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Earthquake vulnerability mapping based on probabilistic seismic hazard analysis (PSHA) in the Nias Islands, Indonesia

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ABSTRACT

The Nias Islands are categorised as seismically active, making them susceptible to earthquakes. The Nias Islands region is situated on the ring of fire and a subduction line that experiences annual movement, which is the primary factor contributing to its susceptibility to earthquakes. The occurrence of earthquakes in the Nias Islands is supported by a documented record of 7,152 incidents with a magnitude strength more than 4 Mw from 1910 to 2022, indicating a 500-year return period. In order to assess the susceptibility of the Nias Islands region to earthquakes, a process called earthquake vulnerability mapping is conducted. This involves utilising the probabilistic seismic hazard analysis (PSHA) approach to calculate the peak ground acceleration value. The investigation commences with gathering seismic events within the study region from the IRIS and BMKG catalogues. The earthquake data was subsequently transformed from magnitude to M_w (magnitude moment), and then de-clustered to isolate the primary event from the entire dataset of earthquakes. First, the a-value and b-value are calculated in order to identify the background earthquake source. Then, PSHA processing is conducted to calculate the spectral acceleration value for each predefined grid. The processing findings indicate that the peak ground acceleration (PGA) value at time 0 s ranges from 0.05 – 1.2 g, the PGA value at time 0.2 s ranges from 1 – 1.2 g, and the PGA value at time 1 s ranges from 0.4 – 0.5 g.

Keywords: Earthquake; Nias Islands; PGA; PSHA

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INTRODUCTION

Indonesia is a country located in the meeting area of three large plates in the world, namely the Indo-Australian plate, the Pacific plate, and the Eurasian plate. The movement of the Eurasian plate and the Indo-Australian plate towards the north suppresses the movement of the relatively stationary Eurasian plate. The movement caused by these three plates will cause collisions that cause earthquakes in Indonesia [1]. This is proven by the record of 51,855 earthquakes occurring in Indonesia from 1907 to 2016 with a magnitude ≥ 4.5 magnitude moment (M_w) [2].

The Nias Islands region is one of the regions in Indonesia with a record of significant and destructive earthquakes. Zebua (2018) explains that the Nias Islands are one of a group of islands on the west coast of Sumatra which is located on the ring of fire along the junction between the Indo-Australian plate and the Eurasian plate. These geographical conditions caused the Nias Islands region to experience earthquakes [3].

The morphological conditions in the Nias Islands region also support the occurrence of earthquakes. Where the morphological conditions are dominated by hills, valleys, and coastal land. The rocks are pre-tertiary (sedimentary rocks and metamorphic rocks), tertiary (sedimentary rocks), and quaternary deposits (coastal alluvial, swamps, and rivers). if rocks of pre-tertiary and tertiary age experience quaternary deposits and weathering, they will be broken down, loose, not yet compact and will strengthen the effects of shocks which makes them prone to earthquakes. Apart from that, the morphology of hills covered with weathering rocks is prone to ground movement because it is triggered by large earthquake shocks and is also supported by high rainfall [4]. Meanwhile, the geological condition of the Nias Islands consists of several formations which can be seen in Figure 1, namely the Labuhanhiyu formation, Rapa-Rapa Formation, Alluvium, Hiligeho formation, Guunung Bala formation, Sipika formation, Bancuh Tanah Bala, Gunung Sitoli formation, Lelematua formation, and Gomo formation.

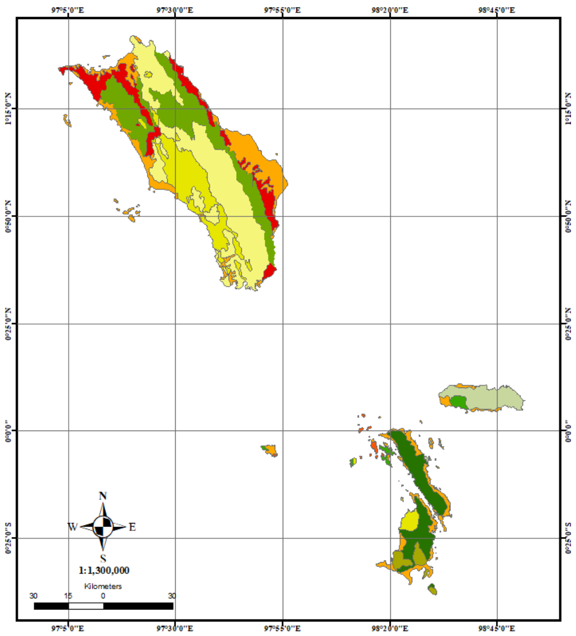

Figure 1. Geological map of the Nias Islands.

In historical records, Nias has experienced four earthquakes that were classified as destructive, in 1861 with a magnitude of 8.5 M_w, in 1907 with a magnitude of 7.4 M_w, in 2004 with a magnitude of 9.2 M_w, and in 2005 with a magnitude of 8.7 M_w. The last earthquake in 2005 claimed the lives of up to two thousand people and destroyed many buildings. Other impacts cause environmental damage, where the earth's surface is lifted and lowered by around one to three meters along the west coast of Nias, the southern and eastern parts of Simelue, and Banyak Island [1].

Natawidjaya (2007) has also explained that in the range of events the earthquake that occurred in 1861 had ruptured the same segment in 2005 [5]. The Nias segment last released its stored energy about 145 years ago. Thus, there is still the potential for earthquakes to occur in the area. One effort that can be made to anticipate and minimize the damage caused by earthquakes is by creating an earthquake vulnerability map which is made by analyzing the value of ground acceleration or peak ground acceleration (PGA).

The PGA value is expressed in g (gravitational acceleration = g) or m/s^2 (1 g= 9.81 m/s^2 or in gal where 1 gal is equal to 0.01 m/s^2, 1 g = 981 gal) [6]. The resulting PGA value shows the level of disaster risk that occurs and can be used as consideration for disaster mitigation, building structure design, and spatial planning in the Nias Islands [7].

Two methods can be used to obtain the PGA value, namely deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA). This research was carried out using the PSHA method which is a technique for analyzing earthquake events for a certain anniversary period by creating the possibility of various levels of ground movement in the research area. This method can also provide a clearer framework so that uncertainty factors can be calculated, identified, and combined with rational approach methods to get a more complete picture of earthquake events thousands of years into the future. This also depends on the completeness of the data in the form of maximum obstacles in the research area, earthquake data, and the natural period or frequency of earthquakes by considering how big the risk of an earthquake occurring. The disadvantage of this method is that many assumptions or uncertainties arise in carrying out the analysis so control or reference parameters are needed [8].

$$P[l \geq i] = \int_r \int_m P\,[l \geq i;\, m, r]\, f_m(m) f_r(r)\, dm\, dr \qquad (1)$$

RESEARCH METHODS

The research was conducted from May to July 2023 at the Class I Deli Serdang Climatology Station, Medan City. The research area is on the Nias Islands, North Sumatra Province with coordinates -2.984º – 2.994º N and 96º – 98.349º E.

Data processing in this research was assisted using Microsoft Word 2019, Microsoft Excel 2019, Visio, Notepad++, Matlab R2007b, Zmap v6, USGS_PSHA 2007, and ArcGIS 10.8 software. The data used in this research include seismic data for the Nias Islands from 1910 to 2022, a base map of Indonesia, a base map for the North Sumatra district, a base map for the North Sumatra sub-district, and data on the PGA and spectral acceleration (SA) values of the Nias Islands from 1910 to 2022 has been processed.

This research began by analyzing earthquake sources in the research area and collecting earthquake catalog data from the IRIS and BMKG catalogs. Earthquake data was collected from 1910 to 2022 at coordinates -2.984º – 2.994º N and 96º – 98.349º E and magnitude > 4 M_w. The catalog data is then converted to a magnitude scale for each scale value obtained in analyzing earthquake risk. This is done to standardize the data with a scale that has been established in Indonesia, namely the M_w scale [9]. Then de-clustering is carried out by separating the earthquake between foreshock and aftershock using time and distance criteria to get the main earthquake. De-clustering earthquake data using Zmap and Matlab software [10].

The data that has been de-clustered is then modeled according to the earthquake source by interpreting geological, geographic, and seismotectonic conditions based on secondary data resulting from earthquakes in the Nias Islands from 1910 to 2022. This earthquake source zone modeling will provide an overview of earthquake events, earthquake frequency, and the relative shift of plates. The earthquake source area is classified into three sources, namely fault earthquake sources, subduction earthquake sources, and background earthquake sources.

The final process carried out in the Zmap software is determining the a-value and b-value parameters and the attenuation function. Determine the a-value and b-value parameters used to predict the maximum earthquake value from the earthquake source. This parameter is determined using the maximum likelihood equation [11]. The attenuation function is based on the similarity of geological and tectonic conditions in a research area. Currently, the Indonesian region does not have data that can be used to derive the attenuation function, so data is needed from other regions that have similar geological and seismotectonic characteristics to the research area. The attenuation function will be adjusted to the earthquake source mechanism that has been modeled.

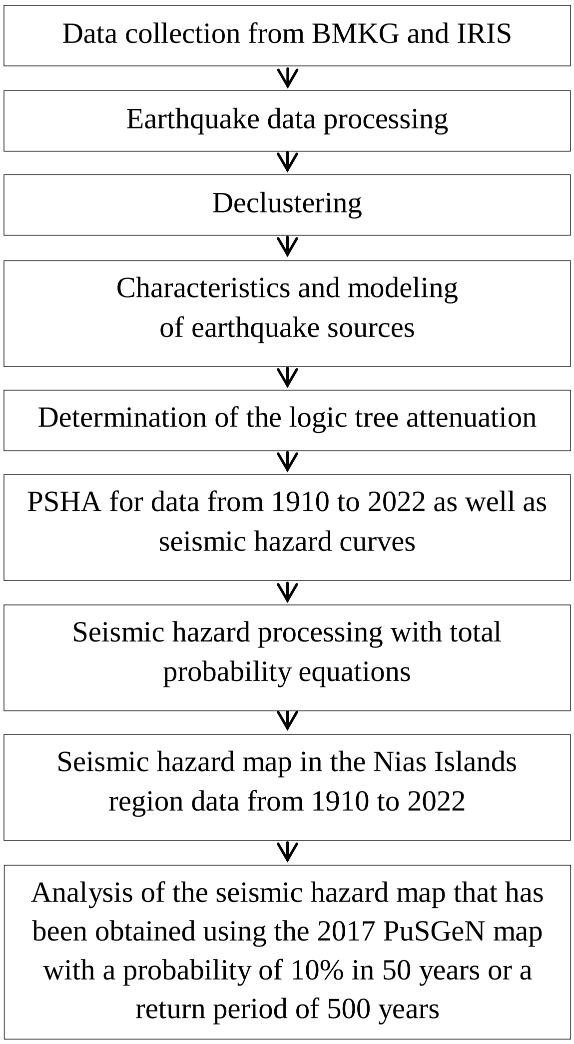

Figure 2. Flow diagram of research procedures.

The results obtained are then analyzed using the PSHA method with Equation (1). Processing earthquake data using this method will produce indicator values for vibration acceleration parameters in the bedrock (PGA and SA). This analysis was carried out with the help of USGS_PSHA software. The final result of the earthquake vulnerability analysis in this study is a map of the maximum earthquake acceleration in the bedrock for a probability of exceeding 10% in the 50-year earthquake return period of 500 years. This processing process can be seen in the research procedure flow diagram in Figure 2.

RESULTS AND DISCUSSION

The source of the earthquake in the Nias Islands area greatly influences the PGA and SA values. The earthquake source consists of three sources, namely fault earthquake sources, subduction earthquake sources, and background earthquake sources. Each of the earthquake source models will be combined and produce an earthquake vulnerability map. By entering the parameter values from the three earthquake sources, the seismic hazard distribution value for all earthquake sources is obtained. The probabilistic seismic hazard calculation is carried out on a probability of exceeding 10% within a 50-year earthquake return period of 500 years.

The results of this research are the values of maximum ground acceleration or PGA and the SA response in bedrock in short periods (T = 0.2 s) and long periods (T = 1 s) in bedrock. Where each acceleration period represents a period of structure vibration for each level. For example, in 0 seconds, it will have quite an influence on the vibration of the building foundation. Then 0.2 seconds will represent the shortest period of vibration of the structure, namely a two-story building. Meanwhile, for a long period of 1 second, it will represent the shock that occurs in a ten-story building. So, if the building stands in an area with a fairly high ground acceleration value at the surface and has a natural structural period that is the same as the earthquake period, then it is certain that there will be implications and resonances that cause the building to possibly experience shocks strong enough to cause damage to the building.

The range of PGA values obtained in the Nias Islands region will be classified into three ranges, namely low range (PGA < 0.05 g and PGA < 0.25 g), medium range (0.25 g < PGA < 0.7 g), and high range (PGA < 0.7 g and PGA > 1.2 g) which can be seen in Figure 3.

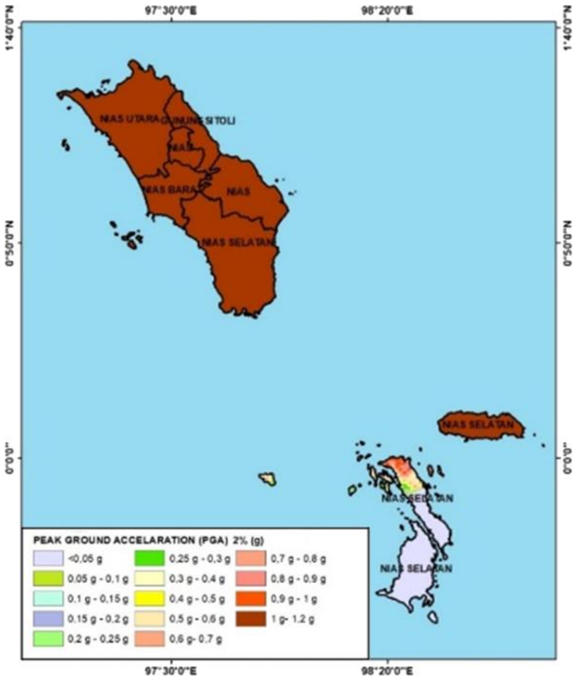

Figure 3. Map of ground acceleration values in bedrock (PGA) at spectral conditions T = 0 second for a probability of exceeding 10% in 50 years.

The PGA value in the South Nias Regency area has a PGA value that is classified as low to high. Meanwhile, Gunung Sitoli, North Nias, Nias, and West Nias regencies have a high range because the areas with relatively high PGA values are close to the Andaman-Sumatra and Nias subduction earthquake source route (megathrust).

The map of ground acceleration on bedrock in the period T = 0.2 seconds shows a range of ground acceleration values in the range of 1 – 1.2 g which is relatively high and covers the five districts of the Nias Islands, namely South Nias, Nias, West Nias, Gunung Sitoli, and North Nias (Figure 4).

Analysis of ground acceleration in bedrock for the period T = 1 s shows a range of ground acceleration values ranging from 0.4 – 0.5 g as shown in Figure 5. The T = 1 s spectral value in the five districts on the Nias Islands is in the medium range with yellow contours.

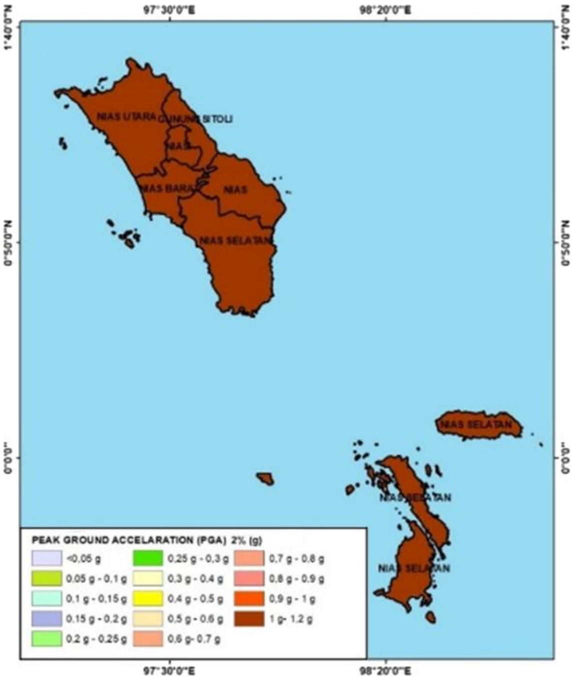

Figure 4. Map of ground acceleration values in bedrock at spectral conditions T = 0.2 s for a probability of exceeding 10% in 50 years.

Based on the results of the PSHA values obtained, almost the entire Nias Islands area is classified as moderate to dangerous damage due to the effects caused by the aftermath of the earthquake disaster. The values obtained by applying the PSHA method are by PSHA theory. PSHA theory states that the resulting PGA and SA values are influenced by the distance of the earthquake source. So the map projects a relatively high range of PGA and SA values along the subduction route (megathrust) Andamana-Sumatra and Nias.

As for this research, validation of the results of earthquake hazard mapping using the PSHA method was compared with the results of seismic hazard values with research that had been carried out in PuSGeN 2017, and it was found that there were differences. These differences include the PGA value in the period T = 0 s, the research results have a range of < 0.05 – 1.2 g, while the 2017 PuSGeN map has a range of < 0.7 g to > 0.8 g. Meanwhile, the SA value (T = 0.2 s) has a range of 1 – 1.2 g, while the 2017 PuSGeN map has a range of > 1.2 g. And likewise, the SA value (T = 1 s) has a range of 0.4 – 0.5 g in the research results, and 0.4 – 0.6 g in the 2017 PuSGeN map [12,13].

This difference in results is due to the earthquake catalog data source and different time ranges from PuSGeN 2017, fault and subduction earthquake source parameters are more widely used in PuSGeN 2017 because the research area covers a global scale. The data source and use of equations in the USGS_PSHA software in this study can also be the cause of differences in research results.

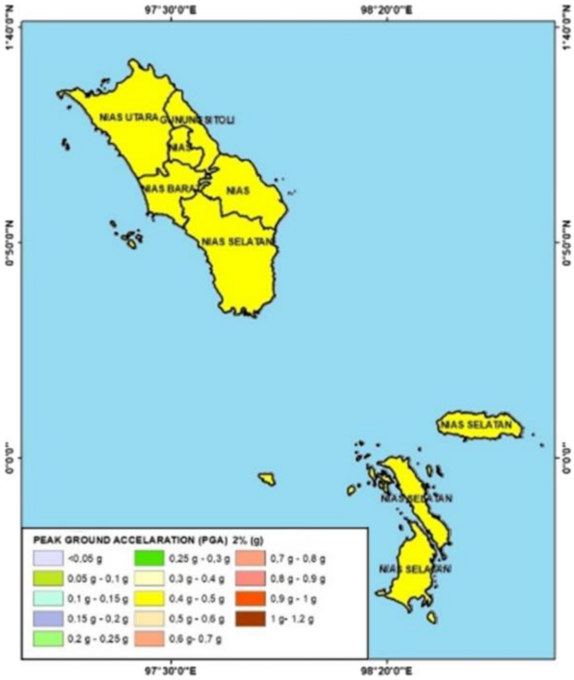

Figure 5. Map of ground acceleration values in bedrock at spectral conditions T = 1 s for a probability of exceeding 10% in 50 years.

Based on the overall results of the ground acceleration values in bedrock, this is an encouragement that the Nias Islands region is an area that is classified as vulnerable to earthquakes. This shows that the traces of earthquakes that occurred on the Nias Islands were quite significant and several earthquakes were recorded which caused quite serious damage. The subduction zone around the Nias Islands is the earthquake route that absorbs and releases the most earthquake energy. The subduction zone consists of Andamana-Sumatra and Nias. This is also supported by the environmental geology information map for the spatial plan (Intra Urban) for the Nias Islands region made by the Department of Energy and Mineral Resources, showing that the Nias

Islands region is dominated by areas with medium to high potential for ground movement and alongside roads. has a relatively high tsunami potential.

CONCLUSION

Based on the research that has been carried out and analyzed, several conclusions have been obtained, namely that the maximum ground acceleration value in the Nias Islands region from 1910 to 2022 has a PGA value with a relatively low to high classification with a value range of < 0.05 – 1.2 g, SA of T = 0.2 s with a relatively medium classification with a value range of 0.4 – 0.5 g, and SA of T = 1 s with a relatively high classification with a value range of 1 – 1.2 g

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