The Spatio-temporal Tectonic Condition and Microzonation Map of Malang Region after the 2021 M6.1 Malang Earthquake for Disaster Risk Mitigation

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Abstract. The M6.1 earthquake which hit Malang and its surroundings in 2021 resulted in fatalities and over 10,400 damaged houses. Several seismicity studies have been carried out for Malang region, but no specific studies have implied the M6.1 Malang earthquake yet. This study addresses such gap by investigating the Spatio-temporal b-value of Gutenberg-Richter Law and generating the microzonation maps of spectral acceleration by considering the effects of the M6.1 Malang earthquake. The earthquake data compiled from the national and international earthquake catalogs were homogenized into a moment magnitude scale. The b-value analysis was calculated using the Maximum Likelihood method and spatio-temporal mapping. Several ground motion prediction equations (GMPEs) were selected for subduction and shallow crustal earthquake sources to generate probabilistic seismic hazard analysis (PSHA). PSHA was conducted using the 2% probability of exceedance in 50 years. The results show that the b-value after the M6.1 Malang earthquake still tends to decrease, indicating a relatively-high stress level which accommodates the potential for large earthquakes in the future. The microzonation maps for Malang region show that the southern part of Malang has a higher spectral acceleration value than the others. Therefore, these findings can be considered in the future disaster mitigation plan.

1. Introduction

Malang is one of the most densely populated areas in East Java after Surabaya with a population density of 752 people/km² [1]. The devastated earthquake hit the Malang region on April 10, 2021, with a magnitude of Mw 6.1 at coordinates 8.84°E and 112.47°S and a depth of 86km. The earthquake caused by the subduction activity showed a thrust fault mechanism [2] which resulted in fatalities and severe building damage. This earthquake was also felt in several areas of East Java with the intensity between II and VII MMI scale. The isoseismal map of the Malang earthquake and its impact in detail is presented in Figure 1. The seismic intensity map conducted by BMKG [3] showed that the Malang region felt the earthquake with an intensity of V MMI scale, which means that the earthquake was almost felt by all residents. Lumajang region has the highest earthquake intensity compared to other regions, with an intensity scale of VII MMI.

Based on data from the Regional Disaster Management Agency (BPBD) [4], the earthquake resulted in 4 deaths and 110 injuries, more than 10,400 houses were damaged, and over 640 public facilities were
destroyed. Therefore, the mitigation effort is crucial to minimize the earthquake disaster risk. Several studies related to seismicity in the Malang region have been carried out, such as the research conducted by [5-7]. However, the study related to the evaluation of tectonic parameters (b-value) and specific earthquake analysis involving the 2021 M6.1 Malang earthquake has not been available yet. Whereas the spatial and temporal variation of the b-value is regarded as crucial clues for the future major earthquake precursors [8]. This study addresses these gaps by investigating the b-value of Gutenberg-Richter Law relating to the tectonic condition of the study area and generating a microzonation of spectral acceleration maps for the Malang region involving the effects of the 2021 M6.1 Malang earthquake. The findings of this study are expected to be one of the references in earthquake disaster mitigation efforts and spatial-building planning in Malang and surrounding areas.

Figure 1. Isoseismal map of the 10 April 2021 Malang earthquake based on MMI scale [3] and graph of losses and casualties due to the earthquake

2. Materials and Methods

2.1. Earthquake data
The data used in this study is earthquake data for the Malang specific region covering coordinates of 7.5 – 10°S and 112-113.5°E from January 1962 to July 2021. Meanwhile, for generating the microzonation maps, earthquake data was taken covering an area within 500km radius from the Malang region with magnitude Mw≥4.5 and a maximum focal depth of 300km. The earthquake data were obtained from the national earthquake catalog (the Meteorological, Climatological, and Geophysical Agency, BMKG) and international earthquake catalogs such as the International Seismological Center – Engdahl, van der Hilst and Buland (ISC-EHB) and the United States Geological Survey (USGS). The earthquake data compilation was then homogenized into the Moment magnitude (Mw) scale, which is commonly used in the seismology field. Conversion from body-wave magnitude (mb) and surface-wave magnitude (Mw) to Mw scale was carried out using the equations in Table 1 [9]:

| Conversion relation | Magnitude range | Standard Error (SE) | Consistency (R²) |
|---------------------|----------------|---------------------|------------------|
| Mw = 1.0332mb - 0.0834 | 3.2 ≤ mb ≤ 8.2 | 0.238 | 0.802 |
2.2. Tectonic parameter

The stress level related to the tectonic condition or rock fragility in seismology field is expressed by the b-value parameter. The seismicity pattern of an area can be determined by analyzing the relationship between frequency and magnitude is described in the Gutenberg-Richter equation [10]:

\[
\log N = a - b M
\]

(1)

where N is the number of earthquakes with magnitude \( M > M_0 \), a and b are constants. The a-value expresses the seismic activity, while b-value represents the earthquake distribution related to tectonic condition. This constant is related to tectonic conditions and rock properties that can describe local stress activity. The b-value is an earthquake parameter that measures the accumulation of stress in rocks. The low b-value is associated with the high shear stress, and vice versa [11]. The estimated b-value is calculated using the simple form provided by Aki-Utsu [12,13] with the following equation:

\[
b = \frac{1}{\bar{M} - M_0} \log e
\]

(2)

where \( \bar{M} \) denotes the average magnitude and \( M_0 \) is the minimum magnitude of earthquake data, which this study used the magnitude completeness (Mc). The b-value parameter was analysed spatially and temporally using Zmap software [14] with a denser grid of 0.03° x 0.03° and a constant radius of 110km.

2.3. Probabilistic Seismic Hazard Analysis (PSHA)

The probabilistic approach for seismic hazard analysis was conducted by calculating the probability of a particular value of x will be exceeded an earthquake event X [15]. Considering the magnitude m and distance R of earthquake event, the formula of total probabilistic model [16-18] is written as follows:

\[
P_x(X > x) = \int_{\frac{\bar{M} - M_0}{M}} \int_{R} P(X > x | m, r) f_m(m) f_r(r) \, dr \, dm
\]

(3)

Where \( M \), m is magnitude, R, r is distance, \( f_m \) and \( f_r \) are probabilistic density function for magnitude and distance, respectively.

| Fault model | Magnitude uncertainty | Ground motion model |
|-------------|-----------------------|---------------------|
| Shallow crustal Fault | \( M_{max} - 0.2 \) | 0.6 | Boore et al. 1997 |
| Characteristic | 0.2 | Boore et al. 1997 |
| Gutenberg-Richter | \( M_{max} \) | 0.66 | Chiuou-Youngs NGA 2006 |
| | \( M_{max} + 0.2 \) | \( \frac{1}{3} \) | Chiuou-Youngs NGA 2006 |
| Subduction model | Magnitude uncertainty | Ground motion model |
|------------------|-----------------------|---------------------|
| Subduction | \( M_{max} - 0.2 \) | 0.2 | Youngs et al. 1997 |
| Trace | 0.2 | Youngs et al. 1997 |
| Gutenberg-Richter | \( M_{max} \) | 0.66 | Atkinson-Boore 2003 |
| | \( M_{max} + 0.2 \) | \( \frac{1}{3} \) | Atkinson-Boore 2003 |
| | \( M_{max} \) | 0.6 | Gregor NJ 2006 |
| | \( M_{max} + 0.2 \) | \( \frac{1}{3} \) | Gregor NJ 2006 |

**Figure 2.** Logic tree for shallow crustal and subduction earthquake source
2.4. Ground Motion Prediction Equation (GMPE)
Some researchers introduced how to select and adjust the GMPE models properly [19-21]. The GMPE selected in this study was based on the seismotectonic conditions classified due to the earthquake source mechanisms. This study applied the GMPE formula of Youngs et al. 1997, Atkinson-Boore 2003 and Gregor 2006 [22-24] for subduction mechanisms. Meanwhile, the GMPE of Boore et al. 1997, Chiou and Youngs NGA 2006 and Boore-Atkinson NGA 2006 [25-27] were selected for the shallow crustal fault mechanisms. The analysis used the Logic tree model in considering the epistemic uncertainty [28] with the same weighting in each GMPE as shown in Figure 2. The magnitude relative distribution for each earthquake source was modelled using the exponential model of Gutenberg-Richter and characteristic with weights of 0.34 and 0.66, respectively.

3. Results and Discussion
3.1. Seismic activity of Malang region
Earthquake data from various earthquake catalogs previously mentioned in the method section were obtained from 1962 to July 2021 with a total of 669 events for the Malang specific region. This earthquake data is then homogenized into a Mw scale with the equation provided in Table 1. The Earthquake catalog and the Frequency-Magnitude Distribution (FMD) based on the Gutenberg-Richter equation (1) of Malang region and its surrounding are presented in Figure 3.

![Figure 3](image)

**Figure 3.** Earthquake catalog and FMD of Gutenberg-Richter Law for Malang region and its vicinity a). Location of earthquake epicenter from 1962 to July 2021 b). FMD before M6.1 Malang Earthquake (from 1962 to 9 April 2021) c). FMD after M6.1 Malang Earthquake (from 10 April to 31 July 2021).

The figure shows that the earthquake tends to occur in the southern Malang region. Earthquakes that occurred in the benioff zone around Malang have a depth of 50-200km, but the distance to the Malang region is closer than the megathrust earthquakes zone, which are hundreds of kilometers further away. However, megathrust earthquakes have a history of large magnitudes and some of them trigger tsunamis, so they are important to consider in seismic analysis. The FMD model after the M6.1 Malang earthquake
is slightly steeper than the one before the large earthquake occurred. The b-value decreased from 0.87 ± 0.03 to 0.85 ± 0.03. In order to get more detailed information about the seismic activity pattern in this region, observations of magnitude and the cumulative number of earthquakes through time were conducted. The correlation between them is displayed in Figure 4.

![Figure 4](image-url)

**Figure 4.** Distribution of earthquake magnitude and their cumulative number through time

The figure reveals that the earthquakes recorded before 1980 were large earthquakes due to the limited earthquake instrument ability. The yellow stars present the events with magnitude M>5.7. The pattern of small earthquakes was shown in the year range of 1998 to 2012 so that then a large earthquake occurred in 2013 (M5.9) due to the accumulation of energy during that year gap. The following pattern can be seen in the year range of 2014 to 2018, where many small earthquakes appeared until then the large earthquakes occurred in 2019 and 2021.

3.2. Spatio-temporal b-value

The b-value analysis through time calculated for the specific area of Malang and its surroundings was observed until April 9, 2021 (before the 2021 M6.1 Malang earthquake occurred). The b-value by time graph is presented in Figure 5. Based on the figure, we can see some pattern of b-value related to the occurrence of large earthquakes. The significant gap of large earthquake occurred after an earthquake with a scale of M6.6 in 1998. There was no earthquake with a scale of M > 5.7 during 1999 to 2012. There is an increase of b-value before finally the large earthquake occurred in 2013. The b-value then significantly decreases, even after the large earthquake in 2019 (M5.7) until April 9, 2021 (before the Malang earthquake occurred). A lower b-value indicates an increase in seismic hazard in this period because it tends to generate large earthquakes relative to the data catalog. In order to observe the b-value for Malang region in more detail, the spatial b-value before and after the 2021 M6.1 Malang earthquake are displayed in Figure 6.
In general, the north and east side of Malang region tends to have the highest b-value, which is about 1.0 to 1.08, both before and after the M6.1 2021 Malang earthquake. The b-value in the epicenter area before the large earthquake occurred is smaller than the surrounding area, which is about 0.88. This condition indicates that the area has more significant pressure than the surrounding area which has a higher b-value. The existence of great pressure causes the emergence of large earthquakes to release earthquake energy. In the spatial b-value map after the 2021 M6.1 Malang earthquake, the area around the earthquake epicenter is still in a green zone, which means that the b-value is still low, even lower than before the Malang earthquake occurred. In addition, the area that surrounds it has a higher b-value, indicating that the area near the epicenter still has the trapped accumulated energy. In general, after the large earthquake occurred, the b-value will increase and then fall again. However, the results of observations in this study show that the b-value after the Malang earthquake still tends to decrease. This means that there is a relatively large level of stress caused by the stress of energy accumulation, which allows for the potential for forthcoming large earthquakes.
3.3. Microzonation map of spectral acceleration

The probabilistic seismic hazard analysis (PSHA) is becoming the essential step to obtain the spectral acceleration value for Malang region. The earthquake catalog used for PSHA is an earthquake catalog within a radius of 500km from the Malang region with a magnitude of Mw>4.5. All the earthquakes (6,943 events) then be homogenized into the Mw scale and be declustered using the Reasenberg method [29]. The shear wave velocity (Vs) 760m/s was employed to obtain the spectral acceleration values at bedrock. The earthquake sources used in this study are subduction earthquakes sources and shallow crustal faults within a radius of 500km from Malang. The earthquake fault sources used were 12 faults, namely Ciremai, Cirebon, Brebes, Semarang, Pati trust, Opak, Cepu, Waru, RMKS East, Bali, Lombok Central and Lombok North fault. Meanwhile, the source of subduction earthquakes divided into Megathrust and Benioff segments followed the previous research [9] is shown in Figure 7.

![Figure 7. The shallow crustal fault and subduction earthquake sources for Malang region](image)

The PSHA for this study was conducted in each grid point of Malang region which the distance between points is about one kilometer using equation (3). Analysis was carried out for 4,224 points within the Malang region to obtain the value of Spectral acceleration (SA) at bedrock for period of 0.0s (peak ground acceleration, PGA), 0.2s (S0), and 1.0s (S1) with 2% probability of exceedance (PE) in 50 years. The results of the spectral acceleration analysis for bedrock PGA values for the Malang region

| Subduction segment | Index | b-value | a-value | Mmax |
|--------------------|-------|---------|---------|-------|
| Megathrust         | M-1   | 1.060   | 5.870   | 8.94  |
|                    | M-2   | 1.020   | 5.010   | 8.91  |
|                    | M-3   | 1.260   | 6.910   | 8.92  |
|                    | M-4   | 1.110   | 6.350   | 9.08  |
| Benioff            | B-1   | 1.120   | 6.020   | 8.84  |
|                    | B-2   | 0.866   | 4.280   | 8.84  |
|                    | B-3   | 1.270   | 6.260   | 8.85  |
|                    | B-4   | 0.982   | 5.350   | 9.01  |

The PSHA for this study was conducted in each grid point of Malang region which the distance between points is about one kilometer using equation (3). Analysis was carried out for 4,224 points within the Malang region to obtain the value of Spectral acceleration (SA) at bedrock for period of 0.0s (peak ground acceleration, PGA), 0.2s (S0), and 1.0s (S1) with 2% probability of exceedance (PE) in 50 years. The results of the spectral acceleration analysis for bedrock PGA values for the Malang region...
are 0.30 – 0.68g. This result covers the PGA result from [7] which is 0.31 – 0.43g and the result of [6], which is 0.50 – 0.65g. The values of spectral acceleration at bedrock in the 0.2s period are higher than the SA values in the 0.0s and 1.0s periods, ranging from 0.61g to 1.30g. As for the 1.0s period, the SA value is 0.30 – 0.48g. This result is larger than the investigation conducted by [7], which is 0.62 – 0.88g and 0.22 – 0.28g for the 0.2s and 1.0s periods, respectively. This difference is because this study has used the latest fault data sources according to the [30] and subduction earthquake source parameters with the latest earthquake catalog data up to July 2021 involving the 2021 M6.1 Malang earthquake. The results of the SA values for 4,224 points were then used as the key values for generating the spectral acceleration microzonation map for the periods of 0.0s (PGA), 0.2s (S<sub>S</sub>), and 1.0s (S<sub>1</sub>). The spectral acceleration microzonation map for PGA, S<sub>S</sub> and S<sub>1</sub> are presented in Figure 8.

![Figure 8. Microzonation map of spectral acceleration at bedrock for Malang region after the 2021 M6.1 2021 Malang earthquake](image)

The spectral acceleration microzonation map for Malang region was generated using ArcGIS Pro based on the SA data at each point location. The PGA map at bedrock is divided into eight SA zones...
with a SA value range of 0.3-0.7g. The $S_5$ and $S_1$ maps at bedrock have ten SA value zones (0.6-1.3g) and four SA value zones (0.3-0.5g), respectively. The results of the SA value ranges in this study are almost the same as the range of SA values on the latest spectral acceleration map of Indonesia [31], where the values are 0.3-0.6g, 0.7-1.2g, and 0.3-0.6g for PGA, $S_5$, and $S_1$, respectively. The three maps show that the southern part of Malang has a higher SA value than the northern part of Malang. Donomulyo, Bantur, Gedangan, and Sumbermanjing sub-districts have the highest SA values for all investigated periods compared to other sub-districts. Spectral acceleration values of Malang region are dominantly influenced by the subduction earthquake sources. The further south, the greater the spectral acceleration value as the depth of the earthquake source tends to be shallower.

4. Conclusion

The seismic distribution related to tectonic conditions and microzonation maps for the Malang region have been conducted. The number of small earthquakes causing the energy of earthquake released more smoothly, while the less frequent earthquakes occur, the possibility of large earthquakes will be greater. The temporal b-value analysis shows a significant decrease of b-value values from 2012 until before the Malang earthquake (April 9, 2021). A decrease in the b-value indicates an accumulation of trapped energy causing a high stress level, which triggers a large earthquake. The spatial analysis result shows the variation of b-value from 0.72 to 1.08. Thus, the b-value map shed light on the indication of a relatively decreased b-value even until the last day of observation. This phenomenon indicates the possibility for future large earthquakes in the study area.

Based on the acceleration microzonation maps at bedrock for Malang region, the range of SA values is 0.3-0.7g for PGA, 0.6-1.3g for a short period ($S_5$), and 0.3-0.5 for a long period ($S_1$). The subduction earthquake sources dominantly influence spectral acceleration values of the Malang region. The further south, the depth of the earthquake source tends to be shallower so that the spectral acceleration is relatively higher. Several areas in the southern Malang region, such as Donomulyo, Bantur, Gedangan, and Sumbermanjing sub-districts have higher spectral acceleration values than other areas. These study findings can be references in earthquake disaster mitigation, such as earthquake-resistant building design and spatial-building planning in Malang and its vicinity.

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