# Mapping risk levels of earthquake damage as disaster mitigation efforts: Case studies in West Java, Central Sulawesi and Lombok

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# Mapping Risk Levels of Earthquake Damage as Disaster Mitigation Efforts: Case Studies in West Java, Central Sulawesi and Lombok

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**Abstract.** Indonesia is the country with the second-highest level of seismicity in the world after Japan. During 2019 there were 11,573 tectonic earthquakes of varying magnitude and depth. With high seismicity and unpredictability when and where it will occur, it demands continued efforts to reduce its impact through disaster mitigation. One of the mitigation efforts is to map the level of risk of damage due to earthquakes. In this paper, we will learn how to make the map in West Java, Central Sulawesi, and Lombok. This area was chosen because of the relatively high level of seismicity and magnitude, as well as a large number of fatalities. Three different methods are used, namely Atkinson Boore for West Java, McGuire R.K for Central Sulawesi, and Fukushima for Lombok. The results of the analysis show that in West Java the areas that have a high level of risk of damage are Sukabumi, Cirebon, Pangandaran, Garut, Cianjur, Indramayu, and Tasikmalaya with MMI V-VI scale. In Central Sulawesi with the intensity of VI-VII MMI is in the districts of Donggala, Sigi, Palu, Mamuju, Poso, North Luwu, and Parigi Moutong. For Lombok are the Regencies of East Lombok, North Lombok, and West Lombok, including Mataram with an intensity of V-VIII MMI. The impact of this intensity is due to damage to certain parts and collapse for strong buildings, buildings that are less strong will be severely damaged.

## INTRODUCTION

The history of earthquakes has existed since humans lived and is one of the causes of natural disasters that cannot accurately predict when, where, and how strong the intensity is. This disaster must be watched closely because it often causes quite fatal damage, even casualties. Earthquakes are defined as ground vibrations due to the sudden release of energy in the earth's crust [1]. The results of monitoring by the Meteorology, Climatology and Geophysics Agency (BMKG) during 2019, in Indonesia there were 11,573 tectonic earthquakes of various magnitudes and depths. With this high frequency of seismicity, mitigation efforts are need and it is continuously updated. Disaster mitigation can be carried out through physical development as well as increasing awareness and capacity to deal with disaster threats.

The relatively high seismicity in Indonesia is due to the fact that Indonesia is part of Southeast Asia which is composed of small continents, uplifted continental shards and is surrounded by active plate edges to form an "ensialic arc system" originating from Gondwana and Cathaysian [2]. Therefore, Indonesian geodynamics cannot be separated from the geological dynamics around it. For example, the results of tertiary geodynamic research in Southeast Asia by Dewey *et al.*. [3] in Tibet, Fuller *et al.*. [4] in Thailand, and Enkin *et al.*. [5] in China, it was concluded that India's

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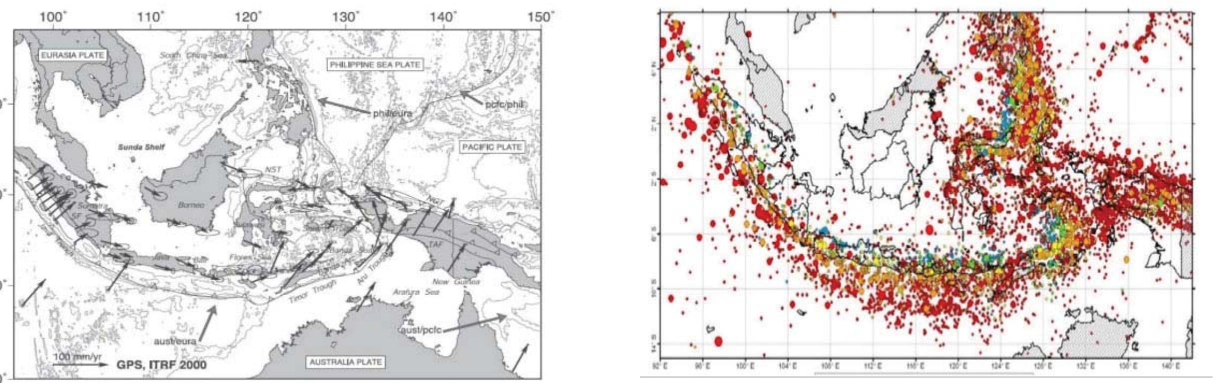
shift to Eurasia caused Indonesia to be pushed north as far as 17o latitude. Another consequence is that the blocks in Southeast Asia experience a small rotation [6]. The dynamics that occur in Southeast Asia continue today.

Past geodynamics from Gondwana and Cathaysian places Indonesia on a complex junction of the world's three major plates and nine smaller plates, where their interactions make Indonesia a highly earthquake-prone region [7] [8]. The movement of the three major plates of the world (Asian Plate, Indian Ocean Plate-Australian and Pacific Plate) as shown in Fig. 1.a. also makes Indonesia the region with the second highest seismic level in the world after Japan with the distribution of seismicity as shown in Fig. 1.b.




(a) (b)

**FIGURE 1.** (a) Map of Indonesian tectonics [9] (b) Earthquake epicenter map M> 5.0 period 1900-2009 in Indonesia [9]

Earthquakes are ground vibrations caused by seismic waves emitted from an elastic energy source that is released suddenly when rocks at the source location are unable to withstand the forces caused by relative motion between rock plates. Basically, the earth's crust vibrates continuously, but this vibration is not an earthquake because of its constant vibrational nature. Earthquakes have a fairly clear start and end time [10]. Judging from the magnitude of the vibration, usually the largest earthquake will begin with an initial earthquake (foreshock) followed by the main earthquake (mainshock) with the greatest energy and end a number of aftershocks [11].

The magnitude of the impact of an earthquake is physically determined by the maximum ground vibration acceleration or Peak Ground Acceleration (PGA) in the affected area. PGA is the value of the largest ground acceleration vibration that has ever occurred at a point in an area calculated from all earthquakes that have occurred in a certain period of time based on the magnitude, hypocenter distance and the dominant period of the soil [12]. According to Handewi *et al.*. [13] every earthquake that occurs will cause a value for the acceleration of the ground at a place (site). This PGA is equal to the greatest absolute acceleration amplitude recorded on the accelerogram of a location during an earthquake [14]. PGA at a location describes the level of earthquake risk at that location [15]. From this PGA value, a PGA map of an area can be made that illustrates the risk map of the level of damage due to earthquakes in that area. This paper will examine how the risk of damage due to the earthquake in West Java, Central Sulawesi and Lombok. These three areas were selected because of their relatively high level of seismicity and magnitude as well as the number of casualties.

## PGA Models from Atkinson And Boore (2003)

The PGA model from Atkinson and Boore (2003) is used for sources subduction earthquakes. This model is used for earthquake hazard analysis in various regions of the world with moment magnitudes between 5 to 8.3. For subduction zones for both interface and intraslab. The form of the attenuation function is as follows [16]:

$$\log y = c_1 + c_2 M + c_3 h + c_4 R - g \log R + c_5 slS_C + c_6 lS_D + c_7 slS_E \tag{1}$$

$$R = \sqrt{D_{fault}^2 + \Delta^2} \tag{2}$$

$$\Delta = 0,00724 \cdot 10^{0.507M} \tag{3}$$

Where:

$y$ = PGA (cm/s$^2$)

$R$ = hypocenter distance (km)
$M$ = Moment Magnitude with M = 8.5 to interface with M> 8.5 and M = 8.0 for intraslab with M> 8.0
$D_{fault}$ = the shortest distance to the source point that is projected to the surface (km)

To convert from the PGA value to intensity (MMI) the equation used is as follows [17]:

$$I_{MM} = 3,66 \log a_0 - 1,66 \tag{4}$$

## The PGA Model from McGuire R.K

The formulation for determining PGA according to the McGuire R K method is as follows [18]:

$$\alpha = 472.3 \times 10^{0.278M} \times (R+25)^{-1.301} \tag{5}$$

$$R = \sqrt{\Delta^2 + h^2} \tag{6}$$

$$\Delta = cos^{-1}[cos\theta_E cos\theta_S + sin\theta_E sin\theta_S cos(\phi_S - \phi_E)] \tag{7}$$

Where:

α = PGA (cm/s$^2$)
$R$ = Hypocentre distance (km)
Δ = Epicentre distance (km)
$h$ = Depth of earthquake source (km)
$\theta_E$ = latitude of the epicenter position
$\theta_S$ = latitude of the observer station
$\phi_E$ = longitude of the epicenter position
$\phi_S$ = longitude of the observer station

Richter formulated the relationship between maximum ground acceleration and earthquake intensity as follows:

$$I_0 = 3 \times (\log a_0 + 0.5) \tag{8}$$

## PGA Model from Fukushima

The formulation for determining PGA according to the Fukushima method is as follows [15]:

$$a_0 = 0.41Ms - log(D + 0.032 \times 10^{0.41Ms}) - 0.0034D + 1.3 \tag{9}$$

Where:

$a_o$ = PGA (cm/s2)
$D$ = Hypocentre distance (km)

In this Fukushima method, the geometric relationship between the hypocentre, epicenter, and observer position is used to determine the distance of the earthquake hypocentre (D). Assuming that the earth is round, a formula can be derived to determine the location of the observer of the hypocentre with the formula:

$$D = \sqrt{(X_s - X_h)^2 + (Y_s - Y_h)^2 + (Z_s - Z_h)^2} \tag{10}$$

Where:

$h$ = Depth of earthquake source (km)
D = Hypocenter distance (km)
$X_h$, $Y_h$, $Z_h$ = coordinates of the epicentre
$X_s$ $Y_s$, $Z_s$ = station coordinates

Richter formulated the relationship between maximum ground acceleration and earthquake intensity as follows:

$$I_0 = 3 \times (\log a_0 + 0.5) \tag{11}$$

Where:

$I_o$ = The intensity at the source of the earthquake (MMI)
$a_o$ = PGA (cm/s$^2$)

## METHOD

The seismicity data used were obtained from three different sources. For the West Java region, it was obtained from the BMKG Yogyakarta database in the period 1997-2018, Central Sulawesi from the International Seismological Center (ISC) database in the period 1985-2015, and for the Lombok region it was obtained from the United States Geological Survey's (USGS) database in 1980-2010. The steps taken to create a map of the level of damage due to the earthquake are as follows:

1. Data collection from data providers as stated above, in the form of latitude, longitude, magnitude, depth, and time of occurrence.
2. Compile earthquake historical data for an area according to the selected period based on latitude, longitude, magnitude, and depth with defined area boundaries and the minimum intensity according to the method.
3. Divide the study area into several grids according to the method chosen using the appropriate program.
4. Calculate epicenter and hypocenter distances according to the method chosen.
5. Calculate the PGA value at each point of the observation grid according to the method chosen.
6. At each place (grid point), the highest PGA value is chosen so that the highest PGA value is obtained at each site in the area studied.
7. Make a PGA contour map using a suitable program, for example, Arcview GIS 3.3.
8. Making maps of the level of risk of damage due to earthquakes according to the study area

## RESULTS AND DISCUSSION

The following section provides a map of the level of risk of damage due to earthquakes in the three studied areas, namely West Java, Central Sulawesi and Lombok. Making maps of the three regions was carried out using different methods. For the West Java region, it was made using the Atkinson Boore method, Central Sulawesi with the Mc Guirre R.K method, and for Lombok the Fukushima method.

### Map of Peak Ground Acceleration

Two data are used to create a map of the level of risk due to earthquakes in the West Java region calculated by the Atkinson-Boore (2003) method, namely the 1997-2018 earthquake data and the Vs30 data from the USGS. This data is then filtered according to the parameters of the Atkinson-Boore (2003) method, including magnitude 5-8.3 SR, type Mw (Moment Magnitude), depth <60 km, and the earthquake is in the subduction earthquake category. After the filter is carried out, the earthquake data that is significant and damaging are obtained as in Table 1.

**TABLE 1.** Significant and Destructive Earthquake Data for West Java in 1997-1208 Based on Parameters of the Atkinson Boore Method (2003) [18]

| Date of Incident | Place of Incident | Longitude (°EL) | Latitude (°EL) | Depth (km) | Magnitude (SR) |
|---|---|---|---|---|---|
| Jakarta | 17/03/1997 | 104.69 | 7.40 | 33 | 6,0 |
| P. Panaitan | 21/12/1999 | 105.64 | 7.21 | 33 | 6,0 |
| Pandeglang | 25/10/2000 | 105,00 | 7.20 | 33 | 6.5 |
| Sunda Strait | 27/06/2002 | 104.18 | 6.96 | 11 | 6.5 |
| Tasikmalaya | 02/09/2009 | 107.32 | 8.24 | 30 | 7.3 |
| Sunda Strait | 16/04/2013 | 104.72 | 6.25 | 48 | 6.7 |
| Sunda Strait | 16/10/2009 | 105.11 | 6.79 | 10 | 6.4 |

Figure 2 shows the PGA map for the West Java region where the areas with the highest PGA values are in the south-southwest part of Sukabumi District, the southwestern tip of Cianjur, Cirebon and Indramayu Districts with PGA values between 100 - 130 gal. This PGA value is equivalent to the VI MMI scale. On this scale the earthquake was felt by everyone, many people ran outside in shock, crockery, small items and books fell from the shelves, pictures fell off the walls etc. [20]. Intensities with an MMI IV-V scale are found in Cianjur, Garut, Pangandaran, Tasikmalaya and Majalengka Districts. The area with the highest magnitude (VII MMI) is in the southern sea of Sukabumi so it does not have a direct impact on humans but can result in a Tsunami. Areas with PGA values between 40 - 90 gal (V MMI) include most of the cities and regencies of Sukabumi, Cianjur, Indramayu, southern parts of Bogor, Bandung, Garut, Pangandaran, northern Kuningan, Majalengka and Subang Districts. Areas with a relatively small level of risk with the MMI IV scale, which is located in the middle of West Java Province from northwest to southeast. An earthquake on this scale can still be felt in the house as if a heavy truck was passing by.

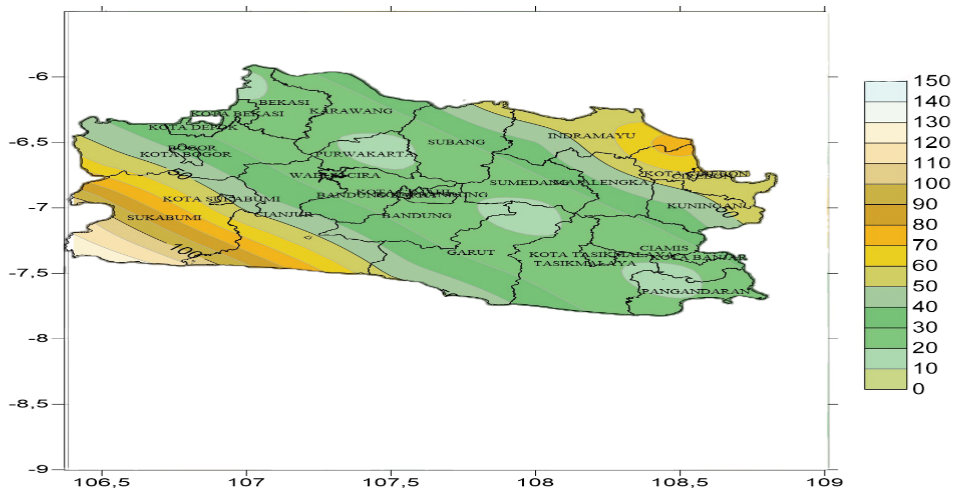
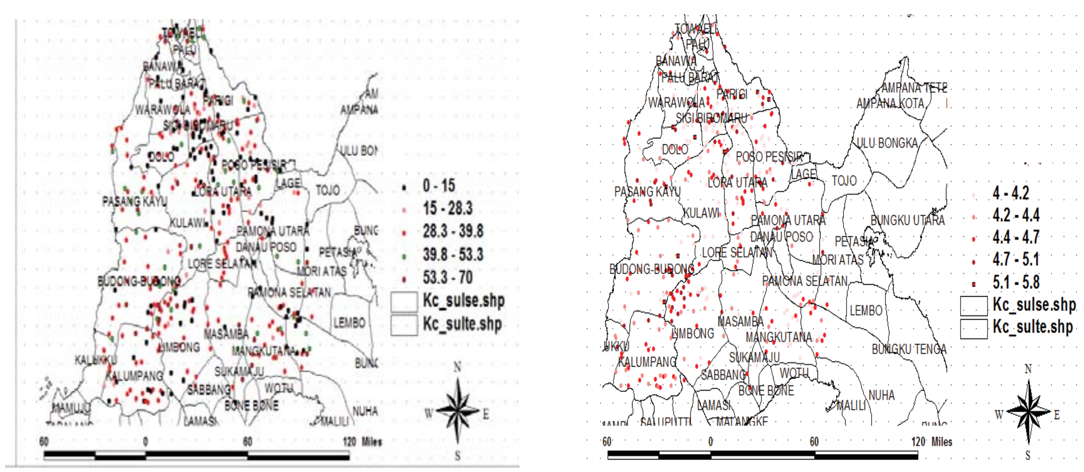



**FIGURE 2.** Map of PGA of West Java Grid 0.5° x 0.5° [18]

The map of the level of risk of damage due to the earthquake in the Central Sulawesi region was made using the McGuire R.K. method. The data were obtained from the International Seismological Center (ISC) database for the period 1985-2015. The parameter of the earthquake is the magnetism ≥ 4 SR with a depth of ≤ 70 km. With this parameter, 266 earthquake events were obtained with details of 19 destructive earthquakes (5-6 SR) and 247 moderate earthquakes (4-5 SR) with the hypocenter and magnitude distribution maps as shown in Fig. 3.




(a) (b)

**FIGURE 3.** (a) Hypocentre distribution map [20] (b) Distribution map of magnitude values [20]

Figure 4 shows a map of the level of risk of damage due to an earthquake in the Central Sulawesi region based on PGA data using the McGuire R.K. method. The PGA value in this region is between 13 - 168 gal. With the conversion from the PGA value to the MMI scale, 3 classes of damage levels were generated in this area, namely V - VI, VII and VIII MMI. There are three locations for the level of damage on the VIII scale. The first location is on the border of four sub-districts, namely Tumoo and Tubadak Sub-Districts, Mamuju District (West Sulawesi Province) with Seko and Limbong Sub-Districts, North Luwu District (South Sulawesi Province). The level of risk has decreased to the MMI VII scale in surrounding sub-districts. The second location is in Poso District, including Panoma Utara, Pamona Timur, Poso Pesisir Selatan and Pamona Puselemba. The third location is in three districts, namely Donggala (Banawa, Pinembani and Rio Pakava Sub-Districts), Sigi (West Dolo, Dolo, Marawola, West Marawola, Kinovaro and Sigi Biromaru Sub-Districts) and Palu City (West Palu and South Palu Sub-Districts). The impact of this scale includes damage to strong buildings with certain parts collapsing and some parts of the wall that collapse.

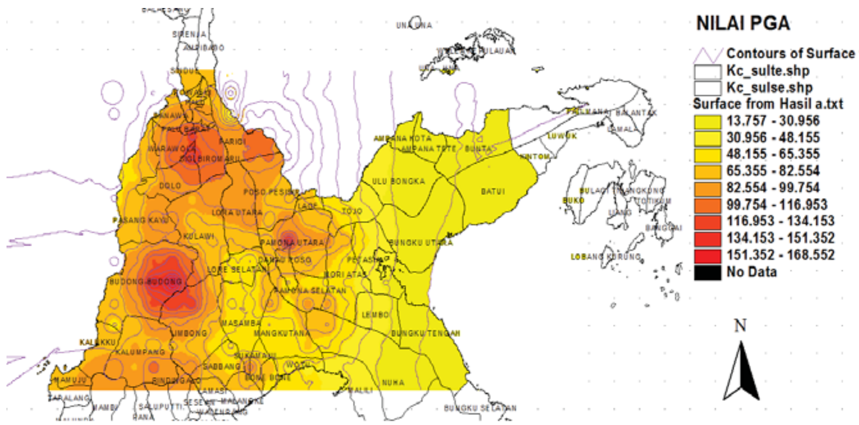



**FIGURE 4.** Map of PGA in Central Sulawesi Grid 0.15° x 0.15° [20]

Areas with an VIII scale but lower PGA scores are in Sausu, Balinggi and Torue Districts, Parigi Moutong District which extends to Pesisir Utara District, Poso Regency. The level of risk of damage is almost the same as T in Rindingalo District, North Toraja Regency. Areas with a level of risk of damage with a scale of V-VI are in almost all areas in the central to eastern part of Central Sulawesi.

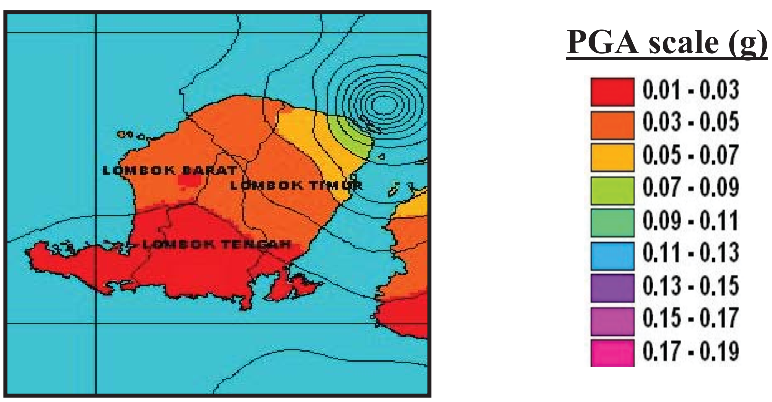



**FIGURE 5.** Map of PGA in Lombok grid 0,25° x 0,25° [21]

The PGA map for the Lombok region based on the Fukushima method with values between 0.1- 0.13 gal is shown in Fig. 5. The conversion from this PGA value to the MMI scale resulted in four classes on the MMI scale, namely IV-V, V-VI, VI-VII, and VII-VIII. The districts with the highest risk of damage on the island of Lombok are East Lombok District, followed by North Lombok and West Lombok, including Mataram City. The sub-districts in East Lombok Regency with a scale of VII-VIII MMI are Sambelia and Sembalun. Almost all sub-districts in North Lombok and West Lombok Regencies are on the VI-VII MMI scale, especially Bayan and Kayangan Sub-Districts.

## Geology and Tectonic Studies

The geological and tectonic arrangements in West Java are strongly influenced by activities in the subduction zone. From the study of the level of risk of damage due to earthquakes in this area in 1997-2018 as reviewed above, it turns out that there is something that happened in the last two years (2019-2020). From January 2019 to April 2020 in West Java there were ten destructive earthquakes. The earthquake occurred four times in Sukabumi and Pangandaran districts four times, and once in Tasikmalaya in Majalengka once. Eight of the ten earthquakes were hypocenter from the subduction zone and the other two were from land faults.

In general, activity at convergent plate boundaries in southern West Java causes a complex geological setting. Hilmi and Iyan [22] in this case said that the follow-up process of activities in the subduction zone has resulted in a geological arrangement in the form of trenches, non-volcanic outer arcs, front arcs, volcanic arcs and rear arcs. Three dominant structures formed on the mainland of West Java, namely the Maratus Pattern, Sundanese Pattern and Javanese Pattern. The geological structures that represent the three patterns are the Cimandiri fault as an interpretation of the Meratus Pattern, the Sunda Basin and the Arjuna Basin interpretation of the Sunda Pattern and the Baribis Fault interpretation of the Javanese Pattern [23]. Earthquakes that occur with earthquake sources on land are caused in large part by the activity of these three dominant structures.

The earthquake in Central Sulawesi was mostly caused by the tectonic activity of the Palu-Koro Fault. This fault is an active sinistral fault with a displacement speed of about 25-30 mm / year which extends approximately 240 km from the north (Palu City) to Bone Bay [24]. From a mapping study on the level of risk of damage due to earthquakes in this area from 1985-2015 as reviewed above, it turns out that there is an agreement with earthquakes that have occurred during the last five years (2016-2020). For example, a large earthquake with an intensity of 7.4 on the Richter scale that occurred on September 28, 2018, had an impact that extended to West and South Sulawesi which also caused a tsunami nearly 5 m high in Palu. Five areas that were severely affected according to the study results, including Donggala, Palu, Sigi, Poso and Parigi Moutong. This earthquake also caused liquefaction in Palu and Sigi.

In the last ten years there were three times the destructive earthquakes on the island of Lombok that occurred in a row. The earthquake occurred on 29 July, 5 and 19 August 2018 with a magnitude 6.4 SR, 7 SR and 6.5 SR. The areas with the most severe damage were Sambelia and Sembalun Districts, East Lombok Regency, Bayan District, North Lombok Regency, West Lombok, and Mataram City. This severely affected area corresponds to a map of the level of risk of damage due to earthquakes which is based on earthquake data from 1980-2010.

Geologically, the island of Lombok is located on the Banda Arc and is one of a series of islands in Nusa Tenggara formed by young volcanoes. Tectonically, this series of volcanoes was formed due to the subduction of the Indo-Australian plate against the Banda Arc [25]. The recent destructive earthquakes that occurred on the island of Lombok were caused by the tectonic structure of the upward fault behind the archipelago or commonly known as the Flores Back Arc Thrust which stretches from northeast Bali to north Flores [26]. The structure of the Back Arc Thrust is formed due to the back edge of the Eurasian Plate against the Indo-Australian Ocean Plate. The phenomenon of the arc continent collision is thought to control the upward fault deformation mechanism in the north of Lombok Island [27]. Deformation of the upward fault in the north of the island of Lombok is what caused destructive earthquakes that occurred in Lombok in July and August 2018.

The suitability between the map of the level of risk of damage due to germination and subsequent earthquake events shows that as one of the disaster mitigation efforts, this research is important to carry out as a material for composing a spatial plan for an area. This map can also be used as a guide in determining the quality of earthquake resistant infrastructure.

## CONCLUSIONS

From the mapping of the level of risk of damage due to earthquakes in the three studied areas, it can be concluded that:

1. Based on earthquake data for 1997-2018, several districts in West Java, the level of risk due to the earthquake, are on the MMI VI scale, including Cianjur, Cirebon and Indramayu districts. Districts with lower risk levels (IV-V MMI) include Cianjur, Garut, Pangandaran, Tasikmalaya and Majalengka. The highest level of risk (VII MMI) is in the south of Sukabumi so it does not have a direct impact on humans but can result in a Tsunami.
2. In Central Sulawesi, based on earthquake data for 1985-2015, several districts have the level of risk due to the earthquake on the VIII MMI scale, including Donggala, Palu, Sigi, Poso and Parigi Moutong (Central Silawesi), Pasang Kayu and Mamuju Districts (West Sulawesi) and Luwu Urata and Toraja Urata (South Sulawesi). The devastating earthquake in 2018 had a very severe impact on these areas.
3. From the map of the level of risk of damage due to earthquakes in the Lombok region compiled based on the earthquake data for 1985-2010, it can be seen that East Lombok is at the highest risk, followed by North Lombok and West Lombok, including Mataram City. These were the areas that were worst affected by the 2018 earthquake.

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