Correlation Analysis of Spatial Distribution, Temporal Seismotectonics, and Return Period of Earthquake in East Nusa Tenggara, Indonesia

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1. Introduction

East Nusa Tenggara Province (ENTP) is one of the areas where the frequency of earthquake occurrences is high. There are about 4,162 tectonic earthquakes occurring in this area in the period of 1918 to 2015 (Figure 1). This is due to Australian plate subduction to Eurasian plates just below ENTP region and some local fault around ENTP region [1–4].

Natural hazards such as tectonics earthquake are often devastating in terms of loss of life and environmental damage. The occurrence of the earthquake is not preventable, but its effect can be minimized through effective prevention and reduction of vulnerability. An earthquake can be predicted through approaches by using various methods with a number of pieces of sophisticated earthquake detection equipment, for example, the calculation of seismicity with the calculation of b-value and the return period of earthquake. The earthquake distribution can be indirectly considered as a fractal (D) that describes seismicity with tectonic parameters (b-value).

One effort to find out the disaster-vulnerable areas from earthquake is by understanding the fault pattern by analyzing the previous earthquakes and calculating the earthquake precursor based on the results of spatial and temporal analysis using b-value and the return period of earthquakes.

b-Value Parameter. The relationship between number of earthquake and magnitude is determined by (1) [5].

\[
\log N = a - bm
\]

(1)

and

\[
N = 10^{a-bm}
\]

(2)

In certain areas and interval time, (1) describe the number of earthquake (N) with magnitude (m), a is seismic activity constant, determined by scene that depends on determination of the volume and time window (time period), and b is tectonics parameter showing the characteristics of the medium with reference to stress or condition of local materials. b-value
statistically can be calculated by using Utsu formula [6], called Maximum Likelihood Estimation (MLE) method:

\[ b = \frac{1}{m - m_{\text{min}}} \log_{10} \bar{m} \]  

(3)

and

\[ \bar{m} = \frac{\sum_{i=1}^{n} m_i}{n} \]  

(4)

\( \bar{m} \) is average magnitude, \( m_{\text{min}} \) is minimum magnitude, and \( n \) is the total number of earthquake data used to calculate b-value.

Utsu [4] pointed out that the MLE method is better than the least square method, especially for data with a small number of earthquake (N) events. The confidence interval for a given probability (Pr) is

\[ b \left(1 - \frac{1.960}{\sqrt{N}} \right) \leq P_r \leq b \left(1 + \frac{1.960}{\sqrt{N}} \right) \]  

(5)

Equation (5) gives a probability of 95%. The degree of certainty of b-value according to Shi and Bolt [7] is

\[ \sigma(b) = 2.30b^2 \sqrt{\frac{\sum_{i=1}^{n} (m_i - \bar{m})^2}{n(n-1)}} \]  

(6)

The relationship between the b-value and the fractal dimension, D, has a positive correlation and is expressed in (7) [8]:

\[ D = \frac{3b}{c} \]  

(7)

D is fractal dimension, b is b-value of Gutenberg-Richter relation, and c is constants that depend on the relative duration of the seismic source and the time constant of the recording system. For crystal stones, the c value is considered 3.0, for the subduction zone (100-700 km) it is suggested to be 2.4, and for most studies of the earthquake it is suggested to be 1.5 [6].

**Return Periods of Earthquake.** The number of earthquakes per year is theoretically calculated by dividing the a-value by the observation period (T).

\[ a_1 = \frac{a}{\log T} \]  

(8)

The number of cumulative frequencies of earthquake per year or called the seismicity index is

\[ N_1(m) = 10^{a_1-bm} \]  

(9)

The occurrence probability of one or more earthquakes greater than m in period T can be formulated as

\[ P(m, T) = \left(1 - e^{-N_1(m)T} \right) \]  

(10)

Given \( N_1(m) \), the mean value of return periods of damaging earthquake can be calculated:

\[ \theta = \frac{1}{N_1(m)} \text{ years} \]  

(11)

### 2. Materials and Methods

Tectonic earthquake data were obtained from the catalog of International Seismological Center (ISC), United States Geological Survey (USGS), and Indonesian Meteorology, Climatology and Geophysics Agency (IMCGA) with depth of \( \leq 600 \) km and magnitude of \( m_b \geq 3 \) in the study area 118° E-128° E and 6° S-12° S. The number of data obtained from the catalog is 4,162 events.

Based on the existence of fault, the study area is divided into 3 clusters (Figure 2), namely:

(i) Cluster 1: 6° S–9° S and 118° E–122.5° E (Flores island, Labuan Bajo, and surrounding areas)

(ii) Cluster 2: 6° S–12° S and 122.5° E–128° E (Alor island, Timor island, and surrounding areas)

(iii) Cluster 3: 9° S–12° S and 118° E–122.5° E (Sumba island and surrounding areas)

The data are processed with Microsoft Excel, ArcGis 9.3, and ZMAP 6.0 software using declustering according to Gardner and Knopoff method to obtain the main earthquakes. The main earthquakes were then processed to obtain the seismicity map (b-value and a-value) using Maximum Likelihood method and map variation of b-value spatially and temporally in ENTP and surrounding areas for each cluster. The flowchart of research can be seen in Figure 3.
Figure 2: Clusters distribution of ENTP and surrounding areas used to find the differences of b-value for each region.

Figure 3: Flowchart of the research.
3. Results

The earthquake in ENTP generally occurred at shallow depth (< 50 km) around the Timor island, moderate depth (50-70 km) around the ocean of Savu or between the Timor island and the Flores island, and deep (> 70 km) around the Flores island (Figure 4).

The 3-dimension view of the earthquake distribution toward depth is presented in Figure 5. Meanwhile, the graphs of frequency-magnitude distribution along with magnitude completeness, a-value, and b-value distributions for all earthquake data are shown in Figures 6, 7(a), and 7(b).

Figure 7(a) shows that the a-values of the ENTP region range from 5 to 8.5, indicating a fairly high level of seismicity.
Maximum Likelihood Solution
b-value = 0.731 ± 0.02, a value = 6.38, a value (annual) = 4.39
Magnitude of Completeness = 4.4

**Figure 6:** Magnitude distribution graph of seismicity in ENTP.

Figure 7(b) shows that the b-values vary from 0.6 to 1.3. This indicates that homogeneous rock types are relatively distributed equally across ENTP and are transported between Flores and Timor or around the Savu sea with the b-value about 0.7. This shows a high level of stress and relatively homogeneous. It is estimated that this could be caused by the faults found in the Timor island, extended toward the Savu sea. It is also due to the subduction of the Australian plate under the Eurasian plate just below the Timor island.

Based on temporal variation of b-values (Figure 8), it is found that there was a significant decline of b-value prior to the occurrence of strong magnitude earthquakes of 7.5 in...
Figure 8: Temporal variation of b-value in ENTP region.

(a) b-value = 0.887 +/- 0.05, a value = 6.54, a value (annual) = 4.61
Magnitude of Completeness = 4.6

Maximum Likelihood Solution
b-value = 0.887 +/- 0.05, a value = 6.54, a value (annual) = 4.61
Magnitude of Completeness = 4.6

(b) b-value = 1.95 +/- 0.09, a value = 11.2, a value (annual) = 9.52
Magnitude of Completeness = 4.6

Maximum Likelihood Solution
b-value = 1.95 +/- 0.09, a value = 11.2, a value (annual) = 9.52
Magnitude of Completeness = 4.6

(c) b-value = 0.92 +/- 0.09, a value = 6.71, a value (annual) = 4.77
Magnitude of Completeness = 5.1

Maximum Likelihood Solution
b-value = 0.92 +/- 0.09, a value = 6.71, a value (annual) = 4.77
Magnitude of Completeness = 5.1

Figure 9: Magnitude distribution graph of seismicity for cluster 1 (Flores, Labuan Bajo, and surrounding areas): (a) for mb > 3 SR, (b) for mb = 3-5 SR, and (c) for mb > 5 SR.
1996 and 2004. This indicates the existence of a high level of stress on the rocks prior to the occurrence of the strong earthquakes [9].

Cluster 1 (Flores island, Labuan Bajo, and surrounding areas) can be depicted as shown in Figure 3 with earthquake number of 1,076 events, with main earthquakes of 537 incidents. After calculated using Maximum Likelihood method, it was found that the b-value is 0.89 and the a-value is 6.54 for mb > 3 SR, the b-value is 1.95 and the a-value is 11.20 for mb = 3–5 SR, and the b-value is 0.92 and the a-value is 6.71 for mb > 5 SR (Figure 9).

Based on spatial variation of seismicity, cluster 1 shows the b-values varied from 0.7 in the eastern Flores island to 1.7 in the western Labuan Bajo and surrounding areas. This implies that the Flores island to the east is categorized as high stress concentration area where weak earthquakes frequently occurred. Moreover, active volcanoes that are located in this area can trigger the occurrence of weak earthquakes. On the other hand, the west part of Flores island which has the b-value tending to be high or is called the creeping area [10] which is an active fault area does not accumulate stress (Figure 10(b)).

Figure 10: Spatial variation of seismicity of cluster 1 (Flores island, Labuan Bajo, and surrounding areas): (a) a-value and (b) b-value.
Cluster 2 (Timor, Alor, and surrounding areas) has 2,435 earthquake events; 1,155 of them were main earthquakes. Using Maximum Likelihood method, it was found that the b-value is 0.712 and the a-value is 6.06 for mb > 3 SR, the b-value is 2.34 and the a-value is 13.50 for mb = 3–5 SR, and the b-value is 0.749 and the a-value is 6.20 for mb > 5 SR, indicating the high stress condition in this area causing a lot of weak earthquakes (Figure 11).

Based on spatial variation of seismicity, the b-value and the a-value variation in cluster 2 (Figure 12(b)) show that the Timor island and Alor islands have a low of b-value, ranging from 0.6 to 0.8 indicates rock conditions in high stress levels. This can be attributed to the large number of local fractures on Timor island and subduction zone under the Timor island [11]. The a-value variation (Figure 12(a)) ranging from 5 to 6.5 indicates a relatively insufficient tectonic state that can hold energy so that earthquakes frequently occur on a small scale.

Cluster 3 (Sumba island and surrounding areas) has 651 earthquake events, where 390 of them were the main earthquake. Using Maximum Likelihood method, it was found that the b-value is 0.87 and the a-value is 6.33 for mb > 3 SR, the b-value is 1.79 and the a-value is 10.40 for mb = 3–5 SR, and the b-value is 0.921 and the a-value is 6.57 for mb > 5 SR. The low b-values indicate that the stress condition in this area is high that caused many weak earthquakes to occur (Figure 13). The existence of small earthquakes around Sumba is likely to be influenced by the local fractures that occur on the Sumba island.

Based on spatial variation of seismicity, the low b-value (0.8-0.9) was observed in the western part of Sumba island, indicating the large number of small-scale earthquakes. Meanwhile, the relatively higher b-value was found in the eastern part of Sumba island, indicating the small number of small-scale earthquakes (Figure 14). This is might occur due
The a-value variation in cluster 3 shows that Sumba island and its surrounding areas have variation of value with range of 6.2-8.2. This shows a lower level of seismic activity compared to two other clusters over a period of 75 years.

The a-value, b-value, and fractal dimensions for each cluster areas are presented in Table 1. These values are an indicator in the seismotectonic spatial distribution analysis. Based on Table 1, the three clusters show the same b-values relatively. The cluster with low b-values indicates that the area in that cluster suffers from many earthquakes. This can also be seen in the fractal dimension values that the high values of fractal dimension were observed in cluster 1 (Flores and surrounding islands) and cluster 3 (Sumba island and surrounding islands) with b-values ranges 1.674-1.874 and 1.704-1.864, respectively. In contrary, a low b-value of fractal dimension was found in cluster 2 (Timor island, Alor island, and surrounding areas), with b-value range being 1.384-1.464. Cluster 1 and cluster 3 areas most likely suffer from the return period of earthquakes in short intervals. Cluster 2, however, has a relatively longer return period of earthquakes, indicating a more irregular geometry that will result in a larger fractional coefficient in the fault system.

To illustrate the earthquake repetition that has been calculated based on the fractal value, it is calculated also based on the earthquake return period as in (8) and (10) presented in Table 2.

Table 2 shows that, in all clusters, earthquake events with 3.0 SR ≤ mb ≤ 3.9 SR have higher seismicity index value (N_i) than earthquake occurrence with the other scale. It is also found that the earthquake with 3.0 SR ≤ mb ≤ 3.9 SR in cluster 2 has the highest seismicity index among other regions. It means that occurrence frequency of earthquake is about 8 times a year and the return period is 0.12185 years (44 days). On a 4.0 SR ≤ mb ≤ 4.9 SR, cluster 2 has the highest seismicity index, 1.59285 with a return period of 0.62781 years.
Figure 13: Magnitude distribution graph of seismicity for cluster 3 (Sumba island and surrounding areas): (a) for \( m_b > 3 \) SR, (b) for \( m_b = 3-5 \) SR, and (c) for \( m_b > 5 \) SR.

(b-value = 0.87 \( \pm \) 0.05, a value = 6.33, a value (annual) = 4.37
Magnitude of Completeness = 4.6

Maximum Likelihood Solution
b-value = 1.79 \( \pm \) 0.09, a value = 10.4, a value (annual) = 8.7
Magnitude of Completeness = 4.6

(b-value = 0.921 \( \pm \) 0.1, a value = 6.57, a value (annual) = 4.62
Magnitude of Completeness = 5.1

Figure 14: Spatial variation of seismicity of cluster 3 (Sumba island and surrounding areas): (a) a-value and (b) b-value.
Table 2: Seismicity and return period of earthquake for each cluster.

| No | Magnitude (Mb) (SR) | Cluster 1 | Cluster 2 | Cluster 3 |
|----|-------------------|-----------|-----------|-----------|
|    |                   | \( N_1 \) (year\(^{-1}\)) | \( \theta \) (year) | \( N_1 \) (year\(^{-1}\)) | \( \theta \) (year) | \( N_1 \) (year\(^{-1}\)) | \( \theta \) (year) |
| 1  | 3-3.9             | 4.27339   | 0.23401   | 8.20681   | 0.12185   | 4.91215   | 0.20358   |
| 2  | 4-4.9             | 0.55433   | 1.80396   | 1.59285   | 0.62781   | 0.62990   | 1.58755   |
| 3  | 5-5.9             | 0.07191   | 13.90682  | 0.30915   | 3.23464   | 0.08077   | 12.38022  |
| 4  | 6-6.9             | 0.00933   | 107.20814 | 0.06000   | 16.66578  | 0.01036   | 96.54470  |
| 5  | 7-7.9             | 0.00121   | 826.47131 | 0.01165   | 85.86689  | 0.00133   | 752.88461 |

Earthquake with 5.0 SR ≤ mb ≤ 5.9 SR cluster 2 has the shortest return period of 3.23464 years, while cluster 1 and cluster 3 were 13.90682 years and 12.38022 years. Earthquakes with mb > 6.0 SR are still rare in the study area. This can be seen from the level of seismicity index and also the length of earthquake return period.

4. Conclusion

It can be concluded that the b-value in ENTP region is relatively low with high stress condition so that there are many weak earthquakes. This result is supported by the variation of b-value and a-value in the ENTP region, respectively, ranging from 0.6 to 1.3 and from 5.0 to 8.5. The temporal variation in ENTP indicates that before the occurrence of big scale earthquakes, i.e., mb 7.5 SR in 1996 and 2004, there was a significant decrease in b-value. The average of the b-values ranges from 0.837 to 0.937 and the a-value is 6.54 in cluster 1, the average of b-values ranges from 0.692 to 0.732 and a-value is 6.06 in cluster 2, and the average of the b-value ranges from 0.852 to 0.932 and a-value is 6.69 in cluster 3. It implies that the b-value and a-value of the clusters are not significantly different.

The result of the fractal dimension calculation shows that clusters 1, 2, and 3 have D values of 1.674-1.874, 1.384-1.464, and 1.704-1.864, respectively. Meanwhile, based on the calculation of the earthquake return period, it is found that each cluster is still dominated by small-scale earthquake with the highest seismicity index and the fastest earthquake return period is in cluster 2 which is 44 days.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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