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Correlation Dimension and Seismic Quiescence around Northern Sumatra

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Abstract. The implementation of the correlation dimension (Dc) analysis is often used to measure the scaling attribute's possible size or grouping of seismotectonic variables. Related to seismicity in certain areas, Dc can suggest the existence of potential seismic gaps to release strain energy in the future. It can be identified that the presence of earthquake precursors can be characterized by changing the pattern of seismicity in space-time correlate strongly with the existence of zones and periods of seismic quiescence before major earthquake events. In this study, the Dc and the difference of Dc (δDc) are evaluated based on previous studies in which Dc is estimated based on the b-value of shallow earthquake data, and δDc is calculated based on the two periods before and during Region Time Length. We found the consistency that the areas filled by large earthquake events are in the zone with relatively high Dc and δDc . Dc tends to have a strong correlation to suggesting the existence of potential seismic gaps to release strain energy. δDc could be correlated with the possible stress transfer that may trigger the next sequence large earthquake.

1 Introduction

According to Mandelbrot (1982), fractal analysis can be used to describe the geometry of objects naturally. Many evidence has been found in space-time, such as seismicity, can be characterized and interpreted by fractal models using power-laws (e.g., Hirata T., 1989; Oncel AO et al., 1995; Sukmono et al., 1996, 1997, 2001, Caneva A., Smirnov V., 2004; Oncel AO, Wilson TH, 2007; Roy S. et al., 2011; Pailoplee and Choowong, 2014; Goebel, T.H.W et al., 2017).

The implementation of fractal analysis is often used to measure the possible size of the scaling attribute or grouping of seismotectonic variables. Associated with active fault segmentation, implies the fractal dimension can be applied to determine the possibility of segmentation that will be broken due to high-stress loading or its perturbation. Fractal applications related to seismicity in certain areas can be used to

characterize the existence of potential seismic gaps to release strain energy in the future (Henderson et al., 1992, Oncel AO et al., 1995, Scholz, 2002).

Wyss et al. (2004), has been pointed out that the application of earthquake statistics, frequency-magnitude distribution (FMD; Gutenberg and Richter 1944), and correlation dimension (Dc) is quite practical approaches used to understand local seismotectonic activities. Both the b values of FMD and Dc values are significantly directly related to stress and earthquake phenomena.

Pailoplee and Choowong (2014) evaluated the a and b values of the frequency-magnitude distribution (FMD) and fractal dimension (Dc) simultaneously for 13 recognized seismic source zones in mainland Southeast Asia including northern Sumatra using a complete earthquake dataset. They found the relationships of Dc-b and Dc-(a/b) are ($Dc=2.80-1.22b$) and ($Dc=0.27(a/b)-0.01$) with similar regression coefficients ($R^2 = 0.65$ to 0.68) for both regressions. Pailoplee and Choowong (2014) pointed out that the Sumatra-Andaman interplate and intraslab, the Andaman Basin, and the Sumatra fault zone were defined as high-tectonic stress regions that may pose risks of generating large earthquakes in the future.

Triyoso et al. (2020b) identified that the presence of earthquake precursors could be characterized by changing the pattern of seismicity in space-time correlate strongly with the existence of zones and periods of seismic quiescence before major earthquake events.

In this study, the Dc and the difference of Dc (δDc) are evaluated based on the result of Triyoso et al. (2020b) in which Dc is estimated based on the b-value of shallow earthquake data, and δDc is calculated based on the two periods before and during Region Time Length.

Referring to Triyoso et al. (2020b), the RTL period selected before major earthquake events are based on the gradient analysis of cumulative shallow earthquake production after the declustering process of the 2017 PUSGEN catalog data. The presence of a quiescence period indicates the relatively long RTL period before the major earthquake event of December 26, 2004 (Katsumata, 2015), wherein this study; it was taken about 15 years, namely the period 1991 to November 2004. While the period from 1963 to 1990 could be categorized as a period with background seismicity with the gradient rate is higher than the quiescence period in RTL.

2. Method

2.1 Data regarding earthquakes

The seismicity data used is based on Triyoso et al. (2020a, b) in which the PUSGEN 2017 (PUSGEN, 2017) earthquake data with the magnitude of $M_w \geq 5.0$ and a maximum depth of 50 km. Data selected inside the circular area of around a 500 km radius with the center radius is (95.328°E, 2.480°N). The selected

earthquake catalog is then carried out by the declustering process to get an earthquake event mutually free or independent. The declustering process is carried out using ZMAP software (Wiemer, 2001).

2.2 Earthquakes' frequency-magnitude distribution (FMD)

The frequency-magnitude distribution (FMD) in general will follow the Gutenberg-Richter (G-R) law (Gutenberg B., Richter C.F., 1944), which can be written as follows,

$$\log_{10} N(M) = a - b(M - M_c) \quad (1)$$

in which $N(M)$ is the cumulative number of events having a magnitude greater than magnitude completeness (M_c), b describes the slope of the size distribution of events and is proportional to the earthquake number, or the rate of the seismicity.

As pointed out by the previous study, the b -value is one of the most important parameters to describe the possible size scaling properties of seismicity; in general, the b -value changes roughly in the range of 0.3 to 2.0, depending on different regions. According to Frohlich and Davis (1993), the regional scale estimate of the b -value will usually be close to 1.

There exist many factors that can cause perturbation of average b -value ($b \sim 1.0$). Based on the previous study, regions having lower b -values are probably regions subjected to higher applied shear stress after the mainshock. In contrast, areas having higher b -values are areas that have experienced slip.

Another result of the previous study also pointed out that the high b -values are reported of the area's regions having increased geological complexity. It indicates the importance of the multi-fracture parts; a low b -value is thus related to a small degree of heterogeneity of cracked medium, high stress, strain, high deformation rate of loading, and quite longer faults segmentation (Bayrak Y., Ozturk S., 2004). To estimate the b -value, the maximum likelihood method is applied (Aki K., 1965) which can be written as follow,

$$b = \frac{\log_{10}(e)}{(\bar{M} - M_c + 0.005)} \quad (2)$$

where $\bar{M}$ is the average magnitude value greater or equal than M_c , and M_c is the minimum magnitude or the magnitude completeness. The 0.05 in equation (2) is a correction constant. M_c in PUSGEN 2017 earthquake catalogs around the study area was around 4.7 based on the period of the year of 1963 to 2016. To estimate the b -value with the standard deviation of 95% confidence limit in each grid, the number of earthquakes (n) can be determined using the equation suggested by Aki (1965) as $\approx (1.96b/\sqrt{n})$. Using about $\pm 0.1 \sim 0.2$ confidence limits regarding the regional b -value ~ 1 for a typical sample consisting of $n \approx 100$ earthquakes. Thus in this study, the b -value is determined based on the maximum likelihood method based on the constant number of at least 100 events in each cell of the observation grid point.

2.3 Seismicity Smoothing and the seismicity rate function

Following the previous study, the seismicity smoothing algorithm using the Gaussian function approach, for example, (Frankel 1995, Petersen et al. 2008, Triyoso & Shimazaki, 2012, Triyoso et al. 2020a, b) is implemented. The study area is firstly gridded, then the counting of number (n_i) of earthquake events with magnitude greater than the reference (M_{ref}) is done in each grid. According to Bender (1983), the number of n_i represents the maximum likelihood estimate of 10^a above the M_{ref} in each grid. Furthermore, the seismicity smoothing using a Gaussian function with correlation distance c of the n_i values in each grid is then done. The smoothed value in each grid i is obtained from:

$$\tilde{n}_i = \frac{\sum_j n_j e^{\frac{-\Delta_{ij}^2}{c^2}}}{\sum_j e^{\frac{-\Delta_{ij}^2}{c^2}}} \quad (3)$$

in which $\tilde{n}_i$ is normalized to preserve the total number of events, Δ_{ij} is the distance between the i -th and j -th cells, and c is the correlation distance. In equation (3), the sum is taken over cell j within a distance of $3c$ from cell i .

Following Triyoso et al. (2020a), the theoretical rate function for a given grid or $v_i (\geq M_{ref})$ is estimated by the equation,

$$v_i(\geq M_{ref}) \approx \frac{N_i}{T} \quad (4)$$

where N_i is the number of earthquakes with magnitude $\geq M_{ref}$ on the grid, i and T is the observation period. v_i is a quantity of 10^a for earthquake events with magnitude greater than or equal to M_{ref} . So the application of the Gaussian function for seismicity smoothing is to set the value of 10^a based on equation (3). By substituting equation (3) with equation (4), we can write the following equation,

$$v_i(\geq m) \approx \frac{\tilde{n}_i(\geq M_{ref})}{T \cdot b \ln(10)} 10^{-bm} (1 - 10^{b(m - M_{max})}) \quad (5)$$

where $\tilde{n}_i(\geq M_{ref})$ is the smoothed value for grid i which is expressed as the number of earthquakes with magnitude greater or equal to the reference magnitude during the period of T years with a certain b -value. The b -value is determined based on the maximum likelihood method based on the constant number of at least 100 events in each cell of the observation grid point of shallow earthquake catalog ($M_c \sim 4.7$, $H \leq 50$ km of the years 1963 to 2016) and $M_{max} \sim 9.2$ (Triyoso et al. 2020b).

2.4 Correlation Dimension and Seismic Quiescence Index

The spatial and temporal distribution patterns of fault and earthquake seismicity were demonstrated to be fractal using a two-point correlation dimension (D_c). To quantify the geometrical object of self-similarity the correlation dimension is a powerful tool (Grassberger and Procaccia, 1983), in which D_c and correlation sum $C(r)$ could be written as follows:

$$D_c = \lim_{r \rightarrow \infty} \left(\frac{\log C_r}{\log(r)} \right) \quad (6)$$

in which $C(r)$ is the correlation function, r is the distance between two epicenters. If the epicenter distribution has a fractal structure, the following relationship would be obtained:

$$C(r) = \left(\frac{2 N_{R < r}}{N(N-1)} \right) \quad (7)$$

in which N is the number of pairs of events separated by distance $R < r$ (Amitrano, 2003, Öztürk, 2012)

$$C(r) \sim r^{D_c} \quad (8)$$

where D_c is the fractal dimension (correlation dimension) and r is distance between two earthquakes would be calculated (in degrees) from:

$$r = \cos^{-1}(\cos \theta_i \cos \theta_j + \sin \theta_i \sin \theta_j \cos(\phi_i - \phi_j)) \quad (9)$$

in which (θ_i, ϕ_i) and (θ_j, ϕ_j) are the latitudes and longitudes of the i th and j th events, respectively (Hirata T., 1989). D_c could be obtained from the slope of the graph of $C(r)$ against r on a double logarithmic coordinate.

Following Pailoplee and Choowong (2014), in this study, D_c and δD_c are evaluated based on the following relationship,

$$D_c = 2.80 - 1.22.b \quad (10)$$

$$D_c = 0.27 \frac{a}{b} - 0.01 \quad (11)$$

where D_c is the Correlation Dimension, a and b are the a and b -values of Gutenberg-Richter Equation (1944).

Decreased earthquake activity can occur in part from or on all mainshock volumes or from mainshock to the next mainshock. The downward trend in seismic activity trend or decrease in gradient rate of seismicity can continue until a major earthquake or mainshock occurs, or a downward trend can happen in a relatively short period before the occurrence of a major earthquake, which further increases the tendency in

earthquake activity. Therefore, the duration of the search for zones and periods of quiescence is very dependent on tectonic activity and structure, loading rate, and stress perturbation, which are important parameters related to the likelihood of earthquake precursors that will occur.

The application of these terminology zones and quiescence periods as precursors of large earthquakes has been used in many seismic studies in various parts of the world and also the Andaman-Northern Sumatra (e.g., Katsumata and Kasahara, 1999, Cao and Gao, 2002, Tsapanos et al. 2014; 2016, Sukrungsri & Pailoplee, 2016).

Referring to the definition of Seismic Quiescence by Wyss and Habermann (1988), in this study, the identification of quiescence zones in the RTL period is quantified with annual seismicity rate so that it can be quantified and mapped two models before the RTL in the quiescence period and during RTL period.

Furthermore, by normalizing the difference of the annual seismicity rate, the scale or index quantification of the zone and quiescence period as a function of the spatial difference annual rate for a particular RTL period will be 0 to 1. This index is defined as the Seismic Quiescence Index or SQI. The SQI is included as one of the components of Dc by the following equation.

$$SQI = \text{abs}\left(\frac{(\text{Seismicity Rate Before RTL} - \text{Seismicity Rate During RTL})}{\max(\text{Seismicity Rate Before RTL} - \text{Seismicity Rate During RTL})}\right) \quad (12)$$

where SQI is seismic quiescence index

Substitute equation 12 into equation 11, we may write

$$\delta Dc = 0.27\left(\frac{SQI}{b}\right) \quad (13)$$

where δDc is the delta Correlation Dimension, SQI is seismic quiescence index, and b are the a and b -values of Gutenberg-Richter Equation (1944).

3. Result and Discussion

Figure 1A shows the result of the annual seismicity rate model of the study area with a radius of 500km, and the center radius is (95.328°E, 2.480°N), with $M_w \geq 5.0$, generated by data before the RTL period of the year of 1963 to 1990. Figure 1B shows the annual seismicity rate model in the RTL period of the year of 1991 to November 2004. Based on Figure 1 (A and B), the quiescence period can be seen clearly by the existence of the difference in a gradient of the rate of earthquake production.

Figure 1. The annual seismicity rate model of the study area with a radius of 500km and the center radius is (95.328°E, 2.480°N), with $M_w \geq 5.0$, generated by data before the RTL period of the year of 1963 to 1990 (A). The annual seismicity rate model in the RTL period of the year of 1991 to November 2004 (B).

Figure 2A shows the Seismic Quiescence Index (SQI), which is based on the results of Figure 1 (A and B). Figure 2B shows the b-value map, in which the b-value is determined based on the maximum likelihood method based on the constant number of at least 100 events in each cell of the observation grid point of shallow earthquake catalog ($M_c \sim 4.7$, $H \leq 50\text{km}$ of the years 1963 to 2016).

Figure 2: The Seismic Quiescence Index (SQI) estimated based on equation 12 (A). The SQI is calculated based on the results of Figure 1 (A and B). The b-value map (B), in which the b-value is determined based on the maximum likelihood method based on the constant number of at least 100 events in each cell of the observation grid point of shallow earthquake catalog ($M_c \sim 4.7$, $H \leq 50\text{km}$ of the years 1963 to 2016).

Figure 3A is the Dc map derived based on equation (10). It shows that Dc tends to have a strong correlation to the suggestion of the existence of potential seismic gaps to release strain energy. Figure 3B shows the δDc map derived based on the equation (13). It shows that δDc is consistent with the places where the sorted of significant earthquakes occurred from December 2004 to 2016 over the entire radius area of the study.

Figure 3. The Dc map derived based on equation 10 (A), and the δDc map derived based on equation 13 (B). It shows that Dc tends to have a strong correlation to the suggestion of the existence of potential seismic gaps to release strain energy, and δDc shows to be consistent with the places where the sorted of significant earthquakes occurred from December 2004 to 2016 over the entire radius area of the study.

Figure 4 is a plot between the b-value with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. Based on figure 4, it can be characterized that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with the relatively low b-value. This finding supports the discovery of the previous study that a relatively low b-value is thus related to a small degree of heterogeneity of cracked medium, significant stress, and strain, high deformation rate of loading, and large faults, as pointed out by Bayrak & Ozturk (2004). Figure 5 shows the plot between the Dc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. Since the Dc is derived based on the b-value, thus the similar finding could be found that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with the relatively high Dc with low b-value.

Figure 6 shows the plot between the δDc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. It can be found that all of a relatively large earthquake with $M_w \geq 6.5$ occurs with the pattern of a relatively high δDc . This finding leads to the interpretation that δDc could be correlated with the possible stress transfer that may trigger the next sequence large earthquake.

Figure 4: Plot between the b-value with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. It can be identified that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with a relatively low b-value.

Figure 5: The plot between the Dc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. Since Dc is derived based on the b-value, thus the similar finding could be found that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with the relatively high Dc with low b-value.

Figure 6: The plot between the δDc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. It can be found that all of a relatively large earthquake with $M_w \geq 6.5$ occurs with the pattern of a relatively high δDc . This finding leads to the interpretation that δDc could be correlated with the possible stress transfer that may trigger the next sequence large earthquake.

4. CONCLUSIONS

In this study, the D_c and the difference of D_c (δD_c) are evaluated based on the result of the b -value of shallow earthquake data, and δD_c is calculated based on the SQI of the two periods before and during Region Time Length. We found the consistency that the areas filled by large earthquake events are in the zone with relatively high D_c and δD_c . In which D_c tends to have a strong correlation to the suggestion of the existence of potential seismic gaps to release strain energy. The result supports the discovery of the previous study that a relatively low b -value and high D_c is thus related to a small degree of heterogeneity of cracked medium, significant stress, and strain, high deformation rate of loading, and large faults. This study found that all of a relative occurrence of a large earthquake is consistent with the pattern of a relatively high δD_c . This finding leads to the interpretation that δD_c could be correlated with the possible stress transfer that may trigger the next sequence large earthquake. The result of this study might be very beneficial for the sake of earthquake mitigation and modeling efforts for seismic hazard study and analysis going forward.

Data availability. The author declares the materials and data used in this manuscript will be made available promptly to the Editorial Board Members and Referees upon request. Earthquake Catalog Data based on the PUSGEN2017 Catalog. It has been public domain data.

Authors Contributions. WT developed the method, did the analysis, and prepared the figures and the manuscript. SS helped in the manuscript preparation and discussion.

Competing Interests: WT and SS declare that they have no conflict of interests.

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Figures

Figure 1

The annual seismicity rate model of the study area with a radius of 500km and the center radius is (95.328°E, 2.480°N), with $M_w \geq 5.0$, generated by data before the RTL period of the year of 1963 to 1990 (A). The annual seismicity rate model in the RTL period of the year of 1991 to November 2004 (B).

Figure 2

The Seismic Quiescence Index (SQI) estimated based on equation 12 (A). The SQI is calculated based on the results of Figure 1 (A and B). The b-value map (B), in which the b-value is determined based on the maximum likelihood method based on the constant number of at least 100 events in each cell of the observation grid point of shallow earthquake catalog ($M_c \sim 4.7$, $H \leq 50\text{km}$ of the years 1963 to 2016).

Figure 3

The Dc map derived based on equation 10 (A), and the δDc map derived based on equation 13 (B). It shows that Dc tends to have a strong correlation to the suggestion of the existence of potential seismic gaps to release strain energy, and δDc shows to be consistent with the places where the sorted of significant earthquakes occurred from December 2004 to 2016 over the entire radius area of the study.

Figure 4

Plot between the b-value with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. It can be identified that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with a relatively low b-value.

Figure 5

The plot between the Dc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. Since Dc is derived based on the b-value, thus the similar finding could be found that most of a relatively large earthquake with $M_w \geq 6.8$ occurs with the relatively high Dc with low b-value.

Figure 6

The plot between the δDc with earthquake sequences with $M_w \geq 6.5$ and $H \leq 50\text{km}$ for the period from December 2004 to the year 2016. It can be found that all of a relatively large earthquake with $M_w \geq 6.5$ occurs with the pattern of a relatively high δDc . This finding leads to the interpretation that δDc could be correlated with the possible stress transfer that may trigger the next sequence large earthquake.