurrence that is can be written in the equation

\[
\gamma = -\ln\left(1 - \frac{P}{10^2}\right) = -\ln\left(1 - \frac{2\%}{100}\right) = 4.0405 \cdot 10^4
\]

(1)

The frequency is related to the return period during \( T = \frac{1}{\gamma} = \frac{1}{4.0405 \cdot 10^4} = 2474.9 \approx 2475\text{years} \)

(2)

whereas the return period \( T = 475 \) is related to the frequency value of 2.1072e-3 or 10%, which is likely to be exceeded for 50 years.

Initially, PGA are calculated on bedrock that does not consider amplification effects. Empirically amplification can be related to the average shear wave velocity up to 30 m. In the Shakemap version 3.5 program[28], the amplification calculation simply follows the steps developed by Borcherdt [29] whose dynamic amplification factor depends on the value of the strong ground motion intensity that occurs in bedrock I (g) that meets equation 1. For example, if the intensity value of strong ground motion I (g) 0.2 g, the value of \( m_a \) according to table 1. is 0.25, and the amplification factor:

\[
F_a = \left(\frac{v}{v_s}\right)^{m_a} = \left(\frac{686}{v_{30}}\right)^{0.25}.
\]

(3)

**Table 1.** Relationship between strong ground motion intensity (g) and \( m_a \) parameters [31]
Input Ground Motion I(g) | 0.1 | 0.2 | 0.4 | 0.5
---|---|---|---|---
Parameter m_a | 0.35 | 0.25 | 0.10 | -0.05

Calculation of the amplification factor can be approached using the average shear wave velocity at a depth of 30 m or Vs30. The direct measurement method in the field is to use a seismic method to determine the velocity such as the microtremor[30], MASW, SPAC, and HVSR methods. But for a large spatial area, this is not reliable so that it can be estimated with a geomorphological gradient. Direct seismic measurement data can be compiled with estimation results, but it has not been discussed in this paper.

![Figure 4](image1.png)

**Figure 4.** (a) PSHA calculation steps, modified[31] (b) Hazard curve for Kutacane for all sources.

### 3. Results and Discussion

In this study, the maps of PGA values on bedrock are displayed for the probabilities values exceeded 10% and 2% in 50 years that related to the earthquake design levels are rare (475 years) and very rare (2475 years) respectively in choosing the performance objectives of a building. All PGA maps produced are made in pairs for both possibilities to be exceeded.

Furthermore, accessing for the input data of the PSHA maps calculation will give us control to modify and increase the resolution for the district scale instead of using the resolution for national map scale. For preliminary microzonation studies, the use of geomorphological slope is sufficient to estimate the distribution of Vs30. The amplification calculation results clearly show that the relatively more densely populated areas in Graben Kutacane PGA values can reach 0.9g and 1.5g for 10% and 2% are likely to be exceeded for 50 years with an increased ratio reaching 1.6 times.
Figure 5. The PGA values distribution of Aceh Tenggara Regency from each earthquake source such as subduction, faults, and background for 10% (rare) and 2% (very rare) are likely to be over 50 years.

Figure 5 shows the spread of Aceh Tenggara Regency PGA values from the source of subduction, faults, and background (sequentially from left to right images) for 10% (top picture) and 2% (bottom picture) likely to exceed for 50 years. Figure 5a and 5b show the distribution of PGA values from earthquake source subduction. The distribution has a contour that is relatively parallel to the Sunda trench arc where the source of the earthquake is sourced from the southwest side of the Aceh Tenggara district. The maximum PGA contribution is around 0.3g and 0.5g for rare and very rare hazard levels. Figures 5c and 5d show the distribution of PGA values from fault mechanism earthquake sources originating from the Sumatran fault[32]. The high PGA value is distributed along the Sumatran fault line. Whereas the earthquake source background in Figures 5e and 5f has a relatively uniform spatial distribution in the Aceh Tenggara district. This indicates that all the earthquake mechanisms at that location are associated with subduction mechanism faults.

To produce a seismic hazard map, the whole mechanism of the earthquake sources that combined with the weighting of the logic tree has been determined. Figures 6a and 6b show the PGA distribution map, respectively. In Figure 6a for 10% over 50 years, it has a maximum PGA value of 0.7g, and figure 6b has a maximum PGA value of 1.5g for 2% exceeded. The maximum value of PGA in this study is comparable with the maximum value of PGA which is produced by PuSGeN 2017 as shown in Figures 7a and 7b. In figures 6a and 6b, the PSHA analysis was carried out with a grid resolution of 0.025 degrees which was higher resolution than that produced by PuSGeN 2017 with a resolution of 0.1 degrees. The results of the calculations appear to be more thorough and the 1.5g PGA value obtained follows the Sumatran fault, while the 2017 PuSGeN results do not continue following the Sumatran fault.
Figure 6. The PGA values distribution of Aceh Tenggara Regency from the total of earthquake source for (a) 10% (b) 2% are likely to be over 50 years.

Figure 7. Aceh Tenggara PGA value from the final PuSGeN 2017 calculation of PGA probability exceeded 2% and 10% for 50 years.

All of the above PGA calculations are carried out on bedrock, while most of the population in the Kutacane Graben stand in alluvium sedimentary basin. Therefore, the determination of the amplified PGA is essentially important. The PGA amplification study requires more detailed information so it is often called microzonation or also called a local scale. There are many ways to do microzonation, either by
simply determining site conditions such as determining Vs30 and determining amplification of strong ground motion[33]. Determination of Vs30 directly on-site requires logistics, design of measurement locations and correct data processing.

The determination of Vs30 on site has been done using the SPAC and HVSR methods but has not been discussed in this paper. The value of Vs30 is only estimated through the geomorphological gradient as is commonly used to calculate the effect of the application on the ShakeMap program[28]. Conversion algorithm from DEM to Vs30 data has been successfully applied to high resolution DEM such as DEMNAS[34]. In the algorithm, there are steps to produce a topographic gradient as shown in Figure 8a before finally producing the Vs30 map as shown in Figure 8b.

\[ \text{Conversion algorithm from DEM to Vs30 data has been successfully applied to high resolution DEM such as DEMNAS[34].} \]

![Figure 8. (a) The topological gradient (b) The Vs30 is estimated from the topological gradient.](image)

The actual amplification calculation is not simple, because it has to do seismic wave propagation modeling. However, practical approaches to simplify using empirical relationship such as equation 3 that have been applied to the shake map program used in this study. We use a Vs30 velocity model, as the function of acceleration value according to table 1 to obtain the amplification factor for ShakeMap, with value 686 m/s which estimated from the slope gradient as shown in figure 8b. The amplification factor is not constant but is a spatial function of Vs30 \((x,y)\) and the value of acceleration itself. The PGA resulting from the amplification is set to the same minimum limit as the PGA acceleration on the base rock. Figures 9a and 9b show the PGA values that have been amplified from soil conditions with Vs30 estimated in figure 8b.

In figures, 9a and 9b, an increase in PGA values of 10% and 2% has been exceeded in 50 years reaching a maximum value of 0.9g and 1.5g respectively. The magnitude of the increase in PGA value due to amplification is 0.4 as shown in Figure 10a with the ratio reaching 1.6 as shown in Figure 10b. From the map, it is seen that the dominant amplification occurs in the Kutacane Graben basin. For more detailed purposes on a local scale or also called microzonation.
Figure 9. Distribution of PGA values for Aceh Tenggara District which have been amplified from all earthquake sources for (a) 10% (b) 2%, likely to be over 50 years.

Figure 10. (a) Distribution of PGA anchoring values after amplification (b) PGA ratio after amplification and PGA in bedrock for 10% is likely to be exceeded for 50 years.

When the map is scaled up from the district scale to the local scale of Graben Kutacane, the PGA value variations can be seen in detail as shown in Figures 11a and 11b. The amplification factor is calculated based on Vs30 which is estimated from site topographic gradient[33]. Due to the sites topography fluctuation the results will show many small spots of high topographic gradient which should not be understood as high spots of Vs30 as shown in figure 11. It is a challenge to develop the sophisticate method for determination of Vs30 not only from site topography gradient but also involving variations
around it. The amplification map accuracy is substantial because it is the final product of PSHA that will be applied for performance based seismic design (PBSD).

![Amplified PGA maps for (a) 10% and (b) 2%](image)

**Figure 11.** Distribution of PGA values on the Kutacane graben local scale that has been amplified from all earthquake sources for (a) 10% (b) 2% is likely to be over 50 years.

For preliminary microzonation studies, the use of geomorphological slope is sufficient to estimate the distribution of Vs30. The amplification calculation results clearly show that the relatively more densely populated areas in Graben Kutacane PGA values can reach 0.9g and 1.5g for 10% and 2% are likely to be exceeded for 50 years with an increased ratio reaching 1.6 times. Strategic Local Seismic Assessment at the Regency level not only gives them access to the maps produced but also understands how the mapping process is produced. So the district government understands how PSHA is carried out and how to use the map. The PSHA method still depends on GMPE that is generally applicable so it still leaves inaccuracies. However, the NDSHA approach that does not use the GMPE approach, and conducts realistic seismic wave propagation can increase the magnitude of the earthquake hazard map produced[35]. Cooperation between the University and the Regency and Provincial Governments is a very appropriate matter in producing a more accurate earthquake hazard map.

4. Conclusions and Suggestion

The dominant PGA value from the Sumatran fault which located at the Kutacane Regency contributes to the Tripa segment, while the earthquake source from the subduction zone is relatively small. In this study, we have access to input data for calculating the PSHA so that it can be modified and increased in resolution for the district scale rather than using a national scale map. For preliminary microzonation studies, the use of geomorphological slope with high-resolution topography is sufficient to estimate the distribution of Vs30. The amplification calculation results clearly show that the relatively more densely populated areas in Graben Kutacane PGA values can reach 0.9g and 1.5g for 10% and 2% are likely to be exceeded for 50 years with an increased ratio reaching 1.6 times. We make a preliminary step to explain the strategic local seismic assessment with making comprehensive results at the Kutacane Regency. These results can be used to understand the seismic hazard level as the mitigation plan in there. In the future, the collaboration improvement between seismologists and the district government will make a well-understood about how PSHA is very important and how to use the map. Our method still depends on GMPE, but from the result which does not use GMPE conducts a realistic seismic wave propagation that can increase the magnitude of the earthquake hazard map produced. Cooperation between the University and the Regency and Provincial Governments is a very appropriate matter in producing a more accurate earthquake hazard map.
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