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Analysis of Seismicity and Return Period of Earthquakes in South Pesisir Regency West Sumatra Province Using the Likelihood Method

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Abstract: The South Pesisir area was one of the areas that was rocked by an earthquake on September 30, 2009. The earthquake that occurred caused damage and loss of life. Based on these conditions, the South Pesisir Regency area was identified as an earthquake-prone area. Therefore, it is necessary to research seismicity and return period in the regency. This research used the statistical likelihood method to determine the accumulated rock stress, seismcity and return period of eartquakes. The data used is earthquake data for the period 1934-2023 with a magnitude ≥4 SR and a depth of ≤300 km. The results of this research provided an overview of the seismicity and return period in the South Pesisir Regency. Seismicity was determined based on rock stress condition (b-value) and on the level seismic activity (a-value). Based on calculations showed that the a-value and b-value for the 20-year and 90-year intervals ranged between 6.16-10.9 and 0.953-2.17, respectively. Earthquakes return periods at intervals of 20 years and 90 years for the magnitude range 4.0-4.4 produced almost the same return period, namely less than one year. Meanwhile, earthquakes with magnitudes of 4.5-6 had recurrence periods ranging from 1 to 63 years.

Keywords: Earthquake, likelihood, return period, seismicity, South Pesisir

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Introduction

West Sumatra Province is a province located in a seismically active region that is located between the meeting of two active tectonic plates Eurasia and Indo-Australia (Syafriani, 2018). The plate movement causes oblique subduction and gives rise to the Sumatra Fault and Mentawai Fault. South Pesisir Regency is located on the west coast of Sumatra which has a physical character from flat to mountainous. The physical characteristics of the area make South Pesisir prone to natural disasters. One of them is an earthquake that can cause damage.

Based on its geographical location, South Pesisir Regency is located in northwestern Sumatra which is adjacent to the subduction zone, the Mentawai fault and the Sumatra fault which causes this area to be under the threat of seismicity (Imani et al., 2019). South Pesisir is prone to the impact of earthquakes and tsunamis caused by earthquakes. Earthquakes that often occur on the South Pesisir was generally caused by subduction zones in the sea and the Sumatra fault which was located on the mainland of Sumatra.

South Pesisir is a coastal area. Coastal areas are prone to natural disasters such as earthquakes, tsunamis, tidal waves, floods and landslides (Rosyidie, 2006). Based on the disaster risk assessment of West Sumatra Province in the range of 2016-2020, South Pesisir Regency is included in an area with a high risk of earthquake disaster. Based on this condition, South Pesisir is identified as an area where earthquakes and tsunamis caused by earthquakes can occur at any time. Disaster mitigation and preparedness efforts are needed in order to minimize casualties and damage due to the impact of the earthquake, one of the ways that can be done is by analyzing seismicity and return period.

Seismicity is a harmonized data system that can provide a systematic description or information about

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rock stress (b-value) and seismicity level (a-value) in certain periods (Chasanah et al., 2013). The return period indicates the repeated interval (years) of earthquake occurs (Primandari & Khotimah, 2017). b-value and a-value are determined by the Mc parameter. 3.The most crucial factor in figuring out the values of b and an is Mc (Rohadi et al., 2007). The importance of determining the correct Mc value is that it has a direct impact on the evaluation of the b-value, which will then affect the evaluation of the a-value (overall seismicity level) (Eluyemi et al., 2019). Analysis return period of earthquakes and seismicity based on the guttenberg-richter (G-R) frequency-magnitude relation. The frequency and magnitude distribution is influenced by the seismotectonic parameter constants b-value and a-value. The frequency-magnitude distribution shown in equation (1) below (Gutenberg & Richter, 1944):

$$log\ N(M) = a - bM \quad (1)$$

where constant a value denotes seismicity, the b value is the slope of log N~M, which connects the relative magnitudes of large and small magnitudes, and N(M) represents the cumulative sum (Nava et al., 2017).

The seismotectonic parameters b-value and a-value are determined using the statistical likelihood method. The likelihood method is a statistical method proposed by Utsu (1965) this method is very suitable for solving some problems about seismology. The likelihood method assumes that the data is exponentially distributed and the maximum magnitude is infinite (Naylor et al., n.d.). The likelihood method can avoid bias in determining the estimated b-value (Geffers et al., 2022). b-value and a-value in the likelihood method in seismology are referred to as rock stress conditions and seismicity levels (JU, 2023). The b value in high rock stress situations is in the range of 0.4 to 0.9, or generally close to 1, the b value in low rock stress areas is between 1.2 (Wiemer & Wyss, 1994).

A high b-values had a medium of high heterogeneity and a low b-values had a medium of low heterogeneity (Raharjo, 2016). b-value had a correlation with stress and strain distribution so that it can be used as an indicator of stress in a region (Ernandi, 2020). a-value is a seismotectonic parameter that describes the level of seismicity in a region (JU, 2023). a-value is a constant that depends on the level of seismicity and the length of time of observation (Nava et al., 2017). a high a-value ≥6 indicates that the region has a high level of seismicity (Rohadi, 2009).

Analysis seismicity and return period of earthquakes is one of the efforts to mitigate earthquake disasters, a low b-value and a high a-value indicate that the area can be considered to have a high level of seismicity and had a large amount of energy still stored so that there is the possibility of a major earthquake in areas.

Method

This research is a descriptive study using secondary data, namely earthquake data range from of 1934–2023 timeframe obtained from the U.S. Geological Survey (USGS) catalog. Seismicity and earthquake return period were analyzed using the likelihood method. Parameters used in this study are longitude, latitude date, month, year, magnitude, depth and time of the earthquake. The earthquake data used has a magnitude ≥4 SR, depth ≤300 km, which is located in the South Pesisir Regency of West Sumatra province with coordinates 0° 983' - 2° 317' S and 100° 316' - 101° 305' E. The data processing steps taken to generate seismicity and return period of earthquake in this study are as follows.

The first, the earthquake parameter data is edited and arranged according to the specified format using microsoft excel, then the data is saved in the form of a.dat file format, then the data file is inputted into the ZMAP software, then decluster is carried out to obtain the main earthquake data.

The second, after the data is declustered, the frequency-magnitude distribution analysis process is carried out to obtained magnitude completeness (Mc), which is used to determine the a- and b-value. b-value, a-value seismotectonic parameters are determined using the likelihood method. The value of parameter b is obtained using the equation below (2) (Utsu, 1966):

$$b = \frac{\log e}{\bar{M} - M_0} \quad (2)$$

where M_0 is the minimum magnitude of the earthquakes (the lower threshold limit where magnitude is not considered) and $\bar{M}$ is the average magnitude and log e is 0.4343.

Then a-value using the equation (3) below:

$$a = \log N(M \geq M_0 + \log(b \log 10) + M_0\, b \quad (3)$$

the parameters b-value and a-value in equations (2) and (3) can be found using the ZMAP ver 6.0 application. ZMAP is a Graphical User Interface (GUI) program for seismicity analysis based on Matlab (Wyss et al., 2001).

The third, determining the seismicity index (N), which is the number of cumulative earthquake frequencies per year, using the following equation (4):

$$N_1(M \geq M_0) = 10^{\,a_1 - bM} \quad (4)$$

where $a_1 = a' - \ log\ T,$ and $a' = a - log(b\ ln\ 10)$, In the fourth step of determining the earthquake return period, a calculation is made to determine the average recurrence of earthquake events using the following equation (5):

$$\theta = \frac{1}{N_1(M \geq M_0)} \quad (5)$$

where θ is average return period of earthquakes, $N_1(M \geq M_0)$ is the seismicity index and M_0 is the low magnitudes.

Then, seismicity and return period analysis to showed the level of seismicity and earthquake recurrence, which can be used as an effort to mitigate earthquake disasters in the South Pesisir Regency area of West Sumatra province to reduce losses due to the possibility of earthquake disasters.

Result and Discussion

The results of this study are the parameters b- and a-values, seismicity index and return period of earthquake processed from secondary data sourced from the U.S. Geological Survey (USGS) catalog. The earthquake data obtained amounted to 190 events in the time period from January 1, 1934 to December 31, 2023. The seismicity map of the South Pesisir Regency shown in Figure 1.

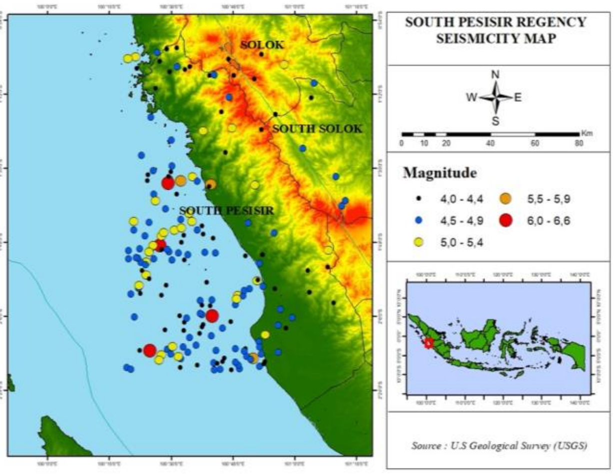
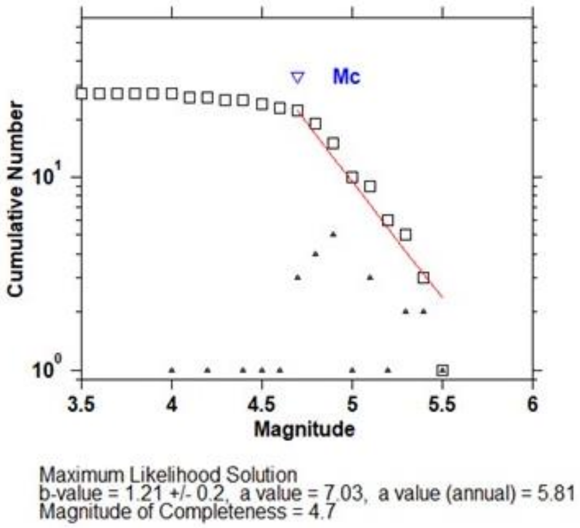


Figure 1. Seismicity map of the earthquake data in South Pesisir Regency

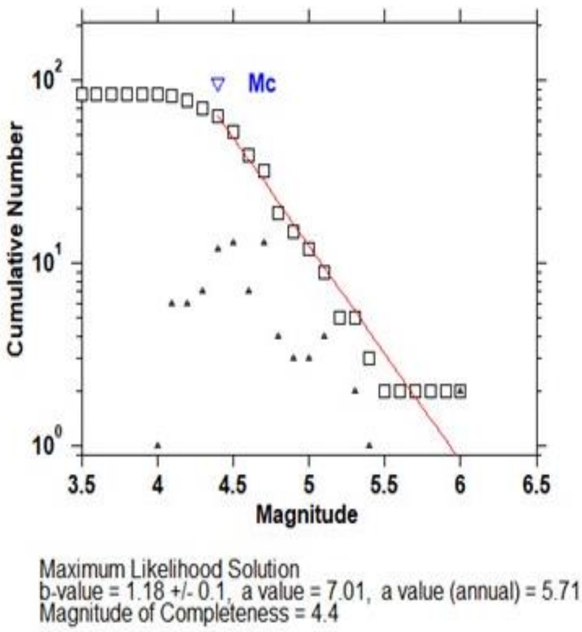
The Regency of South Pesisir has a fairly high level of seismicity that can be seen on Fig. 1. This is evidenced by the number of earthquake events that are quite significant in the South Pesisir region. Earthquakes marked in black have a magnitude of 4.0-4.4, blue color has a magnitude of 4.5-4.9, yellow color has a magnitude of 5.0-5.4, orange color 5.5-5.9 and red color has a magnitude of 6.0-6.6. After going through the data processing process, the results obtained in this study are b-value, a-value, seismicity index and return period of earthquake.

This research involved data processing using the likelihood method with a data period 1934-2023, at time 20-year intervals and in 90 years. After going through the data processing process using the likelihood method, this research obtained results in the form of parameter b- and a-values, seismicity index and return period of earthquake.

The results of the frequency-magnitude distribution analysis using the likelihood method at 20-year intervals shown in Figure 2.



(a)



(b)

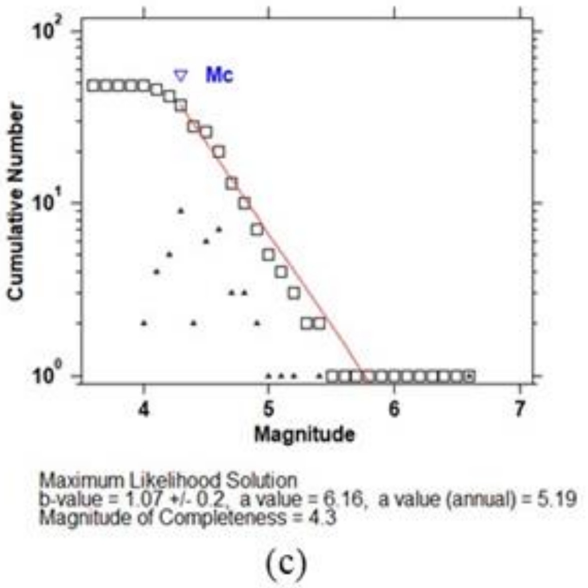


Figure 2. The Frequency-Magnitudo Distribution Curve (a) Period 1974-1993 (b) Period 1994 -2013 (c) Period 2014-2023

The estimation results of b- and a-values at per 20-year intervals are shown in Fig. 2. During the periods 1934-1953 and 1954-1973, two earthquake events were recorded with undefined a-values and b-values (NaN). On the frequency-magnitude distribution curve does not produce a linear trend (G-R) so the estimated b-value, a-value NaN. This is due to statistical fluctuations due to under-sampling or an apparent lag in Guttenberg Richter (G-R) scaling (Geffers et al., 2022). On the Fig. 2(a) period 1974-1993 with 29 earthquake events, an a-value of 7.03 was obtained, indicating that the level of earthquake activity was quite high and the b-value was also relatively high, more than 1.21, so it can be concluded that the rock stress conditions are quite low. The Mc value obtained shows that a magnitude of 4.7 SR will decrease the frequency of earthquake magnitudes. On the Fig. 2(b) period 1994-2013 with 103 earthquake events, the a-value of 7.01 was obtained, indicating that the level of earthquake activity was not too high and the result of the relatively high b value was more than one, namely 1.18, so it can be concluded that it has a fairly low rock stress condition. The Mc value obtained shows that a magnitude of 4.5 SR will decrease the frequency of earthquake magnitudes. Then on the Fig. 2(c) period 2014-2023 with 55 earthquake events, the a-value of 6.16 was obtained, indicating that the level of earthquake activity was not too high and the result of the relatively high b value was more than one, namely 1.07, so it can be concluded that it has a fairly low rock stress condition. The Mc value obtained shows that a magnitude of 4.3 SR will decrease the frequency of earthquake magnitudes.

Based on the estimated b-value, a-value at the earthquake interval per 20 years in each interval shows a high level of seismicity and low rock stress. High a-value and b-value have the potential for earthquake recurrence with low magnitude (Wahyuni et al., 2020). The results of the earthquake return period at the earthquake interval per 20 years, calculated based on the seismicity index value. The return period can be obtained after the seismicity index value is known.

The results of seismicity index calculation at earthquake intervals 20 years using the likelihood method shown in Table 1.

Table 1. Results of seismicity index calculation in each interval

Period Interval	Magnitude Interval	Seismicity Index
1974 -1993	4.0 - 4.4	2.782
	4.5 - 4.9	0.690
	5.0 - 5.4	0.171
	5.5 - 5.9	0.042
1994 - 2013	4.0 - 4.4	3.592
	4.5 - 4.9	0.923
	5.0 - 5.4	0.237
	5.5 - 5.9	0.061
	6.0 - 6.6	0.015
2014 - 2023	4.0 - 4.4	3.082
	4.5 - 4.9	0.899
	5.0 - 5.4	0.262
	6.0 - 6.6	0.005

Based on the calculation results in Table 1, the seismicity index is obtained for each 20-year time interval. The seismicity index is the normalization of the number of earthquakes per year, where earthquakes of a certain magnitude represent the total average earthquake occurrence (Budiman, 2011). In the interval 1934-1953 and the interval 1954-1973 the estimates of b-value, a-value were not obtained, nor was the return period. In the years 1974-1993 to 2014-2023 at magnitudes 4.0 to 4.5 ranged from 0.6909 to 3.5922, from the results obtained it is known that the smaller the magnitude of the seismicity index will be smaller. Furthermore, the seismicity index data in table 1 is processed again by calculating using equation (4), so as to obtain the estimated return period at each interval.

The results of return period calculation at earthquake intervals 20 years using the likelihood method shown in Table 2.

Table 2. Result of return period calculation in each interval

Period Interval	Magnitude Interval	Return Period
1974 - 1993	4.0 - 4.4	0.359
	4.5 - 4.9	1.447
	5.0 - 5.4	5.828
	5.5 - 5.9	23.471
1994 - 2013	4.0 - 4.4	0.278
	4.5 - 4.9	1.083
	5.0 - 5.4	4.213
	5.5 - 5.9	16.392
	6.0 - 6.6	63.773
2014 – 2023	4.0 - 4.4	0.324
	4.5 - 4.9	1.112
	5.0 - 5.4	3.811
	5.5 - 5.9	13.065
	6.0 - 6.6	44.782

Based on table 2 on the 20-year interval earthquake, it can be seen that the earthquake return period at each year interval has a different return period. Based on table 2 shows the earthquake return period in the period 1934-2023, in table 2 it can be seen that the earthquake with a magnitude of 4.0-5.5 in the South Pesisir Regency area has a different return period of about 0.359 to about 23.471 years. In the South Pesisir Regency area earthquakes with magnitudes of 4.0-4.4 SR often occur, this is shown in Table 2 where earthquakes with magnitudes of 4.0-4.4 have relatively short return periods compared to other magnitudes. While earthquakes with a magnitude of 5.0-5.9 have a long return period, so they rarely occur in this region. The results of research showed the South Pesisir Regency area has high seismic activity so that it is prone to earthquakes with a magnitude of 4.0-4.4 and the possibility of earthquakes with a magnitude of 5.5-5.9 SR with a return period of 23.471 years. The greater the magnitude of the earthquake, the longer the return period.

The period 1994-2013, in table 2 it can be seen that the earthquake with a magnitude of 4.0-6.0 in the South Pesisir Regency area has a different return period of about 0.278 to about 63.773 years. In the South Pesisir Regency area earthquakes with magnitudes of 4.0-4.4 SR often occur, this is shown in Table 2 where earthquakes with magnitudes of 4.0-4.4 have relatively short return periods compared to other magnitudes. While earthquakes with a magnitude of 6.0-6.6 have a long return period, so they rarely occur in this region. The results of research showed the South Pesisir Regency area has high seismic activity so that it is prone to earthquakes with a magnitude of 4.0-4.4 and the possibility of earthquakes with a magnitude of 4.0-6.0 SR with a return period of 63.773 years. The greater the magnitude of the earthquake, the longer the return period.

The period 2014-2023, in table 2 it can be seen that the earthquake with a magnitude of 4.0-6.0 in the South Pesisir Regency area has a different return period of about 0.324 to about 44.78 years. In the South Pesisir Regency area earthquakes with magnitudes of 4.0-4.4 SR often occur, this is shown in Table 2 where earthquakes with magnitudes of 4.0-4.4 have relatively short return periods compared to other magnitudes. While earthquakes with a magnitude of 6.0-6.6 have a long return period, so they rarely occur in this region. The results of research showed the South Pesisir Regency area had high seismic activity so that it is prone to earthquakes with a magnitude of 4.0-4.4 and the possibility of earthquakes with a magnitude of 4.0-6.0 SR with a return period of 44.782 years. The greater the magnitude of the earthquake, the longer the return period.

At 20-year intervals in the South Pesisir Regency area, earthquakes with magnitudes of 4.0-4.4 SR occur frequently. This is shown in Table 2 where earthquakes with magnitudes of 4.0-4.4 have relatively short return periods compared to other magnitudes. Meanwhile, earthquakes with magnitudes of 6-6.6 have long return periods, making them rare in this region. This is supported by the theory of rebound elasticity, which states that plates that accumulate energy over a long period of time will release energy in the form of earthquakes with a large scale, so the longer the return period of an earthquake, the greater the magnitude of the earthquake that will occur.

The results of the frequency-magnitude distribution (FMD) analysis using the likelihood method in 1934-2023 earthquake interval shown in Figure 3.

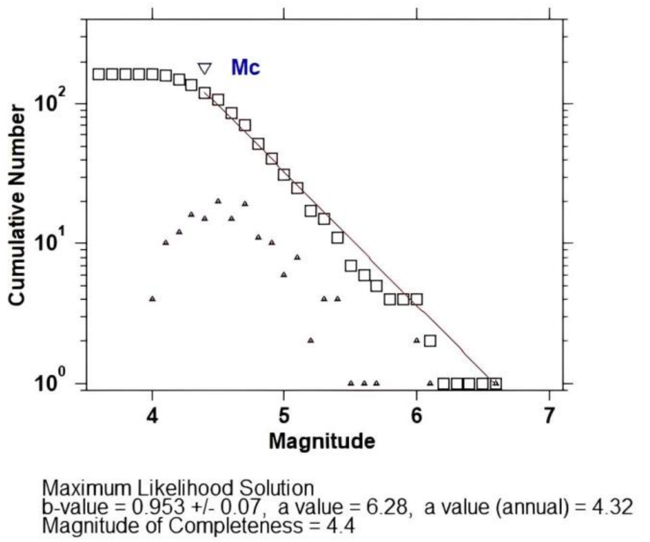


Figure 3. The Frequency-Magnitudo Distribution Curve in 1934 – 2023

Based on Fig. 3, the frequency-magnitude distribution with 190 earthquake events obtained an a-value of 6.28, indicating that the level of earthquake activity is not too high and the result of the b value is quite low, namely 0.953, thus it can be concluded that the rock stress in the period 1934-2023 is not too high. The Mc value obtained shows that a magnitude of 4.4 SR will decrease the frequency of earthquake magnitudes. The characteristics of rocks and the amount of stress contained in a rock can influence the amount of earthquake energy released in an earthquake repetition cycle (Sunarjo, n.d.).

The results of seismicity index calculation for the period 1934-2023 using the likelihood method shown in Table 3.

Table 3. Result of seismicity index calculation for the 1934-2023

Magnitude Interval	Sismicity Index
4.0 - 4.4	1.4891
4.5 - 4.9	0.4970
5.0 - 5.4	0.1659
5.5 - 5.9	0.0553
6.0 - 6.6	0.0184

Based on the result of the calculation in Table 3, seismicity index for the period 1934-2023 is obtained. The seismicity index is the average accumulation of earthquake events in one year, the seismicity index is very important in order to get the value of the earthquake return period. The seismicity index value at the magnitude interval 4.0 to 6.0 ranges from 1.4891-0.0184. It shown in Table 3 that the smallest magnitude interval has the largest seismicity index and vice versa. Furthermore, the seismicity index data in table 3 is processed again by performing calculations using equation (4), so that the estimated return period at each magnitude interval is obtained.

The results of the earthquake return period calculation for the period 1934-2023 using the likelihood method shown in Table 4.

Table 4. Result of return period calculation for the period 1934-2023

Magnitude Interval	Return Period
4.0 - 4.4	0.6715
4.5 - 4.9	2.0117
5.0 - 5.4	6.0264
5.5 - 5.9	18.0535
6.0 - 6.6	54.0833

Table 4 shows the earthquake return period in the period 1934-2023. In table 4, it can be seen that earthquakes with magnitudes of 4.0-6.0 in the South Pesisir Regency area have different return periods, which are around 0.6715 to around 54.0833 years. In the South Pesisir Regency, earthquakes with a magnitude of 4.0-4.4 SR often occur, as shown in Table 4 where earthquakes with a magnitude of 4.0-4.4 have a relatively short return period compared to other magnitudes. Meanwhile, earthquakes with a magnitude of 6.0-6.6 have a long return period, so they rarely occur in this region. The results of research showed the South Pesisir Regency area has high seismic activity so that it is prone to earthquakes with a magnitude of 4.0-4.4 and the possibility of an earthquake with a magnitude of 6.0-6.6 SR can occur in less than 54 years. The greater the magnitude of the earthquake, the longer the return period.

This is also supported by the theory of rebound elasticity, which states that plate movements have a phase of energy collection over a long period of time and then a period of energy release, namely during a large earthquake. The greater the return period of an earthquake, the greater the magnitude of the earthquake that will occur. The analysis of seismicity and earthquake return periods in West Sumatra in the 1961-2010 period, it is stated that the West Sumatra region has a high level of seismicity and is prone to disasters with a value of 6.21 and b value of 0.66, and the largest earthquake return period is 45 years (Chasanah et al., 2013). Morover the spatial variation of seismotectonic parameters in West Sumatra and surrounding areas using the likelihood method, it is stated that the South Pesisir region has a high level of seismicity (Raharjo, 2016).

The results of research, showed the South Pesisir region had a high level of seismicity in range 4-4.4 SR and had a different recurrence period at each magnitude. The results of this study can provide an understanding of the state of seismicity and the possibility of earthquake recurrence in the future and as an earthquake mitigation effort in order to make policies, vigilance, and reduce losses due to the possibility of earthquakes.

Conclusion

The results of seismicity analysis in the South Pesisir Regency area showed that the a-value and b-value ranged between 6.16-10.9 and 0.953-2.17, respectively. Earthquakes return periods at intervals of 20 years and 90 years for the magnitude range 4.0-4.4 produced almost the same return period, namely less than one year. Earthquakes with magnitudes 4.5-4.9 had a return period of 1 to 2 years, magnitude 5.0-5.4 has a return period of 3-6 years. Earthquakes with magnitudes 5.5 ranges from 13 to 23 years. The earthquakes with magnitude 6 ranges from 44-63 years. The South Pesisir Regency area had different return periods for each magnitude and had a high seismicity in the magnitude range of 4-4.4 SR.

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