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ESTIMATES OF A-VALUE AND B-VALUE PARAMETERS FOR ANALYSIS OF SEISMICITY AND POTENTIAL HAZARD STUDIES OF EARTHQUAKE DISASTERS IN THE NORTH SUMATRA REGION

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ABSTRACT
The risk of earthquakes in North Sumatra is very high due to its location in the megathrust zone and several active fault zones. The interaction of the Indo-Australian and Eurasian plates in the megathrust zone as well as local fault activity continues to trigger earthquakes with varying intensities. This study uses earthquake data from the International Seismological Centre (ISC) and the Gutenberg-Richter method to analyze seismicity with a cumulative a-value of 9.0 and a cumulative b-value of 1.2±0.017. The results show a high level of seismic activity and a tendency for large earthquakes to occur. Magnitude of Completeness (Mc) of 4.8 ensures data reliability for magnitudes above this value. The 2000–2022 seismicity map indicates a concentration of shallow earthquakes in the southwest, associated with active faults and megathrust zones, as well as an even distribution of moderate and deep earthquakes.

Keywords: North Sumatra; Gutenberg-Richter; a-value; b-value; Magnitude of Completeness

INTRODUCTION

Extremely intense tectonic activity occurs in Indonesia due to the interaction of four major tectonic plates. Among them, the Indo-Australian, Philippine, and Pacific plates interact with the Eurasian plate. Subduction occurs when these plates converge: the Indo-Australian plate moves from south to north, while the Eurasian plate moves from north to southeast. The convergence zone extends along the southwestern edges of Sumatra, Java, and Nusa Tenggara, ending at the southern fault region of Southeast Sumba in Palu-Koro, including Sumba Island. The dynamic movement of these tectonic plates has produced numerous local faults, triggering seismic activity across various regions (Ibrahim and Subardjo, 2005).

Sumatra Island is geographically traversed by faults, subduction zones, and volcanoes (Metrikasari and Choirudin, 2020). The island lies at the convergence of the Indo-Australian and Eurasian plates, where their collision forms a subduction zone with irregular direction and type of subduction. The area most frequently releasing seismic energy is found in the Sumatra subduction zone. Sumatra Island has two geological conditions affecting its seismic and tectonic activity: first, the subduction zone between the Indo-Australian and Eurasian plates; and second, the Sumatra Fault Zone (SFZ), also known as the Semangko Fault (Daiana et al., 2021). North Sumatra, from Aceh to Lampung, contains 19 active tectonic earthquake segments, one of which is located in North Sumatra at coordinates 1°–4° N and 98°–100° E, covering an area of 71,680 km² (Aritonang et al., 2021).

North Sumatra has three active tectonic earthquake segments: Toru, Angkola, and Barumun. The Toru segment stretches from Padang Lawas and Mandailing to North Tapanuli Regency with a maximum seismic potential of M7.1, length of 95 km, and depth of 20 km, at coordinates 1°15'N and 95°55'E–99°30'E. The Angkola segment has a length of 160 km, depth of 20 km, maximum seismic potential of M7.5, and a slip rate of 19 mm/year at coordinates 99°E–100°E and 0°15'N–1°35'N. The Barumun segment has a length of 125 km, depth of 20 km, maximum seismic potential of M7.1, and a slip rate of 4 mm/year at coordinates 99°30'E–100°30'E and 0°15'N–1°15'N (Aritonang et al., 2021).

Analysis of seismic activity in a region can be performed by examining the relationship between frequency and magnitude, captured through seismotectonic parameters: a-value and b-value (Zakiyah et al., 2021). The a-value reflects seismic activity influenced by rock brittleness—higher a-values indicate more seismically active regions. Conversely, the b-value represents the slope of the linear equation relating earthquake frequency and magnitude (Linda et al., 2019). Both parameters can be estimated using the Maximum Likelihood method (Prasetyo et al., 2019).

Several studies on seismicity in North Sumatra have been conducted. Simamora and Namigo (2016) investigated Magnitude of Completeness (Mc) for Sumatran earthquakes using the Maximum Curvature (MAXC) and Entire Magnitude Range (EMR) methods, finding that Mc values for Sumatra vary between 4.2 SR to 5.6 SR (average 4.6 SR), b-values range from 0.6 to 1.1, and a-values from 5 to 7.5. Siregar et al. (2023) identified b-value distribution in North Sumatra with standard deviation of 0.17, ranging from 0.9 to 1.5, and a-values from 6 to 9, with an annual seismicity index of 0.33 and an average recurrence period of 8.6 years for damaging earthquakes. Metrikasari and Choiruddin (2020) demonstrated that the main earthquake-prone areas on Sumatra Island are in Aceh and North Sumatra provinces.

Based on previous research, North Sumatra is an earthquake-prone province. Therefore, this study applies seismic modeling using the Gutenberg-Richter approach, which is based on the observation that earthquake frequency is logarithmically related to earthquake magnitude. The results of this seismicity modeling are expected to provide a comprehensive picture of seismic activity in North Sumatra Province and serve as a basis for developing more effective disaster mitigation strategies.

RESEARCH METHOD

The research was conducted from March to July 2024 at the 2nd Floor Computer Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Medan State University. This study is quantitative in nature, using secondary earthquake data from North Sumatra Province obtained from the International Seismological Centre (ISC) website.

The tools used include a laptop equipped with: (1) Microsoft Excel 2010 for converting earthquake magnitude scales to M_W; (2) ArcGIS version 10.8 for mapping earthquake distribution and spatially modeling a-value and b-value in North Sumatra Province for the period 2000–2022; and (3) Google Colaboratory for data processing and analysis.

The secondary earthquake data was retrieved from the ISC website (http://www.isc.ac.uk/iscbulletin/search/catalogue/) in CSV format for the period 1 January 2000 to 31 December 2022. The study area is bounded by coordinates 0.323°N–3.959°N and 97.035°E–100.188°E, covering North Sumatra Province. Data collected include longitude, latitude, date, depth, and magnitude types: Magnitude Moment (M_W), Magnitude Body (M_B), Magnitude Surface (M_S), and Local Magnitude (M_L). The magnitude range used is 2.5 to 8.6, with depth ranging from 0 to 300 km.

Data processing involved several steps. First, magnitude conversion to M_W was performed using the following equations (Pawirodikromo, 2012):

$$M_W = 0.143(M_s)^2 - 1.051(M_s) + 7.285$$
$$M_W = 0.114(M_B)^2 - 0.556(M_B) + 5.560$$
$$M_B = 0.125(M_L)^2 - 0.389(M_L) + 3.513$$

Second, earthquake declustering was performed using the Knopoff-Gardner method with the following equations: spatial distance $d = 10^{0.1238\times M+0.983}$ (km); and temporal window $t = 10^{0.032\times M+2.7389}$ if $M \geq 6.5$, otherwise $t = 10^{0.5409\times M-0.547}$. Third, the b-value and a-value were calculated using the Gutenberg-Richter Maximum Likelihood method:

$$\log N = a - bM \quad (1)$$
$$b = \frac{\log e}{\bar{M} - M_0} \quad (2)$$
$$a = \log N(M \geq M_0) + \log(b \ln 10) + M_0 b$$

where N is the cumulative number of earthquakes, $\bar{M}$ is the average magnitude, M_0 is the minimum magnitude (Mc), and b is the constant related to rock brittleness. Finally, spatial distribution modeling of a-value and b-value was performed using the Kriging interpolation method in ArcGIS 10.8

RESULT AND DISCUSSION

Earthquake Data and Declustering

A total of 4,027 earthquake events were recorded in North Sumatra Province between 2000 and 2022, with magnitudes ranging from 2.5 to 8.6 Mw after conversion. Following declustering using the Knopoff-Gardner method, 1,900 mainshock events were identified and used for subsequent a-value and b-value analysis. The magnitude conversion process yielded a minimum magnitude of 4.8, which was consequently set as the Magnitude of Completeness (Mc).

Figure 1 shows the earthquake count histogram before and after declustering. Before declustering, a very significant peak of 1,194 earthquakes occurred in 2005, caused by the major M8.7 earthquake on March 28, 2005 on Nias Island, followed by numerous aftershocks. After declustering, the count in 2005 dropped to 114 mainshocks. Outside of 2005, the annual earthquake count before declustering ranged from 44 to 313 events. The time series plot (Figure 2) shows the cumulative earthquake count, with a sharp increase in 2005. After declustering, the cumulative mainshock count grows more steadily, reflecting the underlying seismicity rate without aftershock clustering.

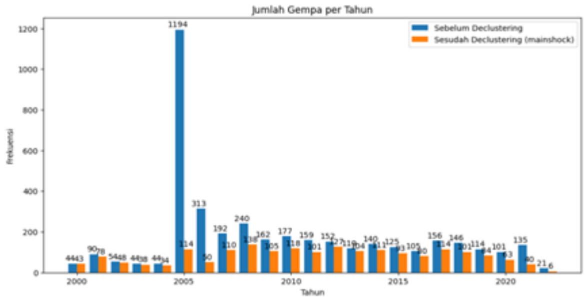

Figure 1. Earthquake count per year before and after declustering in North Sumatra 2000–2022

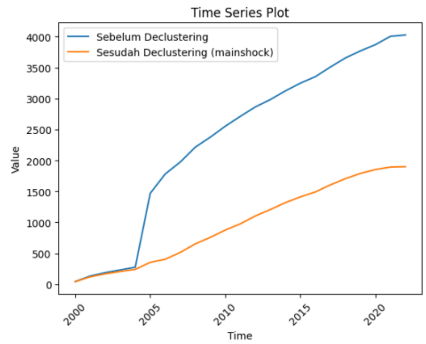

Figure 2. Time series of earthquake count before and after declustering in North Sumatra 2000–2022

Epicenter Distribution Map

The earthquake distribution map for North Sumatra Province from 2000 to 2022 (Figure 3) illustrates the spatial distribution of both mainshocks and aftershocks for earthquakes with magnitude >4 Mw. The map also displays district boundaries, active faults, and the megathrust zone, providing important geological context.

Red dots indicate shallow-depth earthquakes (depth <60 km). A high concentration of red dots in the southwestern part of the province indicates that this area is a highly seismically active zone, reflecting intense tectonic activity associated with active faults and the megathrust zone (Natawidjaja, 2021). Yellow dots represent earthquakes at moderate depth, distributed more evenly across the province, indicating that different parts of the province are susceptible to intermediate-depth earthquakes. Green dots indicate deep earthquakes, scattered across several areas, likely related to the subduction process beneath the tectonic plates, reflecting complex plate interactions. Purple star-shaped symbols represent mainshocks, often followed by aftershocks marked by red, yellow, and green dots.

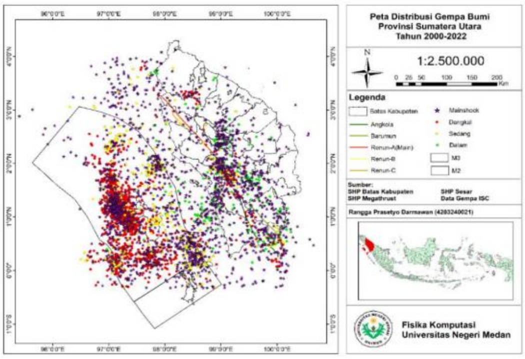

Figure 3. Earthquake epicenter distribution map in North Sumatra Province 2000–2022

Gutenberg-Richter Analysis and Seismicity Parameters

Processing of the mainshock data using the Gutenberg-Richter method produced the frequency-magnitude relationship shown in Figure 4. Notably, the resulting graph is non-linear, exhibiting a polynomial pattern rather than the simple linear relationship typically expected under the Gutenberg-Richter law. The high R^2 value (0.9879) confirms that the polynomial model fits the data well.

This non-linear relationship is consistent with findings from several studies. Speidel and Mattson (1993) noted that frequency-magnitude relationships can be non-linear due to differing tectonic conditions and magnitude ranges. Umino and Sacks (1993) found a non-linear frequency-magnitude relationship in northeastern Japan. Senatorski (2017) demonstrated that non-linear models provide better fits for estimating b-values. Ernandi and Madlazim (2020) also noted that magnitude differences can arise due to rock brittleness and seismic activity levels.

The cumulative a-value for North Sumatra is 9.0, indicating very high seismic activity. The cumulative b-value is 1.2±0.017 (error of 0.017 or 1.43%), indicating a tendency toward larger earthquakes. The error was calculated using the Shi and Bolt method, confirming a high level of reliability in the b-value estimation. The Magnitude of Completeness (Mc) is 4.8, ensuring that earthquake data used in this analysis is complete and reliable for magnitudes at or above 4.8.

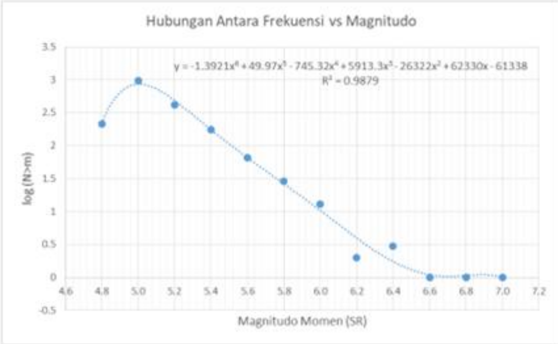

Figure 4. Gutenberg-Richter frequency-magnitude graph for North Sumatra

Spatial Modeling of b-Value

The spatial distribution of b-value in North Sumatra (Figure 5) was modeled using the Kriging interpolation method. Spatial variations in b-value are closely related to changes in stress or tectonic tension (El-Isa and Eaton, 2014). Higher b-value regions (red-orange colors) generally indicate a higher frequency of smaller earthquakes relative to larger ones, while lower b-value regions (green colors) suggest a greater tendency for larger-magnitude events (Gable and Huang, 2023).

Analysis of b-values on the megathrust zone shows a range of 0.6–1.6, significantly different from those on fault zones, which generally range from 1.4–2.6. This is consistent with Gui et al. (2019), who found that megathrust zones tend to have lower b-values, indicating higher stress accumulation and greater potential for large seismic energy releases. Schorlemmer et al. (2005) also noted that normal faults typically have higher b-values than megathrust zones. Studies by Ozturk (2018) in Eastern Anatolia, Turkey, similarly showed that active faults experience frequent smaller earthquakes with higher b-values. The megathrust zone must be closely monitored, as research by the National Earthquake Study Center (2017) indicates that the North Sumatra megathrust zone has the potential to generate earthquakes of M8.7 in the Nias-Simeulue segment and M7.8 in the Batu segment.

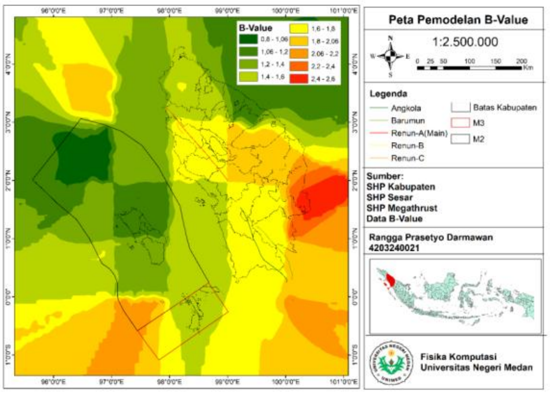

Figure 5. Spatial b-Value distribution modeling map in North Sumatra Province 2000–2022

Spatial Modeling of a-Value

The spatial a-value variation map for North Sumatra (Figure 6) shows significant differences in seismicity levels. Zones with higher a-values (orange to red colors) indicate more intense earthquake activity, while zones with lower a-values (light to dark green) indicate lower frequency.

The relationship between a-value and b-value is directly proportional: lower b-values tend to correspond to lower a-values (Ernandi and Madlazim, 2020). In the Nias-Simeulue and Batu megathrust zones, seismic activity is relatively lower, with a-values ranging from 5.4 to 8.2. This is consistent with the lower b-values observed in the same regions. Zones with low a-values may indicate areas where energy accumulation (asperity) is occurring, which could be a precursor to larger future earthquakes (Raharjo and Triyono, 2016). In contrast, areas near active fault zones show a-values ranging from 9.2 to 14.03, indicating high seismicity characterized by frequent, though not necessarily large-magnitude, earthquakes.

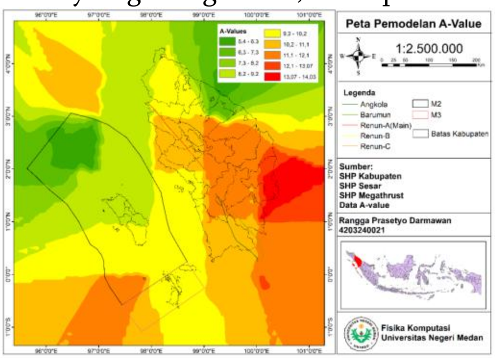

Figure 6. Spatial a-Value distribution modeling map in North Sumatra Province 2000–2022

CONCLUSION AND SUGGESTION

Analysis of the seismicity map of North Sumatra Province from 2000 to 2022 reveals a high concentration of seismic activity in the southwest, dominated by shallow earthquakes associated with active faults and the megathrust zone. The distribution of moderate- and deep-depth earthquakes is more even, indicating earthquake potential across various parts of the province.

Application of the Gutenberg-Richter method yields a cumulative a-value of 9.0, reflecting a very high level of seismic activity in North Sumatra. A b-value of 1.2±0.017 indicates a tendency for larger earthquakes, while the Magnitude of Completeness (Mc) of 4.8 confirms that earthquake data is complete and reliable for magnitudes above 4.8. The frequency-magnitude relationship in this region is non-linear, consistent with findings from complex tectonic environments.

For future research, it is recommended to conduct field studies to obtain empirical data on earthquake distribution and active fault characteristics. Additionally, applying alternative declustering methods and correlating seismic activity with geological data would provide a more comprehensive seismic risk assessment for North Sumatra.

REFERENCES

Aritonang, M., Parera, A. F., & Nasution, N. (2021). Relokasi Hiposenter Gempabumi Di Segmen (Toru, Angkola, Barumun) Dengan Menggunakan Metode Double Difference (Hypo-DD). GRAVITASI: Jurnal Pendidikan Fisika dan Sains, 4(2), 24-29.

Daiana, S. T., Nurhidayah, & Handayani, L. (2021). Studi B-value Sebagai Analisis Seismisitas Berdasarkan Data Gempabumi Periode 1914-2020 (Studi Kasus: Provinsi Bengkulu). Jurnal Sains dan Teknologi Mitigasi Bencana, 16(1), 30-41.

El-Isa, Z., & Eaton, D. (2014). Spatiotemporal variations in the b-value of earthquake magnitude-frequency distributions:

Classification and causes. Tectonophysics, 1-11.

Ernandi, F. N., & Madlazim. (2020). Analisis Variasi A-Value Dan B-Value Dengan Menggunakan Software Zmap V.6 Sebagai Indikator Potensi Gempa Bumi Di Wilayah Nusa Tenggara Barat. Jurnal Inovasi Fisika Indonesia, 9(3), 24-30.

Gable, S. L., & Huang, Y. (2023). New Estimates of Magnitude-Frequency Distribution and b-Value Using Relative Magnitudes for the 2011 Prague, Oklahoma Earthquake Sequence. JGR Solid Earth, 1-17.

Gui, Z., Bai, Y., Wang, Z., & Li, T. (2019). Seismic b-value anomalies in the Sumatran region: Seismotectonic implications. Journal of Asian Earth Sciences, 29-41.

Ibrahim, G., & Subardjo. (2005). Pengetahuan Seismologi. Jakarta: Badan Meteorologi.

Linda, Ihsan, N., & Palloan, P. (2019). Analisis distribusi spasial dan temporal seismotektonik berdasarkan nilai b-value dengan menggunakan metode likelihood di Pulau Jawa. Jurnal Sains Dan Pendidikan Fisika, 15(1), 80-95.

Metrikasari, R., & Choiruddin, A. (2020). Pemodelan Risiko Gempa Bumi di Pulau Sumatera Menggunakan Model Inhomogeneous Neyman-Scott Cox Process. Jurnal Sains dan Seni ITS, 9(2), 102-107.

Natawidjaja, D. H. (2021). Riset Sesar Aktif Indonesia dan Peranannya dalam Mitigasi Bencana Gempa dan Tsunami. Jakarta: LIPI Press.

Ozturk, S. (2018). Earthquake hazard potential in the Eastern Anatolian Region of Turkey: seismotectonic b and Dc-values and precursory quiescence Z-value. Frontiers of Earth Science, 215-236.

Pawirodikromo, W. (2012). Seismologi Teknik & Rekayasa Kegempaan. Yogyakarta: Pustaka Pelajar.

Prasetyo, R. A., A. H., & S. M. (2019). Analisa Data Seismisitas Menggunakan Metode MaximumLikelihood Untuk Mitigasi Gempabumi Kota Sibolga. Jurnal Teknik Informatika Unika St. Thomas (JTIUST), 4(1), 108-116.

Pusat Studi Gempa Nasional. (2017). Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017. Bandung: Puslitbang PUPR.

Raharjo, F. D., & Triyono, R. (2016). Studi Variasi Spasial Parameter Seismotektonik Untuk Mengetahui Kondisi Stress Lokal Tektonik dan Tingkat Keaktifan Kegempaan Di Wilayah Sumatera Barat dan Sekitarnya. Megasains, 7(2), 17-24.

Schorlemmer, D., Wiemer, S., & Wyss, M. (2005). Variations in earthquake-size distribution across different stress regimes. Nature, 539-542.

Senatorski, P. (2017). Effect of slip-area scaling on the earthquake frequency-magnitude relationship. Physics of the Earth and Planetary Interiors, 41-52.

Simamora, J. T., & Namigo, E. L. (2016). Pemetaan Magnitude of Completeness (Mc) untuk Gempa Sumatera. Jurnal Fisika Unand, 5(2), 179-186.

Siregar, U. K., Sirait, R., & Lubis, L. H. (2023). Identifikasi Tingkat Kerapuhan Batuan (B-Value) Dengan Menggunakan Metode Likelihood Di Wilayah Sumatera Utara Periode 1990-2021. Jurnal Kumparan Fisika, 6(1), 37-46.

Speidel, D., & Mattson, P. (1993). The polymodal frequency-magnitude relationship of earthquakes. Bulletin of the Seismological Society of America, 1893-1901.

Umino, N., & Sacks, I. (1993). Magnitude-frequency relations for northeastern Japan. Bulletin of the Seismological Society of America, 1492-1506.

Willemann, R. J., & Storchak, D. A. (2001). Data Collection at the International Seismological Centre. Seismological Research Letters, 72(4), 440-453.

Wiemer, S. (2001). A software package to analyze seismicity: ZMAP. Seismological Research Letters, 72(3), 373-382.

Zakiyah, V. F., Syafriani, Hamdi, & Dwiridal, L. (2021). Seismic Rate Change Analysis

Based On Spatial Distribution Of Seismotectonics In Northern Sumatra. PILLAR OF PHYSICS, 14(2), 75-82