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Earthquake Hazard Mapping Based on Earthquake Intensity Model in North Maluku Islands

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ABSTRACT

Earthquake hazard mapping in the North Maluku region is urgent and essential because this area has a very high earthquake hazard potential. The high level of earthquake vulnerability in the North Maluku region makes it very important to focus mitigation activities to reduce the impact of earthquakes that occur. Earthquake hazard mapping that illustrates the effects of earthquakes on an area is one of the disaster mitigation efforts. In this study, earthquake intensity using the Probability Seismic Hazard Analysis (PSHA) method will be used to analyse the level of earthquake hazard in the North Maluku region. The results of the distribution of Peak Ground Acceleration (PGA) values for North Maluku range from 0.67 - 3.75 g. At the same time, the value of the MMI earthquake intensity scale is in the range of IX-XII. The most incredible earthquake intensity is in the Morotai, West Halmahera, Ternate, Tidore, Bacan, and Obi Island areas. The results of this study can have implications as a reference in safer spatial and infrastructure planning, the preparation of more effective mitigation strategies, and can be a medium for educating the public to be more prepared and responsive to earthquake risks.

Keywords: Intencity, Seismic, PGA, PSHA

ABSTRAK

Pemetaan bahaya gempa bumi di wilayah Maluku Utara sangat mendesak dan penting dilakukan karena wilayah ini memiliki potensi bahaya gempa bumi yang sangat tinggi. Tingginya tingkat kerentanan gempa bumi di wilayah Maluku Utara, maka sangat penting untuk memfokuskan kegiatan mitigasi untuk mengurangi dampak gempa bumi yang terjadi. Pemetaan bahaya gempabumi yang menggambarkan dampak gempabumi pada suatu wilayah merupakan salah satu upaya mitigasi bencana. Pada penelitian ini, intensitas gempabumi dengan menggunakan metode Probability Seismic Hazard Analysis (PSHA) akan digunakan untuk menganalisis tingkat bahaya gempabumi di wilayah Maluku Utara. Hasil sebaran nilai Peak Ground Acceleration (PGA) untuk wilayah Maluku Utara berkisar antara 0,67 - 3,75 g. Sementara itu, nilai skala intensitas gempa MMI berada pada kisaran IX-XII. Intensitas gempa yang paling besar berada di wilayah Morotai, Halmahera Barat, Ternate, Tidore, Bacan, dan Pulau Obi. Hasil penelitian ini dapat berimplikasi sebagai acuan dalam perencanaan tata ruang dan infrastruktur yang lebih aman, penyusunan strategi mitigasi yang lebih efektif, serta dapat menjadi media edukasi masyarakat agar lebih siap dan tanggap terhadap risiko gempa bumi.

Kata kunci: Intensitas, Seismik, PGA, PSHA

INTRODUCTION

North Maluku is an archipelago vulnerable to earthquake disasters as shown in figure 1. This is because North Maluku is located in the Pacific Ring of fire belt area, one of the most seismically active zones (Hamilton, 1979; Mccaffrey, 1988; Spakman & Hall, 2010; Pownal et al., 2013). The presence of microplates, fragments of the main plate trapped between convergent plates, is also responsible for the high level of complexity in the Moluccas Sea. The Moluccas Sea region is an example of ocean basin closure due to the collision of two arcs, Halmahera and Sangihe (Widiwijayanti et al., 2004). The Moluccas Sea is a complex of interactions between the Pacific, Philippine, Eurasian and Australian plates (Pusgen, 2022).

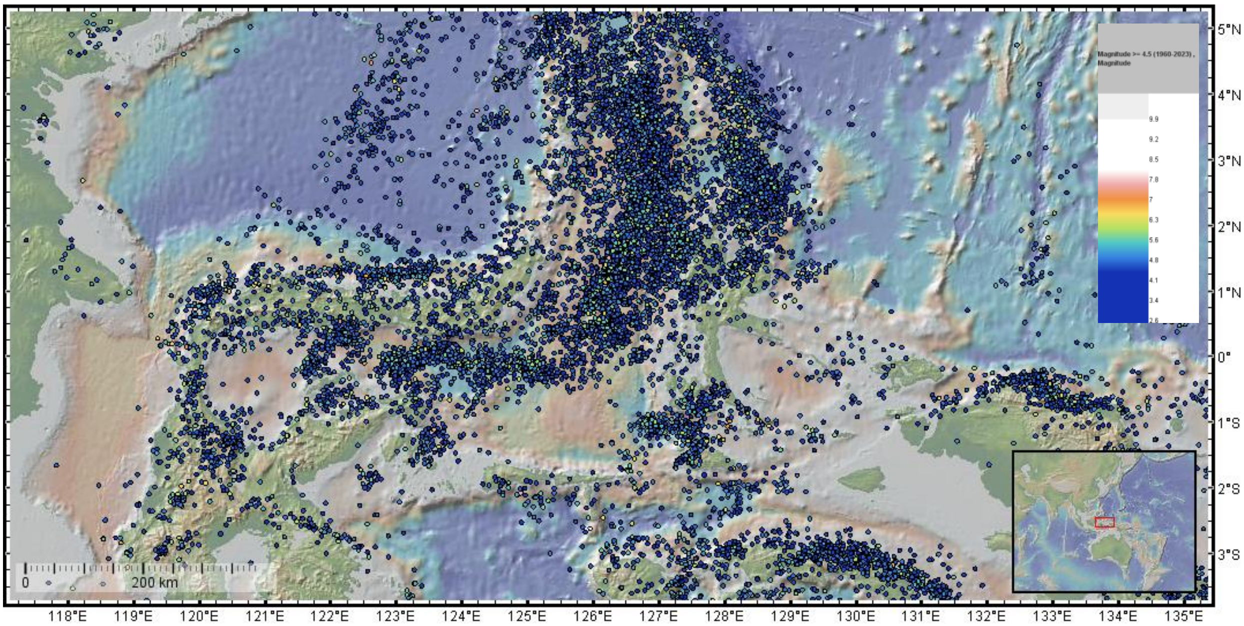

Figure 1. Seismicity map of North Maluku 1960-2023 from USGS-ANSS catalog

Based on the catalogue of earthquakes in the North Maluku region from 1855 to 2008, 16 destructive earthquakes occurred with earthquake intensities ranging from VI to VIII MIMI. They resulted in 81 deaths, 189 people injured, and thousands of houses damaged and even destroyed. On the Earth's surface, natural events such as earthquakes produce ground movements that can cause damage, called seismic hazards (Afnimar, 2009). The level of vulnerability to seismic hazards is based on previous earthquake history, current seismic activity and other geological factors. How strongly an earthquake can be felt and the damage seen in a particular area on the Earth's surface is called earthquake intensity. This is usually measured using the Modified Mercalli Intensity Scale (MMI), which describes the effects of earthquakes on people, structures and the environment and is written in Roman numerals I to XII (Richter, 1958).

Earthquake intensity provides information on how an earthquake is felt by people and structures on the surface but does not provide a picture of potential long-term vulnerability to earthquakes (Ningrum et al., 2022). The likelihood of future earthquakes of different intensities can be used to calculate earthquake hazards. This involves assessing the possible damage from an earthquake, including the impact on buildings, infrastructure and communities. By using seismic intensity data from previous earthquakes, it is possible to develop an understanding of the potential earthquake hazard in a region and design more earthquake-resistant buildings and infrastructure. This is an essential step in earthquake disaster risk mitigation (Ningrum et al., 2021; Ningrum et al., 2024; Saprudin et al., 2024).

In earthquake hazard analysis, Peak Ground Acceleration (PGA) is a frequently used ground shaking characteristic. This research aims to map the earthquake hazard in the North Maluku area using the Probability Seismic Hazard Analysis (PSHA) method, which is then converted into the earthquake intensity scale from BMKG. The novelty of this study lies in the use of the PSHA method so that an analysis of the level of earthquake hazard in the North Maluku region can be produced so that it can be determined which areas have the most devastating earthquake intensity in North Maluku. The results of this study are expected to be a reference in planning policies so that the risk of earthquake hazards can be minimized.

METHODOLOGY

The earthquake hazard risk analysis uses an earthquake source parameter approach using the Probabilistic Seismic Hazard Analysis (PSHA) method with the USGS-PSHA 2007 software developed by Stephen Harmsen and the GUI (Graphic et al.) process by Bella (2008). The data used are from various earthquake catalogues covering the longitude area 124^{o} - 131^{o}E and latitude: -3^{o}LS-5^{o}N for 65 years and limited by the depth of the earthquake source around 0 - 300 km and magnitude ≥ 5 Mw. Earthquake source parameters include geological and geotectonic conditions, analysis of ground motion characteristics, b-value, maximum magnitude, slip-rate, earthquake catalogue, soil conditions and ground motion equations. These earthquake source parameters will be the input data to generate Peak Ground Acceleration (PGA) values.

The concept of the PSHA method was developed and is still used today (Merz & Cornel, 1973). However, the analysis model and calculation techniques are still being developed by the EERI Committee on Seismic Risk (EERI Committee on Seismic Risk, 1989). The stages of the PSHA model and concept developed by EERI are a) identification of earthquake sources, b) characterisation of earthquake sources, c) selection of attenuation functions, and d) calculation of earthquake hazard. In this calculation, the general form of total probability theory is used, which can be expressed in the following equation:

$$P[I \geq i] = \int_r \int_m P[I \geq i | m \ \ dan \ \ r] \, f_M(m) f_R(r) \, dr \, dm \quad (1)$$

Where f_M is the density function of magnitude, f_R is the density function of hypocenter distance, and $P[I \geq i \mid m \text{ dan } r]$ is the condition of the random probability of intensity (I) exceeding value (i) at a location due to earthquake magnitude (m) and hypocenter distance (r). The ground motion equation for each earthquake source used is (Irsyam et al., 2010):

1. Shallow crustal earthquake source for fault and shallow background earthquake source models:
   a. Boore-Atkinson NGA equation (Boore & Atkinson, 2008)
   b. Campbell-Bozorgnia NGA equation. (Campbell & Bozorgnia, 2008)
   c. Chiou-Young's NGA equation. (Chiou & Youngs, 2010)
2. Subduction interface (Megathrust) earthquake source, for subduction earthquake source model:
   a. Geomatrix subduction equation (Youngs et al., 1997)
   b. Atkinson-Boore BC rock and global source subduction equation (Atkinson & Boore, 2003)
   c. Zhao et al. equation, with variable Vs30 (Zhao et al., 2006)
3. Benioof (deep intraslab) earthquake source, for deep background earthquake source model:

a. Equation AB intraslab seismicity Cascadia region BC-rock condition. (Atkinson & Boore, 2003)
b. Geomatrix slab seismicity rock equation, 1997 srl. 25 July 2006 (Youngs et al., 1997)
c. AB 2003 equation intraslab seismicity worldwide data region BC-rock condition. (Atkinson & Boore, 2003).

Data processing to produce PGA values was assisted by using the Z-Map programme and the USGS-PSHA 2007 programme, then the following stages of data processing were carried out:
1. Relocation of earthquake hypocentres on a local scale by clustering.
2. The earthquake data obtained was then converted to the same magnitude scale with the same type of magnitude data, namely the magnitude of the Mw moment using the relationship made by Pusgen (2017) and can be seen in Table 1.

Table 1. Conversion relationship between several magnitude scales for Indonesia (Pusgen, 2017)

Conversion Relationship	Events	Data Range	Conformance (R^2)
$M_w = 1.0107m_b + 0.0801$	19.162	$3.7 \leq m_b \leq 8.2$	69.75%
$M_w = 0.6016M_s + 2.476$	6.718	$2.8 \leq Ms \leq 6.1$	80.13%
$M_w = 0.9239M_s + 0.5671$	6.718	$6.2 \leq Ms \leq 8.7$	81.83%
$M_L = M_w$			

3. Sort the main earthquake data by separating mainshocks from foreshocks and aftershocks using the ZMAP programme (Wiemer, 2001).
4. Data completeness analysis.
5. Determination of the seismic parameter ab-value to describe the frequency of earthquake occurrence of an earthquake source using the ZMAP programme.
6. Determination of attenuation functions still refers to the attenuation functions of other regions with similar tectonic and geological conditions to Indonesia.
7. A logic tree is used by weighting several parameters to overcome the uncertainty in the seismic parameters used.
8. Identification and characterisation of earthquake source zone models. Three earthquake source models are used in this analysis: background earthquake sources, fault earthquake sources, and subduction earthquake sources.
9. The results of the data analysis carried out with the help of the USGS-PSHA 2007 hazard programme are the maximum ground acceleration (PGA) values at a period of T = 1 second for a probability of exceedance of 10%.
10. Mapping the PGA values with the help of the QuantumGIS programme.
11. Convert the PGA value to the earthquake intensity value based on the earthquake intensity scale-BMKG to determine the earthquake-prone areas in the North Maluku region.

RESULTS AND DISCUSSION

The PSHA method produces Peak Ground Acceleration (PGA) values, which are ground-shaking parameters calculated through an attenuation function and then converted into earthquake intensity values using the BMKG Earthquake Intensity Scale (SIG-BMKG) and the modified Mercalli Intensity Scale MMI as shown in Table 2. This scale measures the impact of an earthquake on people, buildings and the surrounding environment. Measuring the earthquake intensity scale level is essential for assessing the potential damage and impact of earthquakes on people and infrastructure based on observations of people affected by earthquakes. This information can help design earthquake-resistant buildings and respond more effectively to disasters (Amelia et al., 2024).

Table 2. Earthquake intensity scale based on BMKG Earthquake Intensity Scale and Modified Mercalli Intensity Scale (MMI)

BMKG SIG Scale	Color	Simple description	Detailed description	MMI Scale	PGA (gal)
I	white	Not felt	Not felt or felt by only a few people but recorded by the device.	I - II	< 2.9
II	green	Felt	Felt by many people but did not cause damage. Light hanging objects swayed and the bedroom windows vibrated.	III - V	2.9 – 88
III	yellow	Slight damage	Non-structural parts of the building experienced minor damage, such as hairline cracks in the walls, the roof shifted down and some fell.	VI	89 – 167
IV	orange	Moderate demage	Many cracks occurred in the walls of simple buildings, some collapsed, glass broke. some wall plaster came off. Almost all roofs shifted down or fell. The building structure experienced minor to moderate damage.	VII - VIII	168 – 564
V	Red	Heavy damage	Most of the walls of permanent buildings collapsed. The building structure suffered severe damage. The railroad tracks bent.	IX - XII	> 564

The PGA values for the North Maluku region have hazard values of 0.67 - 3.75 g for a 10% probability of exceedance in 50 years, where g is the acceleration of gravity as shown in Figure 2. The results of the distribution of PGA values show that the North Maluku region is relatively vulnerable to earthquake hazards because it is still strongly influenced by subduction (megathrust) earthquakes from the Philippine plate, the Maluku and Sangihe seas. The North Maluku region with PGA values ≥ 1.96 g (yellow, orange and red colours) is generally crossed by faults. Moreover, for PGA values in areas not crossed by faults, the value is below 1.96 g (blue and green colours). One of the main parameters in seismic analysis is the PGA value, which measures how fast the ground moves during an earthquake. Physical characteristics of the soil, such as soil type, layer depth, and soil texture at the site, also affect the PGA value.

The Vs30 value is the value of the average velocity of ground shear waves in the soil layer required to categorise soil classes by the National Earthquake Hazards Reduction Programme (NEHRP) and is illustrated in Figure 3. Class C soils with dense soil types and soft rock will dampen earthquake waves better than medium soils (class D) and soft soils (class E), such as sand or mud. Thus, in soils with classes D and E, PGA values tend to be higher because earthquake waves can propagate faster and produce greater accelerations.

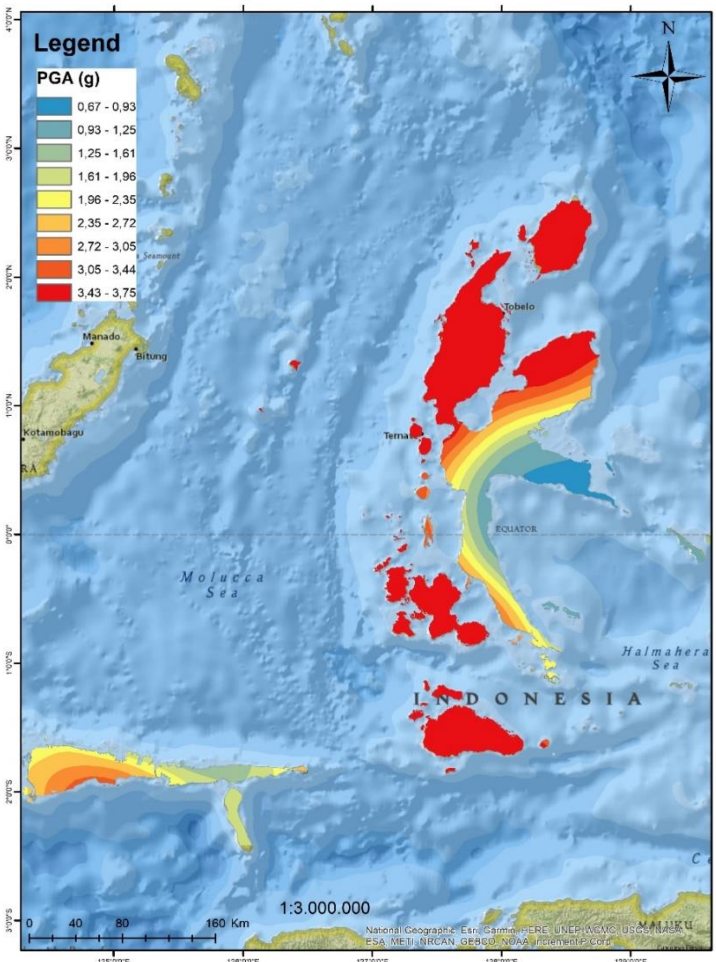

Figure 2. Distribution of PGA values based on 1.0 s response spectrum acceleration with a return period of 500 years

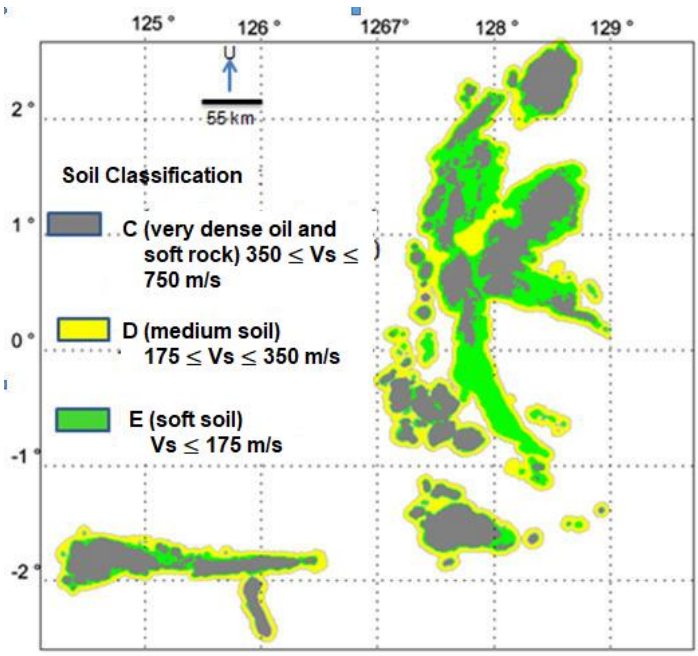

Figure 3. Soil classification map based on NEHRP (Sulaeman & Cipta, 2012)

The earthquake intensity value is obtained by converting the PGA value using the PSHA method. Based on Figure 4, the North Maluku region has a high earthquake intensity, namely IX MMI intensity (yellow), X MMI intensity (light orange), XI MMI intensity (dark orange), and XII MMI intensity (red). The high intensity is influenced by a fault passing the area.

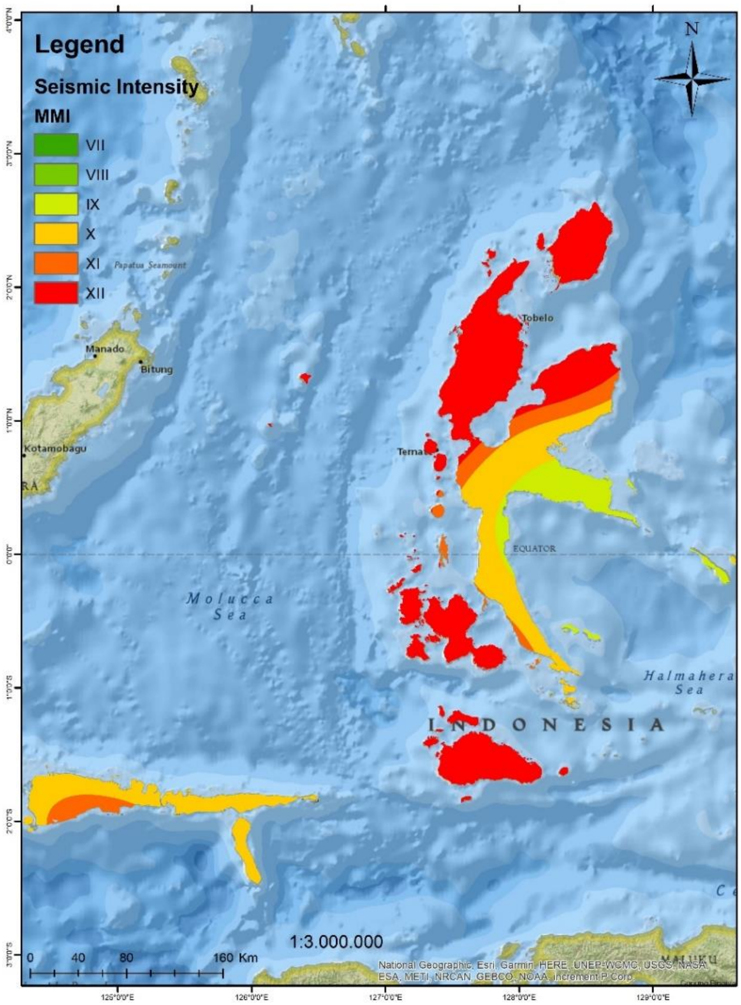

Figure 4. Conversion of earthquake intensity from PGA values in the North Maluku region

CONCLUSION

The results of the PGA value of the North Maluku region using the PSHA method were obtained ≥ 1.96 g. The PGA value was converted using the earthquake intensity scale, and it was found that the North Maluku region had a high earthquake intensity. The MMI earthquake intensity scale value is in the IX-XII range. The highest earthquake intensity is in the Morotai, West Halmahera, Ternate, Tidore, Bacan, and Obi Island areas. The high PGA and intensity values are influenced by faults trailing these areas, requiring more apparent fault parameters with other geophysical methods, such as microseismic methods.

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