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Mapping low earthquake risk areas in North Maluku Indonesia

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सार – मालुकु सागर में जटिल विवर्तनिकी के कारण मालुकु की मुख्य भूमि, विशेष रूप से उत्तरी मालुकु में बार-बार भूकंप आते हैं। 2017-2021 के दौरान, उत्तर में 1099 भूकंप आए, जिनकी औसत तीव्रता 4.4 थी। वर्तमान अध्ययन का उद्देश्य उच्च और निम्न भूकंप प्रभावित क्षेत्रों का पता लगाने के लिए 2017 और 2021 के बीच उत्तरी मालुकु क्षेत्र में अधिकतम स्थलीय त्वरण, अधिकतम स्थलीय वेग और भूकंप की तीव्रता का मानचित्रण करना है। इस अध्ययन में उपयोग की जाने वाली विधि PGV (पीक ग्राउंड वेलोसिटी) के साथ PGA (पीक ग्राउंड एक्सेलेरेशन) मान की गणना करना था। भूकंप की तीव्रता की गणना उस समीकरण का उपयोग करके की जाती है जो पीजीए को एमएमआई से जोड़ता है। उत्तरी मालुकु क्षेत्र में पीजीए मान 18-20.3 गैलन तक है और पीजीवी मान 8.6 से 9.6 सेमी/सेकेंड तक है। भूकंप की तीव्रता एमएमआई III मापक्रम पर थी क्योंकि उत्तरी मालुकु में कई सक्रिय भ्रंषों के कारण 4-5 की तीव्रता वाले भूकंप आते हैं जिनकी गहराई 10-50 किमी तक होती है। अंत में, इस अध्ययन के परिणाम से उत्तरी मालुकु में भूकंप के प्रभाव के कम या उच्च जोखिम वाले क्षेत्रों के बारे में महत्वपूर्ण जानकारी मिलने की उम्मीद है।

ABSTRACT. Complex tectonics in the Maluku Sea cause frequent earthquakes in the mainland of Maluku, especially North Maluku. During 2017-2021, 1099 earthquakes occurred in the North, with an average magnitude of 4.4. The current study aims to map the maximum ground acceleration, maximum ground velocity and earthquake intensity in the North Maluku region between 2017 and 2021 to find areas with high and low earthquake impact. The method used in this study was to calculate the PGA (Peak Ground Acceleration) value with PGV (Peak Ground Velocity). Earthquake intensity is calculated using the equation that relates PGA to MMI. The PGA value in the North Maluku region ranges from 18-20.3 gal. and PGV values range from 8.6 to 9.6 cm/s. The earthquake's intensity was on the MMI III scale because several active faults in North Maluku cause earthquakes with a magnitude of 4-5 with a depth varying from 10-50 km. Finally, the result of this study is expected to provide important information about areas with a low or high risk of earthquake impacts in North Maluku.

Key words – Peak ground acceleration, Peak ground velocity, Modified mercalli intensity.

1. Introduction

The Maluku is one of the provinces in Indonesia which is located in 3° 40′ LS - 3° 0′ LS 123° 50′ BT - 129° 50′ BT. Maluku region is an example of the closure of the Ocean basin caused by the collision of two oceanic arcs, namely the Halmahera and the Sangihe arcs. This area is one of the places where the convergence process happens. In the Maluku Sea, three plates are diverging: the Eurasian, Philippine and Australian plates (Ranging, *et al*., 1999; Gunawan, *et al*., 2016).

The PGA map is an indicator used to estimate the soil damage caused by an earthquake. Areas with a high PGA value have a significant earthquake hazard. On the contrary, areas with a low PGA value will have a low earthquake hazard risk (Taruna, *et al*., 2018). The maximum ground acceleration value in an area can be obtained through two methods: by recording the Accelerograph and by calculating the value using an empirical formula (Massinai & Kiki, 2016).

Measuring PGA using Accelerograph and estimating the value of PGA with empirical methods is very useful in a building or road construction process to reduce the impact of earthquakes because the shocking impact caused by earthquakes can affect the balance of building construction (Massinai & Kiki, 2016; Xie, *et al*., 2023).

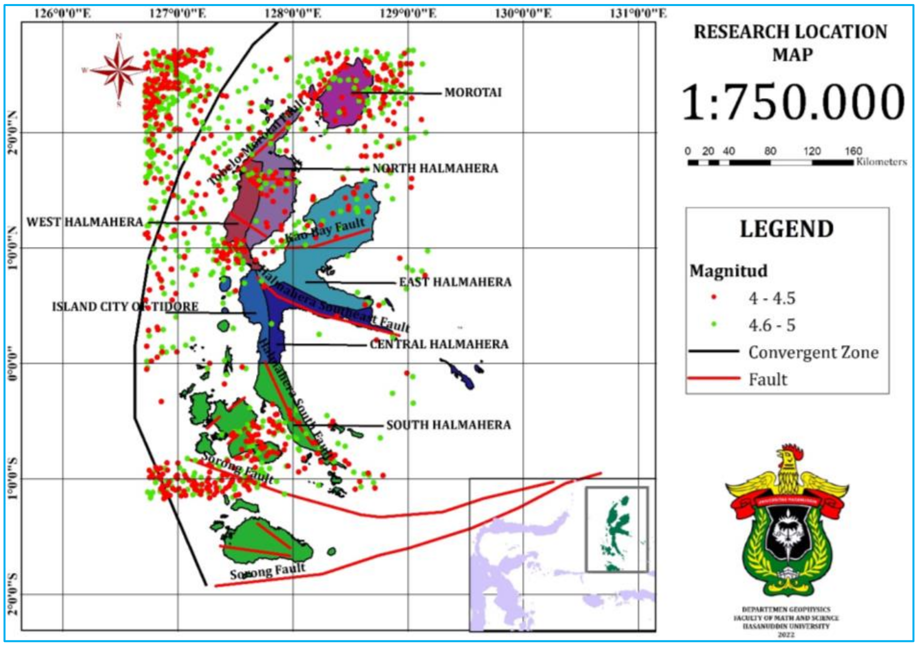

Fig. 1. The Map of Research Locations

Apart from PGA, other parameters commonly used to estimate the damage and strength of an earthquake are PGV (Peak Ground Velocity) and earthquake intensity (An, *et al*., 2023). PGV is the value of the maximum ground velocity on the surface of an area within a certain period caused by an earthquake. Similar to PGA, the PGV value can also be obtained through two methods: by conducting observation and calculation using an empirical formula (Du, *et al*., 2019). Mapping the PGV value is very beneficial to determine areas with high and low hazard impact caused by an earthquake so that the effects of earthquakes can be diminished (Corchete, 2010).

Earthquake intensity is the visible damage on the earth's surface. Seismic hazard also has a very close relationship with the intensity of an earthquake. The higher the value of an earthquake intensity in an area, the higher the damage caused by the earthquake will be, and *vice versa*. Earthquake intensity is measured using the MMI (Modified Mercalli Intensity) scale (Linkimer, 2008).

This study uses empirical methods to calculate maximum ground acceleration, maximum ground velocity, and earthquake intensity in North Maluku. This paper can be a reference providing information about areas with a low earthquake impact risk in North Maluku.

2. Methods

The research site chosen was in North Maluku (See Fig. 1). The data used are secondary data of earthquake records in terms of magnitude, arrival time, and earthquake coordinates obtained from USGS (United States Geological Survey) from 2017 to 2021.

The data processing was conducted as follows:

First, the recorded earthquake in the North Maluku area from 2017-2021 data on the USGS website https://earthquake.usgs.gov was downloaded. Then, the process of determining observation points in the North Maluku area was carried out. Subsequently, the PGA, PGV, and earthquake intensity values were calculated. Finally, a mapping process was conducted to determine the PGA, PGV value, and earthquake intensity distribution in the North Maluku area. The PGA, PGV and MMI calculations in this study specifically do not represent wave movements from vertical or horizontal components because the method used in the study uses an empirical approach that takes into account the epicenter distance and earthquake intensity, but this is sufficient to determine areas that have high earthquake impacts or low.

2.1. *Peak Ground Acceleration (PGA)*

Several empirical formulas for calculating PGA: Esteva's (1974), Donovan's (1973), Mc. Guire’s, Fukushima-Tanaka (1990), and Kanai's (1966) formula is shown in equation (1), (2), (3), (4) and (5), respectively (Douglas, 2021) (Zera, *et al*., 2021) (Sari, *et al*., 2021).

$$a = \frac{5600 \exp^{0.8*Mw}}{(R+40)^2} \qquad (1)$$

$$a = \frac{1080\ \exp^{0.5*Ms}}{(R+25)^{1.32}} \tag{2}$$

$$a = \frac{472*10^{0.278*Ms}}{(R+25)^{1.301}} \tag{3}$$

$$\begin{aligned}\text{Log}\, a = 0.41*Ms - \log\left(R + 0.032*10^{0.41*Ms}\right) \\ -0.0034R + 1.30\end{aligned} \tag{4}$$

$$\begin{aligned}a = \frac{5}{\sqrt{T_0}}*10^{0.61*Mw} - \left(1.66 + \frac{3.6}{R}\right)\log R \\ + 0.167 - \frac{1.83}{R}\end{aligned} \tag{5}$$

where, a, Mw, Ms, R and T_0 is ground acceleration (gal), magnitude moment, magnitude surface, hypocenter distance (km) and dominant period (s), respectively.

In 2003 the Central Weather Bureau of Taiwan obtained an empirical relationship between PGA and intensity as follows (Wu, *et al*., 2003; Razin, *et al*., 2021):

$$a = \exp\left(\frac{I-0.7}{2}\right) \tag{6}$$

$$I = I_0 \exp^{-0.00051*\Delta} \tag{7}$$

$$I = 1.5*(M-0.5) \tag{8}$$

where, I, I_0 and Δ is Intensity of observation station, Intensity of earthquake source, Epicenter distance, respectively.

2.2. *Peak Ground Velocity (PGV)*

PGV is the value of ground velocity in an area impacted by an earthquake event at a certain period. The greater the PGV value of an area, the greater the risk of damage impacted by an earthquake (Akkar & Ozen, 2005). The PGA and PGV values are highly needed in infrastructure planning to determine the dominant frequency of the building to be built according to the frequency of the response of the ground when a disturbance or earthquake occurs (Corchete, 2010).

The PGV value can be obtained through two methods, *i.e*., by recording the results directly from the seismometer (the same as the PGA value) and by calculating using empirical formulas. The following is the empirical equation of PGV that connects PGV with intensity (Wu, *et al*., 2003):

$$\text{PGV} = \exp\left(\frac{I-1.89}{2.14}\right) \tag{9}$$

The I value can be calculated using equation 7.

2.3. *Earthquake Intensity*

In 1905, geophysicist G. Mercalli coined a parameter that describes the damage caused by an earthquake called earthquake intensity. The power scale compiled by Mercali and Cancani is divided into twelve classifications, but this scale must be adapted to specific (Novikova & Trifunac, 1993). The magnitude, distance of the epicenter, the depth of the earthquake and the geological conditions of an area can significantly affect the earthquake's intensity. These factors allow the earthquake's intensity to be felt in the same intensity in a different area than the earthquake source (Trifunac, 2000).

The following equation connects MMI (Modified Mercalli Intensity) with ground acceleration (PGA) (Wald, *et al*., 1999).

$$\text{MMI} = 3.66 \log a - 1.66 \tag{10}$$

where α is PGA

3. Results and discussion

Calculating the maximum ground acceleration value and maximum ground velocity using equation (6) and (9) because equation (6) and (9) uses the distance to the earthquake epicenter in calculating ground acceleration and maximum ground velocity. The use of epicenter distance better represents the PGA and PGV values. While earthquake intensity is calculated using the equation (10). the following is a picture of the result of the interpolation of the maximum soil acceleration (PGA) value of North Maluku:

Based on the map of maximum ground acceleration above, the value of the maximum acceleration of the North Maluku region is classified as moderate, and the value is likely to be relatively the same in each area. The green area has a relatively low maximum ground acceleration of 18-19.5 gal, which covers parts of North Halmahera, Tidore Islands City, and Central Halmahera because these areas have low seismic activity. Meanwhile, areas with a high maximum acceleration ranging from 19.5 to 20.3 gal are indicated in red, including the Morotai region, some areas of South Halmahera and West Halmahera, East Halmahera and Central Halmahera. The high maximum acceleration exists because the area has an active fault that can cause an earthquake with a magnitude of 4.5-5 at a relatively shallow depth.

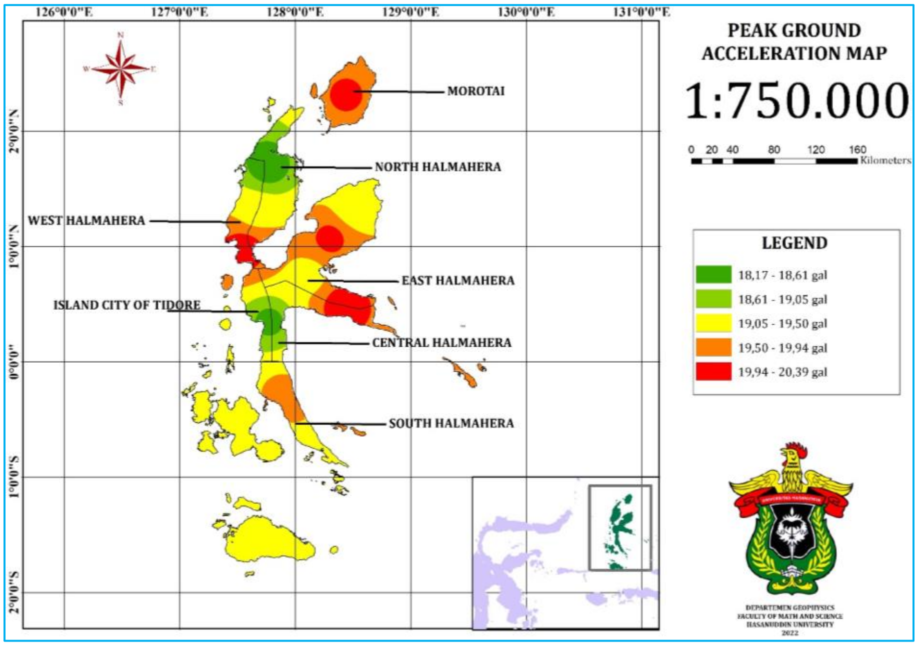

Fig. 2. The map of maximum ground acceleration

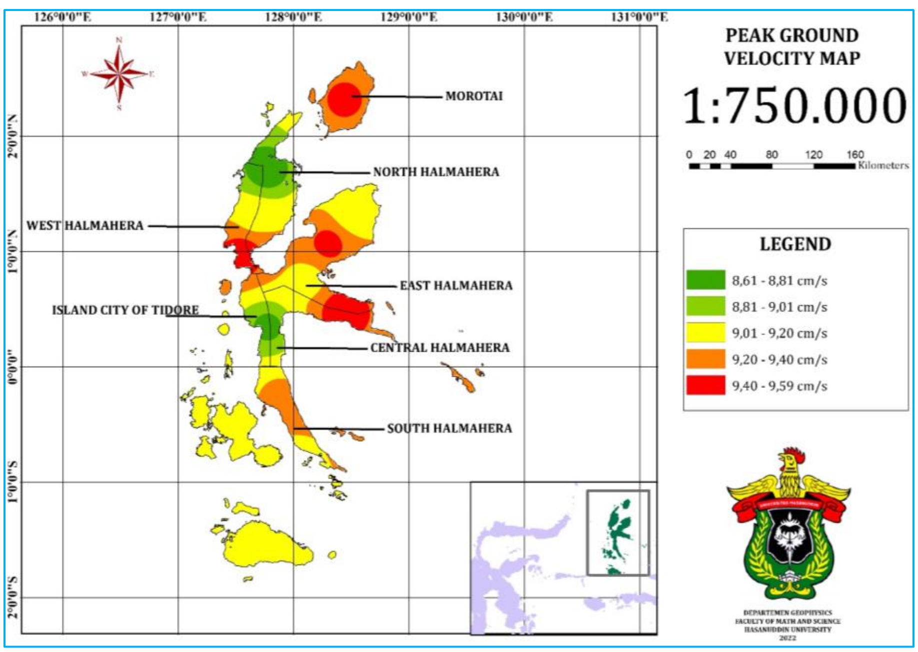

Fig. 3. The map of maximum ground velocity

According to the research conducted by (Zulkifli, *et al*., 2016) in the same area, the results show that the Morotai area and several areas traversed by an active fault have a high PGA value. These results are similar to the current study's results in mapping the PGA. Areas traversed by faults such as Morotai, East Halmahera, South Halmahera and Central Halmahera have a high PGA value. That is because the area traversed by the fault has a seismic activity that is high enough to cause earthquakes with a sufficiently large magnitude compared to areas that are not traversed by the fault, in which there is less seismic activity.

TABLE 1

Some research related to this paper

References	Peak Ground Acceleration (PGA)(gal)	Peak Ground Velocity (PGV) (cm/s)	Modified Mercalli Intensity (MMI)
(Zera, *et al*., 2021)	9.500 – 264.156	–	–
(Razin, *et al*., 2021)	12.404–74.733	6.032–32.210	–
(Lantu, *et al*., 2016)	12.67 – 46.33	6.15 – 20.67	VII
(Harlianto, *et al*., 2016)	250 – 350	–	IV – IX
(Zulkifli, *et al*., 2016)	0.21–0.44	–	–
(Du, *et al*., 2020)	8.73– 285.9	0.2 – 13.1	II – VIII
(Manea, *et al*., 2021)	<10 – 215	–	–

After conducting a calculation, the maximum ground velocity range in the North Maluku region is between 8.6-9.6 cm/s. Judging from the entire ground velocity map in Fig. 3, the areas with relatively high ground velocity values are in the Morotai Regency, some parts of West Halmahera, East Halmahera, and Central Halmahera. This happens because the area has an active fault that causes earthquake activity with a high magnitude. The areas with relatively low ground velocity values are North Halmahera, Tidore Islands City and Central Halmahera. These areas' low value of ground velocity is due to the relatively low seismic activity occurring at relatively deep depths.

In a study conducted by (Razin, *et al*., 2021) in the West Nusa Tenggara area using the same empirical formula in mapping the maximum ground velocity value, the results of the analysis show that the maximum ground velocity value has a linear relationship with the maximum ground acceleration value. The higher the maximum ground acceleration value in an area, the higher the maximum ground speed value will be and *vice versa*. The study's results above have some similarities in mapping the maximum ground velocity value in the current study, *i.e*., areas with a high maximum ground acceleration value also have a high maximum ground velocity value and *vice versa*.

Based on PGA and MMI empirical relation complete region of North Maluku is expected an intensity of III on MMI scale, classified as being felt by many people but not causing damage. An intense earthquake causes light objects to sway and glass windows to shake. Judging from the three parameters calculated using an empirical formula, areas that are safe and only have a minor earthquake impact when an earthquake occurs are some areas of North Halmahera Regency, Tidore Islands City, and parts of Central Halmahera.

Research results from (Zera, *et al*., 2021), (Razin, *et al*., 2021), (Lantu, *et al*., 2016), (Harlianto, *et al*., 2016), (Zulkifli, *et al*., 2016), (Du, *et al*., 2019), (Manea, *et al*., 2021) the PGA value depends on the size of the magnitude, the distance from the earthquake source and the geological conditions that make up an area. The greater the magnitude and the smaller the distance from the source of the earthquake, the greater the PGA value and vice versa. The influence of the geological conditions that make up an area, the denser the rocks that make up an area, the PGA value will be small and if the rocks that make up an area are soft, the PGA value will increase.

PGV value according to research results (Razin, *et al*., 2021), (Lantu, *et al*., 2016), (Du, *et al*., 2020) the factors that affect the PGV value of an area are the same as the PGA, so the higher the PGA value of an area, the greater the PGV value and *vice versa*. For MMI according (Lantu, *et al*., 2016), (Harlianto, *et al*., 2016), (Du, *et al*., 2020) the magnitude of the MMI scale has a linear relationship with PGA and PGV. the higher the PGA and PGV values, the higher the MMI scale value and *vice versa*. The three parameters PGA, PGV and MMI show the high of the impact risk caused by an earthquake in an area.

(Razin, *et al*., 2021), (Lantu, *et al*., 2016) have almost the same range of PGA and PGV values with different research locations. This can happen because the empirical formula used is the same in estimating PGA and PGV values at the research locations of the two papers and the data used has almost the same magnitude range, ranging from 4.5 - 7.

4. Conclusions

The PGA in the North Maluku region is relatively close to the range of 18-20.3 gal and The PGV in the

North Maluku region ranges from 8.6 to 9.6 cm/s, classified as moderate. As the intensity of the earthquake is converted to MMI, North Maluku is at a scale of III MMI. PGA and PGV method are successfully expect to add important insight to the local government in order to know areas with a low and high earthquake impact risk.

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