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Mapping Risk Level Based on Peak Ground Acceleration and Earthquake Intensity Using Multi-event Earthquake Data in Malang Regency, East Java, Indonesia

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ABSTRACT

This research aimed to identify the earthquake hazard, developing a peak ground acceleration (PGA) and earthquake intensity map to reduce earthquake disaster risk in Malang, East Java, Indonesia. This map is based on historical data of earthquake occurrence in 2011-2021 using the International Seismological Centre (ISC) earthquake catalog. Peak ground acceleration was analyzed using Donovan and McGuire equation, and the earthquake intensity was analyzed using the Wald equation. The result of this study represented peak ground acceleration value in Malang Regency, which was varied from 23.687 – 33.069 gal (Donovan attenuation equation) and 22.245 – 31.705 gal (McGuire attenuation equation). While based on earthquake depth, Malang Regency had a damage capacity of IV-V MMI on an intensity scale. This intensity was equivalent to the formation of cracks in the ground. Almost all residents also feel the vibrations. The most severe damage was due to the earthquake on April 10, 2021, at 14:00:16 WIB spoiled Dampit and Bantur district's public facilities. This study provides an overview of the riskiest area affected by the disasters that can be used for disaster mitigation in Malang regency.

1. INTRODUCTION

Malang is located in the south of East Java. It is a high earthquake risk area (Bachri et al., 2021). It is caused by the tectonic activities from some faults around it, including the Grindulu fault in Pacitan and the Klangon fault in Madiun (Lestari et al., 2019; Yusvinda et al., 2021). It is also close to the megathrust subduction zone. This zone stretches along with the southern islands of Sumatra, Java, and Nusa Tenggara islands. This region was shaped from the result of a convergence of the Indo-Australian Plate and the Eurasian plate with moves varying from sixty-three mm/yr in the south and 54 mm/yr inside the northern part of Sumatra Island and Java Island (Chasanah & Handoyo, 2021a; Chasanah & Handoyo, 2021b; McCaffrey, 2009). Therefore, tectonic earthquakes often occur in this zone (Hariyanto et al., 2021). In addition, Malang is also close to some active volcanoes such as Mount Kelud, Mount Arjuno-Welirang, and Mount Merapi, so volcanic activity triggers the earthquakes.

More than 30 earthquakes with a magnitude of more than 4.0 Mw occurred in Malang and its surrounding areas in the last ten years. An earthquake 6.1 Mw occurred on April 10, 2021, at 14:00:16 of Western Indonesia Time, located at 8.83º south latitude and 112.5º east longitude. This earthquake occurred in the sea at a distance of 96 km south from Kepanjen district, Malang regency, East Java, at a depth of 80 km (Figure 1). The earthquake was felt in almost all areas of East Java. There was at least one fatality, one minor injury, and damage to several public facilities such as hospitals and government offices (BMKG, 2021).

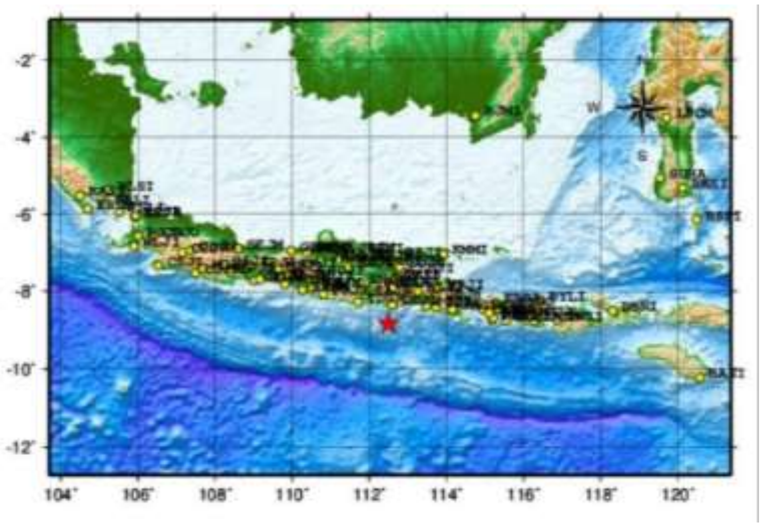

Figure 1. The Epicenter Map of Malang Earthquake (star red dot, and the yellow dots are the accelerograph station) that occurred on Saturday, April 10, 2021 at 14:00:16 WIB at sea 90 km southwest of Malang (BMKG, 2021).

Based on the description of tectonic conditions and the data on earthquake studies in the Malang district, earthquake disaster mitigation is urgently needed in order to reduce the impact caused by earthquakes. There are several methods used in earthquake disaster mitigation, including the study of the seismicity of an area, mapping of earthquake vulnerability based on geographic information systems, and regional and city spatial planning in accordance with earthquake hazard studies (Ashadi & Kaka, 2019; Bachri et al., 2021). Regional and city spatial planning in accordance with an earthquake hazard study used an assessment method based on the Peak Ground of Acceleration (PGA) parameters and earthquake intensity (Yao et al., 2020).

The determination of the scoring method is based on the PGA parameter because this parameter is considered to be representative of the physical impact of the earthquake (Yao et al., 2020). The physical effect of an earthquake is determined by way of the peak ground acceleration or PGA in the affected area. PGA is the largest value ground acceleration vibration that takes place at a point in an area which is calculated based totally on data on all earthquakes that have occurred in a certain period of time based on numerous earthquake parameters (Ashadi & Kaka, 2019).

Previously, a study using the PGA value scoring method for the entire East Java region was conducted by Kumala et al. (2016). It was found that Malang Regency had a PGA value of 0.358 gal (Kumala, 2016). Based on remote sensing, GIS, and field observations, this is different from this research because the subject of disaster mitigation is different, namely for landslide disaster mitigation (Bachri et al., 2021). The results of this study were not detailed. It only represented one point in each district, so it is necessary to conduct research on mapping PGA parameters in the Malang. In this study, PGA was determined by using empirical calculations with the Ground Motion Prediction Equation (GMPE) by Donovan and McGuire (Douglas, 2003). While the intensity of the earthquake using the Walld method (Campbell, 1997; Wibowo & Sembri, 2016; Yao et al., 2020), empirical calculations using the McGuire and Donovan methods were used because there is a limit on the coefficients so that the prediction of ground motion increases the magnitude function value and decreases the distance function value (Douglas, 2003). The risk level of an earthquake will be divided into three: low, middle, and high. The results of this study are expected to provide an overview of the areas with most at risk of being affected by disasters and can be used as consideration for disaster mitigation.

2. METHOD

This research was conducted in Malang Regency with coordinates 7.22° – 9.52° S and 112.12° – 112.60° E (Figure 2). The physiographical conditions of Malang (Figure 2) are highly variable and dominated by undulating and hilly soil that is prone to landslides (Bachri et al., 2021). Then, Malang was divided into several parts with a grid size of 0.025º x 0.025º to make it easier to read the results of the calculation of the PGA value and the intensity of the earthquake in each regency.

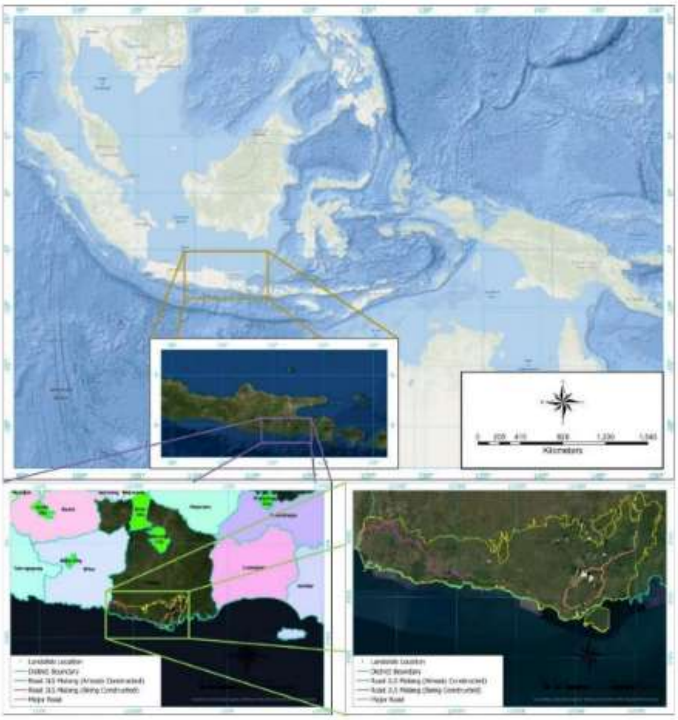

Figure 2 Research location (Bachri et al., 2021).

The research data gained from the earthquake recording stations in Malang and its surroundings which were taken from the official website of the Meteorology, Climatology and Geophysics Agency (BMKG). As well as the data on earthquakes that occurred in Malang and its surroundings with coordinates 7.22° – 9.52° S and 112.12 – 112.60° E from January 2011 to April 2021. The earthquake data taken from the International Seismological Center (ISC) earthquake catalog with an earthquake depth of < 100 km and a magnitude of 4 Mw.

Over a period of 10 years, there have been 76 earthquakes around Malang with a magnitude more than 4 Mw, both on land and in the southern seas of Malang. The earthquake catalog data was then converted to all units of magnitude into surface-wave magnitude (*Ms*) with the following empirical equation:

$$Ms = \frac{0.8Ml - 0.01Ml^2 - 1.2}{0.56} \tag{1}$$

where *Ml* is local magnitude (Lowrie, 2007).

One of the parameters to calculate the PGA value is the distance of the earthquake hypocenter from the epicenter to the measurement point/station. After obtaining surface-wave magnitude value and determining the distance of the earthquake hypocenter to the measurement point (station), the PGA value was processed using the empirical formulation of Donovan and McGuire.

2.1 Peak Ground Acceleration (PGA)

Earthquakes are usually observed by means of a floor acceleration fee or known as PGA within the affected vicinity. The importance of the PGA value is proportional to the absolute amplitude pace recorded with the aid of the accelerogram at the scene in the course of the earthquake (Basid et al., 2021). The PGA value at the earthquake incident location describes the risk levels. PGA can be calculated by the following equation:

$$y = b_1 e^{b_2} R^{-b_3} \tag{2}$$

with y is maximum ground acceleration (gal); m is magnitude surface; R is hypocenter distance (km) and *b1, b2, b3* are the constant value obtained from the empirical equation between the PGA from the accelerogram measurement results with the hypocenter distance (Lowrie, 2007).

Maximum ground acceleration is a parameter that can be determined directly by using an accelerogram. Another way to determine the value of ground acceleration for an earthquake is empirical formula calculations, including Donovan, McGuire, W.V. Mickey, Esteva and Boore (Douglas, 2003).

Another method that used other parameters was using the rock lithology equation, the effect of sediment thickness and amplification, namely the Kanai Method. However, the PGA value based on the empirical formula used in this study was only influenced by the magnitude of the surface, as well as the distance from the source of the earthquake to the calculation points (Douglas, 2003). The following is the empirical formulation of PGA used in this study:

2.2 Donovan's Empirical Method

Donovan's Empirical formulation was discovered by Neville C. Donovan (Senior Engineer in California, USA (Donovan, 1973; Kurniawan, 2016). This formula was calculated based on the recorded data of the earthquake that occurred on February 9, 1971 in San Fernando which had a strength of 6.5 *Ms* or also known as the Sylmar earthquake. The following is Donovan's empirical equation:

$$\mathrm{PGA} = \frac{1080 \exp(0.5\, Ms)}{(\Delta + 25)^{1.32}} \tag{3}$$

where PGA is the peak ground acceleration value (gal), *Ms* is the surface magnitude, and Δ is the hypocenter distance (km) (Donovan, 1973).

2.3 McGuirre's Empirical Method

This empirical method was found by Robin K. McGuire in 1963. This was based on an earthquake in South California along the San Andreas fault. The following is a calculation of McGuire's empirical formula:

$$\mathrm{PGA} = \frac{472.3 \exp(0.27\, Ms)}{(\Delta + 25)^{1.301}} \tag{4}$$

where PGA is the peak ground acceleration value (gal), *Ms* is the surface magnitude, and Δ is the hypocenter distance (km) (Mcguire, 1978).

2.4 Earthquake Intensity

The level of earthquake damage is expressed in intensity, which is calculated based on the damage that occurred in the affected area. The intensity provided an overview of the strength of the earthquake at the center and in the area around the epicenter (Sunarjo et al., 2012). The intensity value is usually based on the distance to the epicenter, i.e., the closer the area to the hypocenter (the center of the earthquake), the greater the intensity value, and vice versa. If the distance is further from the center of the earthquake, the intensity value will decrease (Sungkowo, 2018). Earthquake intensity values can also be determined from the Peak Ground Acceleration (PGA) calculation as used in this study.

The intensity scale used in Indonesia is the Modified Mercalli Intensity (MMI) scale, also known as the Mercalli Intensity Scale which can be calculated using the following empirical equation:

$$\mathrm{IMM} = 3.66 \log(\mathrm{PGA} - 1.66) \tag{5}$$

where PGA is Ground Acceleration (gal) (Wald et al., 1999). The conversion of intensity values can be seen in Table 1. The calculation of MMI scale earthquake intensity value was performed by the Wald method using the PGA value that has been obtained from previous calculations (Eq. 4). The mapping of the distribution of PGA values and earthquake intensity was carried out using Arc View GIS software.

Table 1 Convert MMI units to MMI index (Wald et al., 1999)

No	IMM Scale	Index Intensity
1	< 0.17	I
2	0.17 – 1.4	11 – III
3	1.4 – 3.9	IV
4	3.9 – 9.2	V
5	9.2 – 18	VI
6.	18 – 24	VII
7	34 – 65	VIII
8	65 – 124	IX
9	> 124	X

3. RESULTS AND DISCUSSION

The results obtained from this study were PGA and earthquake intensity in the Malang area of the Kendeng route, which had a northwest-southeast direction and then visualized with a zoning map. The PGA value showed the acceleration of ground vibration from rest until the ground moves at a certain speed if there was a shock or an earthquake. This value was calculated based on the distance to the hypocenter, the magnitude of the earthquake, and the dominant period in the study area. Based on the results of the empirical equation of Donovan and McGuire's attenuation method (Eqs. 2 and 3), PGA values and earthquake intensity for 33 regencies were obtained and shown in Table 2.

Table 2 The PGA value in each regency in Malang regency based on the analysis of the Donovan and McGuire attenuation method

No	REGENCY	Latitude (°)	Longitude (°)	Peak Ground Acceleration (gal)			
				Donovan	Mc.Guire	MMI Donovan	MMI McGuire
1.	Ampelgading	112.900	-8.250	29.351	27.682	V	V
2.	Bantur	112.550	-8.325	29.475	27.727	V	V
3.	Bululawang	112.475	-7.925	30.273	28.683	V	V
4.	Dampit	112.650	-8.100	29.445	27.741	V	V
5.	Dau	112.500	-7.800	32.863	31.501	V	V
6.	Donomulyo	112.775	-8.250	28.192	26.351	V	V
7.	Gedangan	112.525	-7.950	29.132	27.479	V	V
8.	Gondanglegi	112.425	-8.325	29.325	27.641	V	V
9.	Jabung	112.625	-8.350	30.623	29.054	V	V
10	Kalipare	112.625	-8.175	26.610	24.994	V	V
11.	Karangploso	112.800	-7.950	32.325	30.925	V	V
12.	Kasembon	112.575	-7.900	24.557	23.087	V	V
13.	Kepanjen	112.425	-8.200	29.174	27.540	V	V
14.	Kromengan	112.600	-7.875	27.485	25.862	V	V
15.	Lawang	112.350	-7.800	31.322	29.838	V	V
16.	Ngajum	112.575	-8.125	30.097	28.601	V	V
17.	Ngantang	112.500	-8.125	23.687	22.245	IV	IV

18.	Pagak	112.700	-7.850	28.441	26.661	V	V
19.	Pagelaran	112.525	-8.050	28.850	27.109	V	V
20.	Pakis	112.375	-7.900	32.220	30.778	V	V
21.	Pakisaji	112.525	-8.250	31.568	30.104	V	V
22.	Poncokusumo	112.700	-7.950	29.684	28.005	V	V
23.	Pujon	112.600	-8.050	27.622	26.120	V	V
24.	Singosari	112.850	-8.050	32.315	30.899	V	V
25.	Sumber Pucung	112.450	-7.850	27.671	25.981	V	V
26.	Sumbermanjing	112.650	-7.875	28.708	27.022	V	V
27.	Tajinan	112.700	-8.325	31.118	29.590	V	V
28.	Tirto Yudo	112.500	-8.175	29.267	27.594	V	V
29.	Tumpang	112.675	-8.050	30.778	29.215	V	V
30.	Turen	112.825	-8.275	29.176	27.444	V	V
31.	Wagir	112.750	-8.000	33.069	31.705	V	V
32.	Wajak	112.700	-8.175	29.489	27.783	V	V
33.	Wonosari	112.550	-8.000	28.048	26.512	V	V

The PGA value and earthquake intensity based on the analysis of historical earthquake data in Malang over ten years are presented in Table 1. The PGA value (Table 2) is mapped (Figures 3a and 3b), while the earthquake intensity value is mapped into an earthquake intensity map (Figures 4a and 4b). This PGA value is used to decide the strength of the construction to be constructed in the area. The distribution of PGA also seemed to be strongly influenced by the source of subduction earthquakes and faults. It could be perceived that the further south, the higher the PGA value. Likewise, the PGA value was larger for the area around the fault (Figures 3a and 3b). Based on the PGA map, due to the combination of three earthquake sources, namely background, fault, and subduction (megathrust), East Java can be divided into three earthquake zones according to the intensity of damage caused above the subsurface. The three zones are zone 1 with PGA values ranging from 15.60 to 21.88 gal indicated in green, zone 2 with PGA values ranging from 21.88 to 28.16 gal shown in yellow, and zone 3 with PGA values ranging from 28.16 – 34.44 gal indicated in red (Figures 3a and 3b).

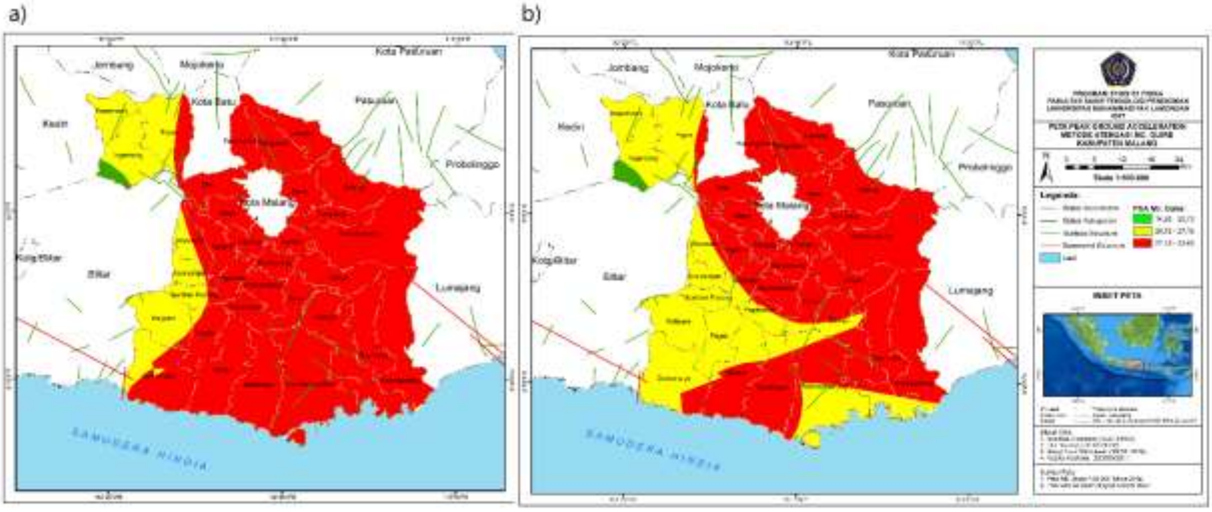

Figure 3 Distribution of PGA values using the Donovan (a) and McGuire (b) attenuation method

The PGA values calculated were only those on land, which ranged from 23.687 to 33.069 gal (Donovan attenuation equation) and from 22.245 gal to 31.705 gal (McGuire attenuation equation (Table 1). The lowest PGA was found in parts of the Ngantang regency, while the highest PGA was found in Wagir, Karangploso, and Singosari districts.

Based on the PGA value using Donovan attenuation, Malang could be grouped into three parts: normal, medium, and high areas. Each area was marked with green, yellow, and red (Figure 3a). The normal area covered only a small part of Malang, namely Ngantang. The medium area covered the western part of Malang Regency, which included Kesamben, part of Pujon, Kalipare, and some areas with PGA values ranging from 21.88 to 28.16 gal. Meanwhile, the areas with relatively high PGA, above 28.16 gal, covered most Malang.

PGA value distribution using McGuire attenuation also consisted of 3 regional divisions marked in green, yellow, and red. Each of which indicated the level of PGA values (Figure 3b). The normal area covered only a small part of Ngantang; the medium area had more coverage than the distribution of PGA values with Donovan attenuation. Most of them were located in the western and southern parts of the Malang regency, which were marked in yellow with a value ranging from 20.72 to 27.19 gal. Meanwhile, areas with high PGA ranging from 27.19 to 33.65 gal covered most Lawang to Gedangan (Figure 3b).

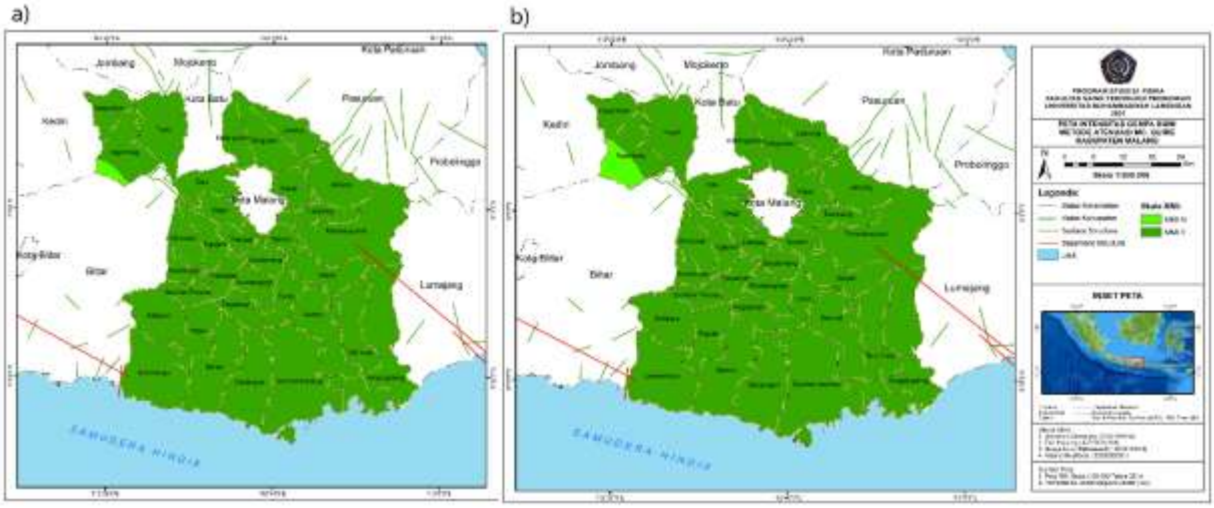

Figure 4 The distribution of earthquake intensity values using the Donovan (a) and Mc Guire (b) attenuation method.

An earthquake with a magnitude of Mw 6.1 occurred on April 10, 2021, at 14:00:16 WIB located at 8.83º latitude and 112.5º east longitude 96 km south of Kepanjen, Malang, East Java, at a depth of 80 km, caused some considerable damage. Majang Tengah village office, houses, and Bantur community health center were lightly damaged (BMKG, 2021). Damage and collapse of buildings due to earthquakes occurred because the buildings could not anticipate the ground vibrations. The magnitude of ground vibration because of an earthquake turned into inspired through 3 things: the supply of the earthquake (supply), the path of wave propagation (path), and the impact of nearby soil situations (site).

It is understood that a large and close earthquake source will cause large ground vibrations. Likewise, local soil conditions in the form of thick and soft sediment deposits will also cause amplification phenomena that increase the value of soil vibrations on the surface.

Earthquake intensity measures the level of damage perceived on the earth's surface. The PGA value (Table 2) is converted to the MMI scale to know the magnitude of the earthquake intensity. The earthquake intensity mapping can be seen in Figures 4a and 4b. Based on the mapping of the earthquake intensity in Malang regency, which stated the level of damage caused by the earthquake on the MMI scale, most regencies in Malang were not more than the MMI VI scale. The risk caused by an earthquake was not more than the MMI VI scale, namely minor damage to buildings specially designed to withstand earthquakes and significant damage to buildings with standard structures and collapsed buildings with poor (Kumala, 2016).

These results align with Kumala (2016), which studied the analysis of PGA value of all cities and regencies of East Java, but the focus the area largest than this research. They used the earthquake catalog data from 1900 to 2015, with site 109º – 116º E and 6º – 12º S. They got PGA value (0,2 – 0,4) gals and (0,45 – 0,65) gals in condition for 10% and 2% PE in 50 years (return 500 years and 2500 years) in bedrock (Kumala, 2016). Their results make sense because it affects their largest focus area. It would make the acceleration smaller and the dominant period longer. Our study had a longer epicenter distance and greater PGA value.

The research focused on densifying the landslide hazard and developing a landform map in the same area, Malang Regency, East Java, Indonesia (Bachri et al., 2021). They produce landform and landslide maps from the geomorphological approach, the morphology, morphogenesis, and morph arrangement conditions were obtained from the remote sensing data, GIS, and field observation. In contrast, morph chronological information was obtained from a geological map. Their research result showed that the Malang regency is dominated by a high level of landslide susceptibility, with a majority of moderate to strongly eroded hill morphology (Bachri et al., 2021).

Based on the analysis of the earthquake that occurred in Malang Regency on April 10, 2021, 6.1 Mw, the results of accelerograph data analysis showed that the earthquake with a magnitude of 6.1 was recorded on the ground acceleration sensor as many as 81 observation stations spread throughout Indonesia. PGA IV-V MMI scale, namely at the level of the earthquake felt. By taking into account the epicenter's location and the hypocenter's depth, the earthquake that occurred was an intermediate type of earthquake due to subduction activity. The source mechanism analysis results show that the earthquake has a thrust fault mechanism (BMKG, 2021). The review of BMKG is in line with this result that Malang Regency is on level VI-V MMI scale of earthquake intensity.

Based on the discussion above, it is necessary to pay close attention to building construction in Malang Regency, especially for buildings with about three floors and buildings that reach 15 floors. Thus, there is no fatal damage if there is an earthquake of a similar type or a larger one.

4. CONCLUSION

The distribution of PGA values and earthquake intensity in Malang based on the earthquake catalog of the last ten years are between 23.687 – 33.069 gal (Donovan attenuation equation) and 22.245 – 31.705 gal (McGuire attenuation equation) with earthquake intensity ranging from IV MMI to V MMI. The lowest PGA is found in Ngantang regency, while the highest PGA was in Wagir, Karangploso, and Singosari. This intensity is equivalent to cracks in the ground, and almost all residents feel vibrations. The most severe damage from the earthquake on April 10, 2021, at 14:00:16 WIB was the damage to public facilities in the Dampit and Bantur regencies. This study provides an overview of the riskiest areas of being affected by disasters and can be used for disaster mitigation in Malang regency.

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