FARADAY:
Journal of Fundamental Physics, Research, and Applied Science
Vol. 2, No. 1, January 2026, pp. 7–15, e-ISSN: 3109-1318

Seismicity Analysis of Earthquakes in Bengkulu Using Gutenberg-Richter and Omori Laws

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Article Info

Article History:

Received 12 26, 2025
Revised 01 31, 2026
Accepted 02 06, 2026
Published 07 02, 2026

Keywords:

Earthquake
Seismicity
Gutenberg-Richter
Omori Utsu
Bengkulu

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ABSTRACT

Bengkulu Province is one of the regions in Indonesia with high seismic activity because it lies within the Sumatra tectonic plate zone and is crossed by the Sumatra Fault system. This tectonic setting makes Bengkulu highly vulnerable to earthquakes. This study analyzes the seismic characteristics of Bengkulu using the Gutenberg–Richter law and examines the aftershock pattern following the major earthquake of June 4, 2000, based on the Omori–Utsu law. The data were obtained from the USGS earthquake catalog, consisting of earthquake records from 2015–2025 and aftershock data for 30 days after the mainshock. The Gutenberg–Richter analysis evaluates the relationship between $log_{10}N$ *and moment magnitude (Mw) to determine the a and b values. Meanwhile, the Omori–Utsu analysis examines the relationship between* $log_{10}\, n(t)$ *and* $log_{10}\,(t + c)$ *to obtain the parameters p and k. The results show that Bengkulu's seismicity is dominated by small to moderate earthquakes with relatively low b-values, indicating high tectonic stress conditions. The aftershock analysis produced a p-value of 1.4822 with an* R^2 *value of 0.7767, showing rapid aftershock decay consistent with the Omori–Utsu law. These findings confirm Bengkulu has a high seismic hazard level, emphasizing the need for continuous mitigation and preparedness efforts.*

1. INTRODUCTION

Indonesia is located at the confluence of three major tectonic plates: the Pacific Plate, the Eurasian Plate, and the Indo-Australian Plate. These three plates form a subduction zone system that remains active to this day (Jayadi et al., 2025). This condition places Indonesia as part of the Global Ring of Fire, resulting in a relatively high frequency of earthquakes and seismic activity compared to other countries. One form of seismic event that frequently occurs is earthquakes, which cause damage almost every year in various regions of Indonesia (Hakim, 2024).

An earthquake is a movement of the ground caused by tectonic activity, such as the movement of the earth's plates and ground cracks. Indonesia is located at the junction of the Australian, Eurasian, and Pacific plates, so it frequently experiences high-intensity earthquakes, especially near the plate boundaries. Earthquakes can cause damage to buildings and loss of life. Undersea earthquakes can also trigger tsunamis in coastal areas (Murtianto, 2016).

Bengkulu Province is prone to earthquakes because it is located at the center of three active tectonic zones: the Sumatran Fault, the Mentawai Fault, and the Sumatran subduction zone. This subduction zone is where the Eurasian and Indo-Australian Plates meet, resulting in high earthquake activity in this region (Mase, Sugianto, & Refrizon, 2021). Geographically, Bengkulu is located in the western part of the Bukit Barisan Mountains on Sumatra Island, covering an area of approximately 19,788.7 km². This region borders directly on the Indian Ocean and has a coastline of approximately 525 km, increasing the risk of earthquakes, especially subduction earthquakes (Zulyanto, 2010). South Bengkulu Regency is a coastal area prone to earthquakes due to its proximity to the Manna Segment of the Sumatran Fault and the Sumatran Subduction Zone, placing it at risk of earthquakes from land faults or subduction earthquakes (Kencoro et al., 2023). The presence of other active segments of the Sumatran Fault also increases the possibility of earthquake hazards in the Bengkulu region (Ardiansyah, 2018; Hadi, Farid, & Fauzi, 2012).

The Bengkulu region has experienced major earthquakes, such as the 2000 Bengkulu–Enggano earthquake and the 2007 earthquake. Both earthquakes caused severe damage to buildings and important facilities, especially in South Bengkulu. The 2000 earthquake occurred due to the subduction of the Indo-Australian plate beneath the Eurasian plate, an area with the potential to produce major earthquakes. The earthquake was also followed by a series of aftershocks (Farid & Mase). Analysis of this mainshock is very important because the frequency and strength of aftershocks can indicate stress conditions, energy release processes, and the complexity of the earth's crustal structure in the Bengkulu area. Therefore, statistical analysis is needed to clarify the characteristics of the seismicity in the region quantitatively.

One frequently used analysis is the Gutenberg–Richter law, which explains the relationship between earthquake frequency and magnitude. Parameter a indicates how active an area is in earthquakes, while parameter b reflects the stress conditions in the Earth's crust and the properties of the rocks. Therefore, the b value is often used as a marker for the likelihood of a region experiencing a major earthquake (Diantari et al., 2018; Popandopoulus & Chatziioannou, 2014; Godano et al., 2014; Han et al., 2015; Marzocchi et al., 2016). Furthermore, to analyze aftershocks, the Omori and Omori–Utsu laws are used, which show how the number of aftershocks decreases over time after the mainshock. Parameters p, k, and c describe the rate at which activity decreases and how energy is released after an earthquake (T. Utsu).

This study utilizes earthquake data from the United States Geological Survey (USGS) catalog, which boasts a high level of accuracy and consistency. Thus, seismicity analysis in the Bengkulu region can be conducted systematically in accordance with international standards, both for aftershock studies following the 2000 major earthquake and for medium-term seismicity studies. The purpose of this study is to analyze the seismicity characteristics of the Bengkulu region using the Gutenberg–Richter law and to explore the aftershock reduction pattern based on Omori's law. This is expected to provide a better understanding of seismic behavior and serve as an initial basis for earthquake hazard studies and disaster risk reduction efforts in the region.

2. METHOD

This study uses earthquake data from the United States Geological Survey (USGS) catalog, which includes earthquakes in the Bengkulu region during the period of December 2015 to December 2025, as well as aftershocks for 30 days after the Bengkulu earthquake of June 4, 2000. The studied area has coordinates of 2°16′ to 3°31′ South Latitude and 101°1′ to

103°41′ East Longitude. The parameters analyzed include the time of earthquake occurrence, moment magnitude (Mw), hypocenter depth, and epicenter location. Data completeness is determined using the completeness magnitude (Mc) with the maximum curvature method. All magnitude data, especially the wave body magnitude (mb), are converted to Mw using the equation (Taruna et al., 2021):

$$Mw = 0{,}1140mb^2 - 0{,}556mb + 5{,}560 \quad (1)$$

The data is grouped based on the magnitude interval, then counted how many times it occurs, and the value of $\log_{10}$N is used For determine parameters a and b in Gutenberg–Richter law. In analysis earthquake follow-up, used Omori– Utsu law with the equation (Rodrigo et al., 2021):

$$n(t) = \frac{k}{(t+c)^p} \quad (2)$$

where $n(t)$is the aftershock rate (events/day) at elapsed time t(days) after the mainshock, and k, c, and $p$are model parameters. To avoid the singularity at $t = 0$and to reduce early-time incompleteness, $c$was fixed at 1 day.

Because the aftershock data were tabulated in multi-day time bins (e.g., 1–3 days, 4–7 days), the rate was computed for each bin $i$as:

$$n(t_i) = \frac{N_i}{\Delta t_i}, \quad (3)$$

where $N_i$is the number of aftershocks in the bin and $\Delta t_i$is the bin duration (days). The representative time $t_i$was taken as the midpoint of each bin. Parameter estimation was performed by linear regression of the log-transformed form:

$$\log_{10} n(t) = \log_{10} k - p \log_{10}(t+c). \quad (4)$$

The goodness of fit was evaluated using R^2on the log-transformed relationship.

The June 4, 2000 Bengkulu earthquake was treated as the mainshock. Aftershocks were selected from the USGS catalog using both temporal and spatial criteria. Temporally, events were included if they occurred within 30 days after the mainshock origin time ($0 < t \leq 30$ days). Spatially, events were included if their epicenters were located within a circular window of radius Rcentered on the mainshock epicenter (latitude–longitude of the mainshock), and within the same regional tectonic setting (Bengkulu subduction environment). In this study, $R = 100$km was used (sensitivity tests with Rin the range 50–150 km can be applied if needed). Events were also filtered to remove duplicates and obvious catalog artifacts.

Earthquake magnitude–frequency characteristics in Bengkulu (2015–2025) were evaluated using the Gutenberg–Richter (G–R) relationship:

$$log_{10}N(M \geq m) = a - b\,m \quad (5)$$

where $N(M \geq m)$is the cumulative number of earthquakes with magnitude greater than or equal to m, and $a$and $b$are constants describing the seismic productivity and the relative proportion of small-to-large earthquakes, respectively. Earthquake records were obtained from the USGS catalog for 2015–2025, and magnitudes were expressed in moment magnitude (Mw) after conversion from mb as described in the Methods section.

The magnitude of completeness (M_c) was determined using the maximum curvature (MAXC) method, defined as the magnitude at which the non-cumulative frequency–magnitude distribution reaches its maximum. Only earthquake events with $M \geq M_c$were used for subsequent estimation of the Gutenberg–Richter parameters to avoid bias due to catalog incompleteness.

The b-value was estimated using the maximum likelihood estimation (MLE) method, which provides a more robust and unbiased estimate than linear regression. For discretized magnitude data, the b-value was calculated as:

$$b = \frac{\log_{10} e}{\bar{M} - (M_c - \Delta M/2)} \tag{6}$$

where $\bar{M}$is the mean magnitude of earthquakes with $M \geq M_c$and $\Delta M$is the magnitude bin size. The uncertainty of the b-value was estimated as $\sigma_b = b/\sqrt{N}$, where $N$is the number of events used in the analysis.

3. RESULTS AND DISCUSSION

3.1. Gutenber-Richter Analysis Results

The table below presents the earthquake data used in this study. The data was obtained from the United States Geological Survey.

Table 1. Distribution of Earthquake Frequency Based on Magnitude in the Bengkulu Region 2015-2025

Body magnitude (Mb)	Number of earthquakes (N events)	Moment magnitude (Mw)	$\log_{10}$ N
4.0	155	5.16	2,190332
4.2	138	5.24	2,139879
4.4	94	5.32	1,973128
4.6	83	5,40	1,919078
4,8	54	5,48	1,732394
5,0	34	5,57	1,531479
5,2	31	5,66	1,491362
5,4	15	5,75	1,176091
5,6	6	5,84	0,778151
5,8	6	5,93	0,778151
6,0	2	6,03	0,30103

The value of N indicates amount earthquake Earth at each magnitude interval during period observations 2015–2025, whereas magnitude moment (Mw) obtained through conversion from body magnitude (mb). The value of $\log_{10}$(N) is base 10 logarithm of amount earthquake and nature not dimensionless. Based on Table 1, activities earthquake in the Bengkulu region during the period the dominated by earthquakes magnitude small until medium, with amount events that tend to occur decrease along increasing Earthquake Mw value with Mw around 5.16–5.4 occurring most frequently, while earthquake with Mw ≥ 6.0 relative rare, which reflects characteristics general activity tectonic where earthquakes occur small more often happen compared to earthquake large. The data in Table 1 below used for build connection frequency – magnitude in analysis Gutenberg–Richter law through graph of $log_{10}N$ against Mw.

The magnitude of completeness (M_c) was determined using the maximum curvature (MAXC) method, defined as the magnitude bin where the non-cumulative frequency reaches its maximum. Based on the magnitude–frequency table, the maximum number of events occurs at Mw = 5.16; therefore, M_c = 5.16. Only earthquake events with magnitudes equal to or greater than this value were included in the Gutenberg–Richter parameter estimation.

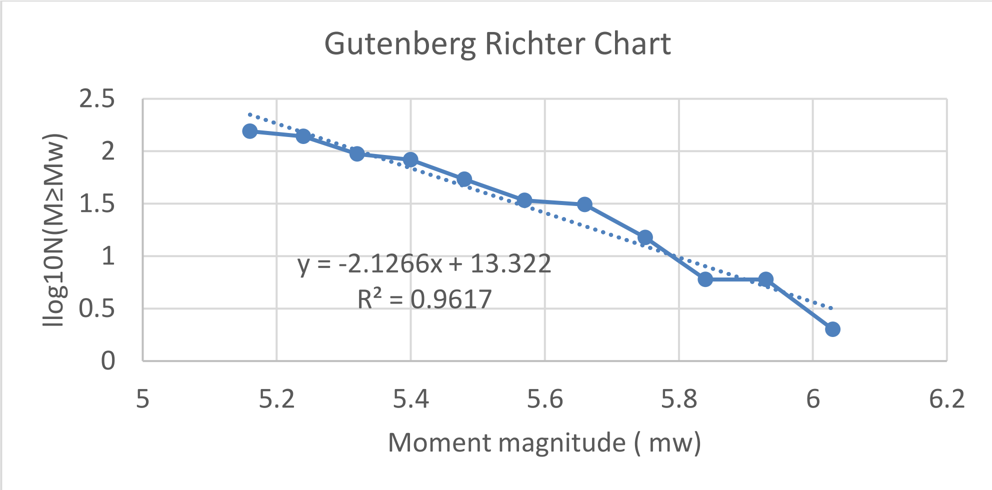

Figure 1. Gutenberg–Richter frequency–magnitude distribution for earthquakes in the Bengkulu region (2015–2025). The plot shows the relationship between moment magnitude (Mw) and the logarithm of cumulative earthquake frequency $\log_{10} N(M \geq Mw)$. Only earthquake events with magnitudes equal to or greater than the completeness magnitude ($M_c = 5.16$) were used in estimating the Gutenberg–Richter parameters.

Based on chart the relationship between $log_{10}N$ and Mw in Figure 4, a straight line is obtained which shows Gutenberg-Richter law. The value of a obtained from point through the line with $log_{10}N$ axis and reflects level activity earthquake in Bengkulu, which was quite tall Because the position of the area located in a subduction zone active with existence fault big. Value b obtained from slope of the line and shows comparison between earthquake small and large; value b which is relatively low (≈0.99) indicates existence pressure high in the area, which allows occurrence earthquake big. This result in accordance with history Bengkulu earthquake, such as in 2000 and 2007, as well as study previously in Bengkulu and western Sumatra (Mase et al., 2021; Farid & Mase, 2020), although there is a little difference Because difference data period, boundaries, and methods measurement magnitude. The value of b = 0.99 is also the same with the global average (b ≈ 1.0) and shows characteristics distribution earthquake in the subduction zone active Indo-Australia–Eurasia with balance between earthquake small and big.

The cumulative number of earthquakes $\boldsymbol{N}(M \geq m)$was then calculated and plotted against Mw on a logarithmic scale. The resulting frequency–magnitude distribution follows a linear trend in accordance with the Gutenberg–Richter law. The b-value was estimated using the maximum likelihood estimation (MLE) method, yielding a value of $b = 1.88 \pm 0.08$for earthquakes with $M \geq 5.16$. The corresponding a-value was calculated as $a = 12.48$. The use of cumulative frequency and MLE ensures that the estimated parameters are not biased by catalog incompleteness or magnitude binning effects. The obtained results indicate that seismicity in the Bengkulu region is dominated by small to moderate earthquakes, with a rapidly decreasing cumulative occurrence toward larger magnitudes. The revised b-value reflects statistically robust magnitude–frequency characteristics and provides a reliable basis for interpreting the regional seismic regime.

3.2. Omori's Law Analysis Results

Table 2 summarizes aftershock counts within 30 days after the June 4, 2000 mainshock using multi-day time bins. To ensure consistency with the Omori–Utsu formulation, the dependent variable was defined as the **aftershock rate** $n(t)$(events/day) computed for each bin as $n(t_i) = N_i/\Delta t_i$, with the representative time $t_i$taken as the bin midpoint. The aftershock decay was then fit to the Omori–Utsu model $n(t) = k/(t+c)^p$with $c = 1$ day.

Table 2. Distribution of Aftershock Numbers after the Bengkulu Earthquake on June 4, 2000

Time since mainshock (days)	Aftershocks N_i	Duration Δt_i(days)	Midpoint t_i(days)	Rate $n(t_i) = N_i/\Delta t_i$(events/day)
1-3	100	3	2.0	33.33
4-7	75	4	5.5	118.75
8-14	34	7	11.0	4.86
15-21	26	7	18.0	3.71
22-30	5	9	26.0	0.56

The log–log regression of $\log_{10} n(t)$versus $\log_{10}(t+c)$yields $p = 1.72$and $k = 3.20 \times 10^2$, with a coefficient of determination $R^2 = 0.888$on the log-transformed fit. This indicates a rapid decay of aftershock rate over time and an improved internal consistency between the model definition of $n(t)$, the tabulated data structure, and the applied Omori–Utsu fitting approach.

The parameter t indicates the time since the major earthquake occurred, in days. Meanwhile, n(t) is the number of small earthquakes that occur each day. The value of c is set to 1 day to avoid problems when t = 0. All logarithms used are base 10 and have no units. According to Table 2, the largest number of small earthquakes occurred on the first to third day after the major earthquake, with a total of 100 small earthquakes, indicating high activity at the beginning. As time progressed, the number of small earthquakes decreased; on days 5 to 10 and days 20 to 25, only 1–3 events occurred. This pattern reflects the rapid initial release of energy from large earthquakes and gradually decreases, and indicates a process of stress stabilization in the fault system, which is characteristic of large tectonic earthquakes in active subduction zones such as Bengkulu.

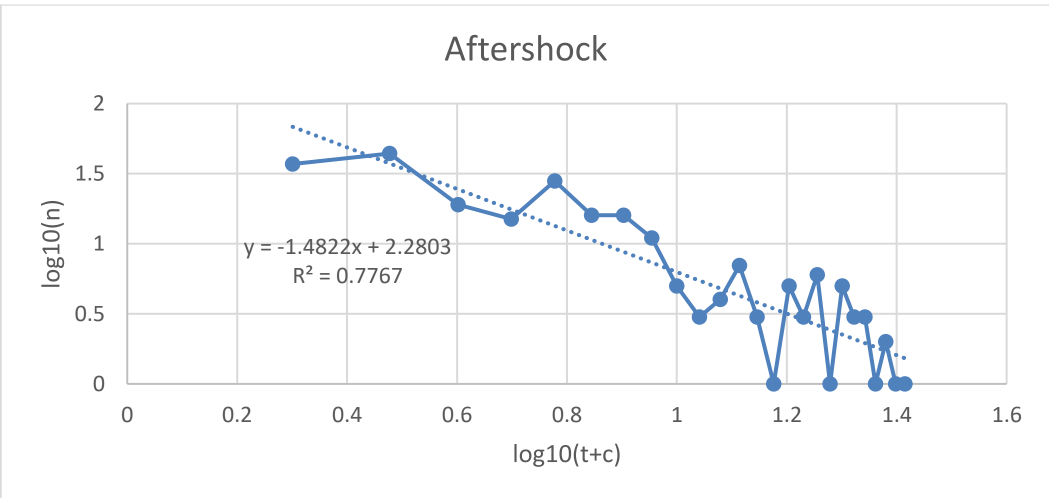

Figure 2. Omori–Utsu aftershock decay for the June 4, 2000 Bengkulu earthquake. The plot shows $\log_{10} n(t)$versus $\log_{10}(t + c)$, where $n(t)$is the aftershock rate (events/day) computed from multi-day bins as $n(t_i) = N_i/\Delta t_i$using bin midpoints t_i, and $c = 1$day. The fitted line corresponds to the Omori–Utsu model $n(t) = k/(t + c)^p$

Chart earthquake follow-up show connection between amount earthquake follow-up n(t) and time after earthquake main, in form scale logarithm. Chart This made with plotting $\log_{10}$ n(t) against $\log_{10}$ (t + c) for make it easier observation to Omori– Utsu law. Graph shows a decreasing line in a way slowly, which means frequency earthquake follow-up the more reduce along walking time, according to with Omori's law. The determination value R^2 = 0.7767 shows that around 77.67% of variation frequency earthquake follow-up can explained by time after earthquake main. This is show that the Omori– Utsu model Enough accurate although Still There is variations caused by structure complex geology. The decay value p = 1.4822 is bigger from general average value (0.9–1.3), meaning decline activity earthquake aftershocks occurred in Bengkulu more fast compared to usually. Characteristics This related with structure tectonic, where b values are low show existence pressure high in the subduction zone between Indo-Australia and Eurasia, whereas high p-value show response fast from system fault to release energy. Segment Bengkulu– Enggano subduction as well as Sumatran fault in the Manna segment plays a role important in pattern earthquake, so that increase risk occurrence earthquake in South Bengkulu and coastal areas surrounding area.

4. CONCLUSION

Based on results analysis earthquake in the Bengkulu region using Gutenberg–Richter and Omori– Utsu laws, show that the Bengkulu region has level high seismicity and conditions complex tectonics. From research in the period 2015 to 2025, it was recorded that incident earthquake dominated by earthquakes sized small until medium, whereas earthquake big happen with higher frequency low. High value of parameter a show activity high earthquake, whereas mark low b describes pressure large tectonic conditions. This influenced by the Sumatran subduction zone and the system plate active fracture. This also shows possibility occurrence earthquake big in the Bengkulu region. Analysis earthquake follow-up to the event the earthquake in Bengkulu on June 4, 2000 showed amount earthquake most follow-ups happen after earthquake main, then slowly reduce. Declining pattern This in accordance with Omori– Utsu law with the parameter p value is 1.4822 and the coefficient R^2 determination of 0.7767, which shows that this capable explain decline frequency earthquake follow-up with good. Findings This confirm that the Bengkulu region has potential danger high earthquake. Therefore, information results analysis This important and can used as base in evaluate risk earthquake, planning use land, as well as develop and strengthen mitigation strategies disaster earthquake in Bengkulu Province.

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