Temporal Investigation of the Frequency-magnitude Distribution and Fractal Dimension in the Northern Thailand: A comparison

Kanokkarn Vejchakom* and Santi Pailoplee

Morphology of Earth Surface and Advanced Geohazards in Southeast Asia Research Unit (MESA RU), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

**Corresponding author E-mail: k.vejchakom@gmail.com*

ABSTRACT

According to the Indo-Australian and Eurasian plate collision, a large number of seismogenic fault zone were dominant as the intraplate earthquake sources within the Mainland Southeast Asia or the Thailand-Laos-Myanmar border. Up to the present, hazardous earthquakes were generated continuously in 35 yr during 1980-2015. Therefore, this study aims mainly to investigate the earthquake activates and pattern of earthquake occurrence in this region. Regarding to statistical seismology, both b value of the frequency-magnitude distribution and fractal dimension (Dc) were, therefore, analyzed temporally. In addition in terms of the utilized dataset, both dataset of before- and after-declustering were recognized. As a result, it reveals that both b and Dc value analyzed by the after-declustering dataset is meaningless in term of seismotectonic meaning. In contrast, the before-declustering dataset is meaningful for both b and Dc analysis. Based on the before-declustering dataset, b value is decrease continuously during 35 yr of 1980-2015 before both Mae Lao and Tarlay earthquakes posed. In addition, the Dc values are drop down suddenly during or after these earthquakes were generated. This may imply the earthquake precursor which useful for earthquake mitigation in any site of interest the future. For b-Dc relationships, both Mae Lao and Tarlay earthquakes express the different correlation. Mae Lao earthquake indicate the positive relation while Tarlay earthquake express negative relation. This relation, therefore, may accord to the different characteristic or activities of each fault zone. To further refine seismic activities (b value) and seismic pattern (Dc) value including their relationship in this region, more detailed case studies of earthquake that generated in different seismogenic fault are need.

Keywords: Earthquake Catalogue; Earthquake Declustering; b value; Fractal Dimension; Thailand-Myanmar Borders.

1. Introduction

The Indo-Australian plate has been moved and subucted northward underneath the Eurasian plate since 40 million years ago (Molnar and Topponnier, 1977). Seismotectonically, this plate collision initiates interplate earthquake sources called the Sumatra-Andaman Subduction Zone (Figure 1a). In addition, it also causes intraplate earthquake sources where the inland seismogenic faults are dominant (Figure 1b). As an example of intraplate fault zones in the northern Thailand, there are the Mae Tha fault zones and also the Lampang-Thoen fault zone (Pailoplee et al., 2009). Therefore, a large number of earthquakes are generated continuously within the Eurasian plate (Pailoplee et al., 2013).

According to previous research work, the TLMB which encompasses major cities and hydropower dams along the Mekong River (Mekong River Commission, 2010). There had generated a large number of hazardous earthquakes (Figure 1b) such as magnitude 6.2 (1989), magnitude 6.8 (1995), magnitude 6.3 (2007), magnitude 6.8 (2011) (Pailoplee et al., 2013) and latest event is Mea Lao earthquake with magnitude 6.2 (2014) as shown in Figure 1b. The occurrence of earthquakes on the TLMB causes damage to northern Thailand, northern Laos and eastern Myanmar.

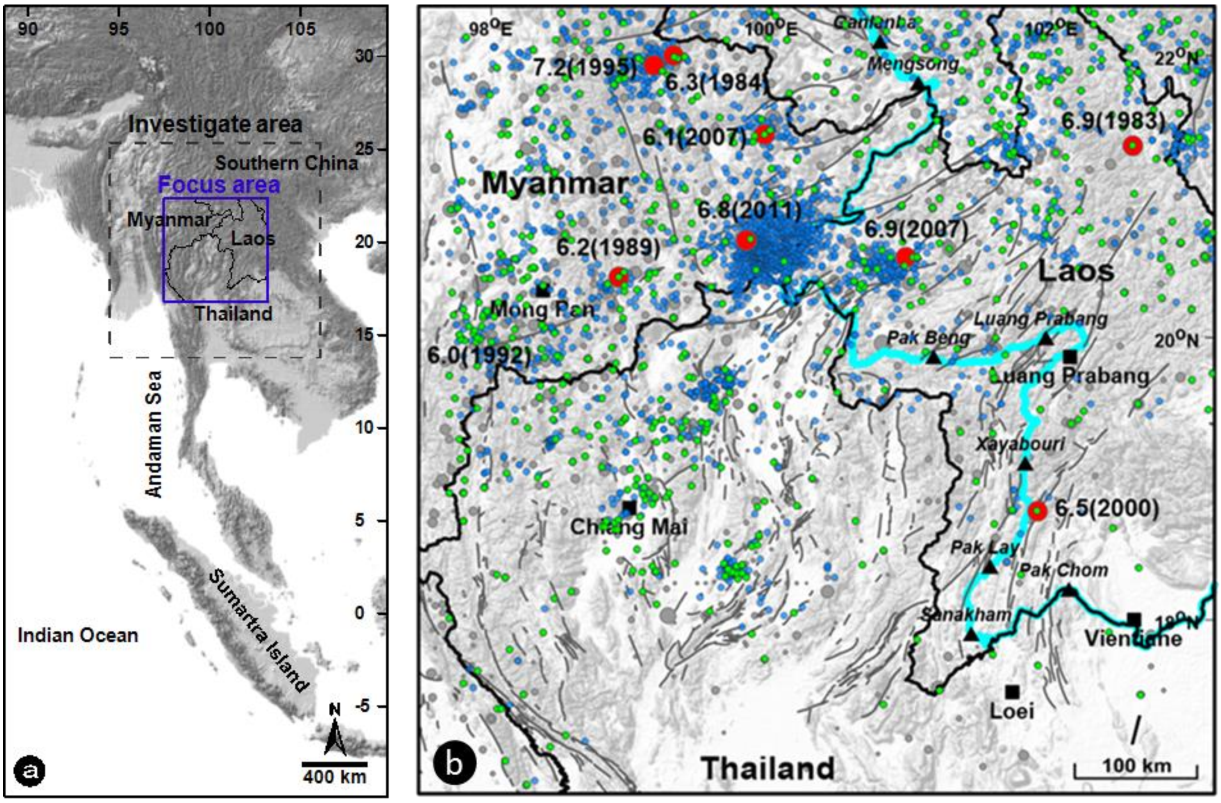

Figure 1. (a) Map of the mainland Southeast Asia showing the study area (blue square) and the boundary of earthquake investigation (black dash line square). (b) Map of study area showing the earthquake with Mw≥ 6.0 (red circles) within the TLMB. The fault lines, hydro power dam, major cities are shown with thin grey lines, black triangles and black squares, respectively. The blue and green dots are the earthquake dataset occurred during 1965 to 2016 that before and after declustering process, respectively.

However in the study of earthquake characteristic or pattern, it is difficult to investigate the earthquake source in the TLMB because of the complexity in the seismotectonic setting and the blind faults made by the covering of quaternary sediment within the basin (Fenton et al., 2003). Scientists applied statistics to study earthquakes characteristics and estimate the changes of earthquakes activities in study area. In order to do so, they used methods such as the frequency-magnitude distribution model (FMD; Nuannin et al., 2005), fractal dimension (Dc; Chen et al., 2006), Pattern informatics (PI; Wu et al., 2008), seismic rate change (Z; Wyss and Habermann, 1988), and region-time-length algorithm (RTL; Chen and Wu, 2006) etc. In addition, some previous works reported that the spatial distribution of b value and Dc values have a relationships implying the accumulated tectonic stress and seismic pattern, respectively (Pailoplee et al., 2014). The main aim of this study is, therefore, analyzing the temporal variation of both of b and Dc values in the study area. The epicenters of 2 case studies of significant earthquakes were recognized, i.e., Mea Lao (2014) and Tarlay (2011) earthquakes. In addition in technical term, this study also considered both b and Dc based on 2 different earthquake dataset, i.e., dataset i) before and ii) after declustering.

2. Dataset and Completeness

2.1. Earthquake catalog collection

The earthquake catalogues are one of the most important products of seismology (Woessner and Wiemer, 2005) and they are important in the study of earthquake characteristics using statistical analysis. In this study, we used the earthquakes that occurred on the TLMB recorded from 1966 to 2016. This yielded approximately 12,133 recorded earthquake events (blue dots in Figure 1b). These catalogue were reported by i) the International Seismological Centre (ISC), ii) the National Earthquake Information Center (NEIC) and iii) the Global Centroid Moment Tensor (GCMT). The earthquake magnitude were reported variously in body-wave magnitude (Mb), surface-wave magnitude (Ms), local magnitude (Ml) and moment magnitude (Mw) scales. In order to homogenize the magnitude scale, all different scales were converted empirically to the Mw which represent directly the seismotectonic activities.

2.2. Earthquake decluttering

Normally, the earthquakes occurrences can be sorted out into 3 types which are i) foreshock, ii) mainshock and iii) aftershock. Seismically, only mainshocks indicate directly about the tectonic stress accumulated in any specific area (Nuannin et al., 2005). Therefore, both foreshock and aftershock clusters should be screen and remove from the utilized earthquake catalogue in any seismicity investigation in the statistical approach. According to the assumption of Gardner and Knopoff (1974), the earthquake dataset of the TLMB were declusted statistically (Figure 2). As a result, the mainshock catalogue comprises a total of 2,195 earthquake events with Mw $\geq$ 0.1 from 1964 to 2016 (green dot in Figure 1b).

As mentioned above, both earthquake dataset of i) before and ii) after declustering were utilized in this analysis in order to test technically the possibility of using the dataset. Therefore, in this temporal investigation of the seismicity, i.e., b and Dc values, the earthquake data within 300-km radius (Kupta, 2002) from the hazardous Mea Lao and Tarlay earthquakes were selected from both the earthquake data of the before- and after-declustering process. As a result, 4 case studies of temporal investigation were demonstrated in this analysis.

3. Frequency-magnitude Distritubion (b Value)

According to Gutenberg and Richter (1944), the empirical relationship of the FMD is shown in Equation (1)

$$\log(N) = a - bM \qquad (1)$$

Where N is the cumulative number of earthquakes with magnitude greater or equal to M. a and b are constants, positive and vary in any specific time and space window. The a value is all of the activity level of seismicity, and the b value is the slope of FMD. In seismological context, b value related to the variation of the tectonic stress accumulated (Mogi, 1967; Scholz, 1986). Lower b value relates with large tectonic stress, strain and faults (Manakou and Tsapanos, 2000).

For example in case of the after-declustering dataset within 300-km radius from the Mea Lao earthquake, the 492 earthquake data were recorded during 1965-2016. The FMD plot (Figure 3a) represented the y-intercept as a value is 3.13. The b value indicated by slope is 0.634 ± 0.04. The magnitude of completeness is 4.0.

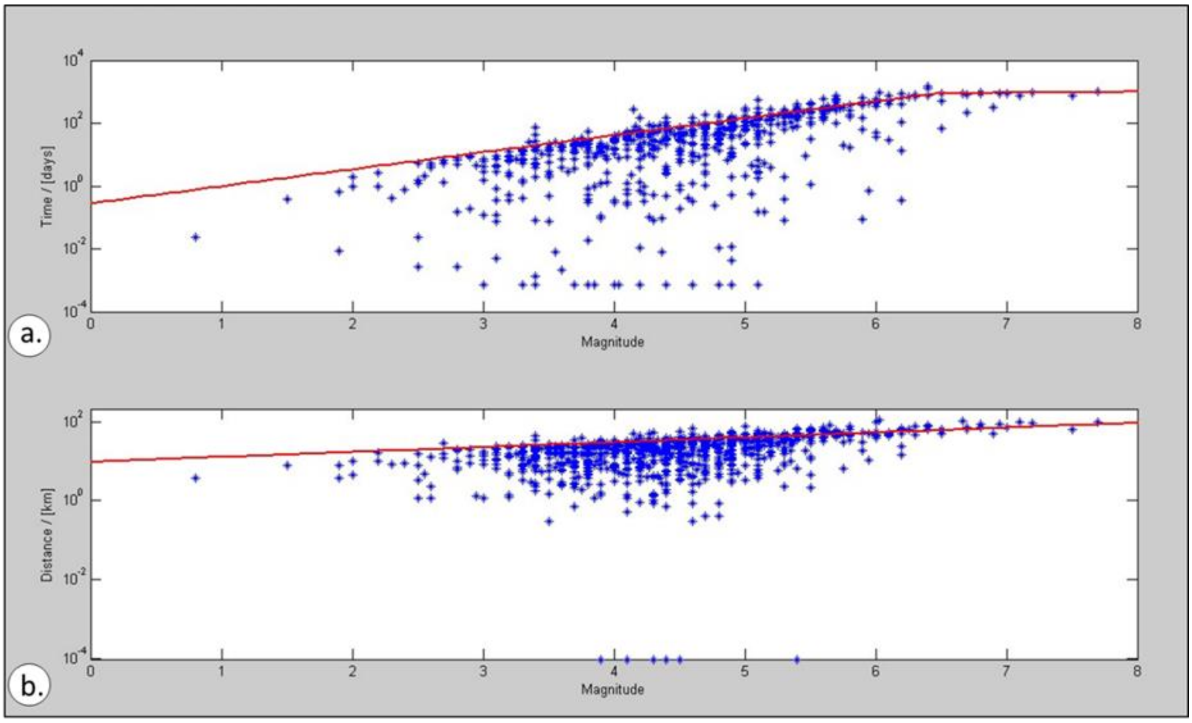

Figure 2. Diagram showing the declustering process of the earthquake data in the TLMB according to Gardner and Knopoff's declustering model (red line). The earthquake data (blue dots) upper both red lines of (a) different of occurrence time and (b) distance from each earthquake event were defined as the earthquake mainshocks. Meanwhile, the other data below the redline were classified as foreshocks or aftershocks.

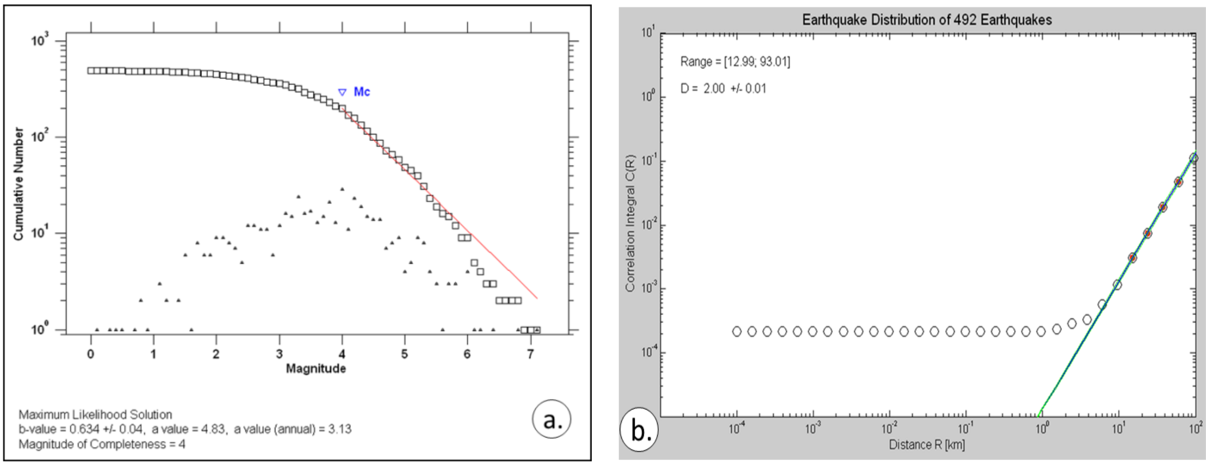

Figure 3. (a) The FMD plot of the Mea lao after declustering dataset. The triangles and squares represent the number and cumulative number of each individual seismicity magnitude level, respectively. The red line indicates the FMD linear regression fitted with the observed data. The Mc is defined as the magnitude of completeness (Woessner and Wiemer, 2005). (b) Graph showing the relation between log (Cr) and log (R) of the Mea lao after declustering dataset. The slope of linear fit (green line) is the fractal dimension (Dc).

4. Fractal Dimension (Dc Value)

The fractal dimension (Dc value) is estimated using the correlation dimension by the correlation integral technique. This technique measures the spacing of a set of points are earthquake epicenters

(Grassberger and Procaccia, 1983). The correlation dimension is widely applied in spatial term of earthquake epicenters distribution. That is preferable because of its greater reliability and sensitive to small changes in clustering properties (Kagan and Knopoff, 1980; Hirata, 1989). So, the fractal dimension of epicenter distribution of earthquake was calculated from the correlation technique given relation by Grassberger and Procaccia (1983) is defined as Equation (2).

$$D = \frac{\lim_{r\to 0} \log(C_r)}{\log r} \quad (2)$$

Where (Cr) is the correlation function as expressed in Equation (3).

$$C_r = \frac{2(N_{(R<r)})}{N(N-1)} \quad (3)$$

Where $N_{(R<r)}$ is the number of points separate by distance R less than r. N is the total number of points analyzed. If the epicenters distribution of earthquake has a fractal structure, the correlation integral is related to the standard correlation function as illustrated in Equation (4).

$$C_r \sim r^{D_c} \quad (4)$$

Where Dc is a fractal dimension, more strictly, the correlation dimension (Grassberger and Procaccia, 1983). By plotting Cr against r on a double logarithmic coordinate, we can calculate practical fractal dimension value (Dc) from slope of this graph.

The distance (r) between two events, (θ_1, ϕ_1) and (θ_2, ϕ_2) are the colatitudes (θ) and longitudes (ϕ), is calculated by using the formula given by Hirata (1989) as expressed in Equation (5).

$$r = \cos^{-1}(\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2)) \quad (5)$$

The slope is obtained by fitting a least-square line in the scaling region. The fractal dimension D_c gives an estimate of the fractal characteristics of fault system. Seismically, the Dc values close to 3 designate the earthquake fractures are generated within the volume source of crust. Meanwhile, the Dc values close to 2 imply the earthquake occurrence is being filled up by plane. And also, the Dc values close to 1 means line sources (Aki, 1981).

For example in case of the after-declustering dataset within 300-km radius from the Mea Lao earthquake, i.e., the same dataset used in FMD plot in Figure 3a. We found the slope from the relation between distance (R) and correlation intregral (Cr) as 2.00 ± 0.01. That slope indicated the fractal value (D), considered in distance between 12.99 km. to 93.01 km as shown in Figure 3b. This D value specify the earthquake distribution pattern as plate source.

5. Result

5.1. Temporal variation of b and Dc values

As mentioned above, we focus on the temporal variation of the tectonic stress (i.e., b value) and the seismic pattern (Dc) before both Tarlay and Mea-Lao earthquakes. The earthquakes data was divided into temporal term and analysed both b and Dc as shown in Table 1

For the Mea Lao earthquake, the b values analyzed from the before-declustering dataset reveal that b value varies temporally during 1980-2016 with the b values are in the range of 0.62-1.40 (Table 1a and Figure 4a). The highest b value of 1.40 expresses at 1980. After that the b value decrease contineously until 2000. The b values are stable at 0.62-0.75 from 2000 to 2016 (Figure 4a). In case of the Tarlay earthquake, we found the highest b value (b = 1.08) analyzed from the before-declustering is at 1985 (Table 1c and Figure 4c). After that, b values between 1990-2016 are dropped down to 0.65-0.70 (Figure 4c).

Table 1. The result of temporal Mc, a, b, and Dc investigation analyzed at the epicenters of the Mea Lao and Tarlay earthquakes busing the earthquake dataset that before and after declustering process.

(a) Mea Lao before declustering

Year	EQ number	Mc	a	b	Dc
1965-1980	57	4.8	7.06	1.40 ± 0.20	0.65 ± 0.01
1965-1985	143	4.9	6.21	1.20 ± 0.10	1.45 ± NaN
1965-1990	326	4.6	4.73	0.87 ± 0.06	1.73 ± NaN
1965-1995	536	4.5	4.31	0.75 ± 0.04	1.38 ± NaN
1965-2000	682	4.0	3.68	0.62 ± 0.02	1.32 ± 0.03
1965-2005	858	4.2	4.23	0.74 ± 0.03	1.82 ± 0.03
1965-2010	1446	4.0	3.91	0.66 ± 0.02	1.75 ± 0.03
1965-2015	2516	4.0	3.92	0.65 ± 0.02	1.17 ± 0.02
1965-2016	2521	4.0	3.92	0.65 ± 0.02	1.55 ± 0.07

(b) Mea Lao after declustering

Year	EQ number	Mc	a	b	Dc
1965-2000	169	4.2	3.12	0.63 ± 0.05	2.01 ± 0.02
1965-2005	228	4.2	3.4	0.69 ± 0.05	2.00 ± 0.02
1965-2010	386	4.0	3.12	0.63 ± 0.04	1.98 ± NaN
1965-2015	490	4.0	3.12	0.63 ± 0.04	2.00 ± 0.01
1965-2016	492	4.0	3.13	0.63 ± 0.04	2.00 ± 0.01

(c) Tarlay before declustering

Year	EQ number	Mc	a	b	Dc
1965-1985	241	4.9	6.01	1.08 ± 0.09	1.12 ± 0.01
1965-1990	637	4.3	4.07	0.65 ± 0.02	1.89 ± 0.02
1965-1995	950	4.3	4.12	0.65 ± 0.02	1.87 ± 0.02
1965-2000	1168	4.3	4.21	0.67 ± 0.02	1.91 ± 0.01
1965-2005	1418	4.3	4.33	0.70 ± 0.02	1.92 ± 0.03
1965-2010	2262	4.3	4.35	0.70 ± 0.02	1.97 ± 0.02
1965-2015	3410	4.3	4.31	0.68 ± 0.02	1.35 ± 0.03
1965-2016	3420	4.3	4.33	0.68 ± 0.02	1.35 ± 0.03

(d) Tarlay after declustering

Year	EQ number	Mc	a	b	Dc
1965-1995	184	4.2	3.14	0.59 ± 0.04	1.91 ± 0.01
1965-2000	251	4.2	3.31	0.63 ± 0.04	2.10 ± 0.01
1965-2005	347	4.2	3.48	0.67 ± 0.04	1.99 ± 0.03
1965-2010	537	4.2	3.51	0.67 ± 0.04	2.05 ± NaN
1965-2015	640	4.0	3.23	0.62 ± 0.03	2.13 ± 0.01
1965-2016	643	4.0	3.23	0.62 ± 0.03	2.17 ± 0.01

For Dc investigation in the Mae Lao earthquake location, the Dc values varies between 0.65-1.75. At 1980, Dc is 0.65 and increase continuously to 1990 at Dc = 1.73 (Table 1a and Figure 4a). Thereafter Dc decrese during 1995-2000 down to 1.32-1.38. and increase up to 1.75-1.82 at 2005-2010 (Figure 4a). However during and after the Mae Lao earthquake was generated at 2014, the Dc value is decrease again down to 1.17-1.15 (Figure 4a). Similar to the Dc values estimated at the Talay earthquake (Table 1c and Figure 4c), the Dc varies between 1.12-1.97. At the short time of 1965-1985, the Dc is comparatively low at 1.12. After that, 20 yr durig 1990-2010, the Dc values reveal the comparatively high at Dc = 1987-1997 (Figure 3c). In final, the Dc value drop down to 2.13-2.17 before the Talay earthquake was generated.

Regarding to the after-declustering dataset, both b and Dc value analyzed here are insufficient variation. All results show the stable b and Dc in both Mae Lao and Tarlay case studies as illustrated in Figures 4b and d (see also Table 1b and d). At the Mae Lao earthquake epicenter, b value is constant around 0.63-0.69 while Dc value is around 1.98-2.01 (Figures 4b). For Tarlay earthquake, b value is at 0.59-0.67. Although Dc value is in the range of 1.91-2.17, this Dc range do not show any significant variation (Figure 4d).

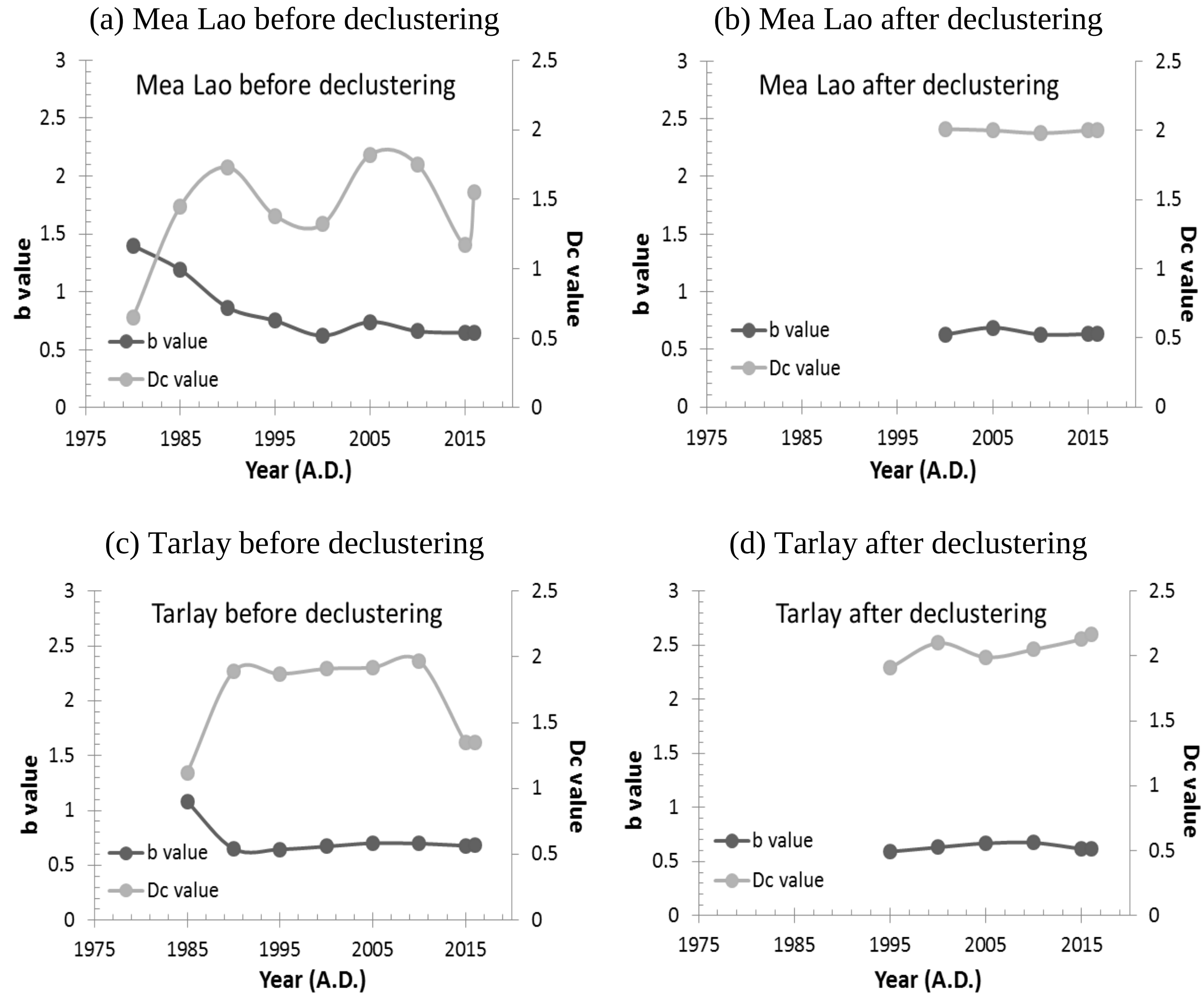

Figure 4. Graphs showing the temporal variation of b (black line) and Dc (grey line) values from 4 case studies. The utilized datasets are comprise of (a) Mea Lao before declustering, (b) Mea Lao after declustering, (c) Tarlay before declustering, and (d) Tarlay after declustering.

5.2. b and Dc relationship

The b-Dc relationship has been suggested as an effective indicator of seismic hazards (Bayrak and Bayrak, 2011; 2012). Emiprically, the b-Dc relationship can be either a positive or a negative correlation. For example, a positive correlation was defined at the earthquake source zone in Northeast India (Bhattacharya et al., 2010). A negative correlation was revealed at some seismogenic source in Japan (Hirata, 1989) and the volcanic earthquake at Long Valley Caldera in California, USA (Barton et al., 1999).

In this study, we obtained the relations between b and Dc values of the Mea Lao and Tarlay earthquake sources (Figure 5). In case of Mae Lao earthquake, the relationship between b and Dc of the before-declustering dataset is Dc = 1.42b + 0.53 (Figures 5a). Meanwhile by utilizing the after-declustering dataset, the b-Dc relationship is Dc = 0.14b + 1.91 (Figures 5b). These relationships are contributed based on the R^2 0.24 and 0.16, respectively. Seismotectonically, the b-Dc relationship of the Mae Lao earthquake is the positive relation indicating that low/high b value relates to low/high Dc value (Figures 5a and b). The positive correlation of Mae Lao earthquake conforms to the previous work that investigated at the earthquake source zone in Northeast India (Bhattacharya et al., 2010)

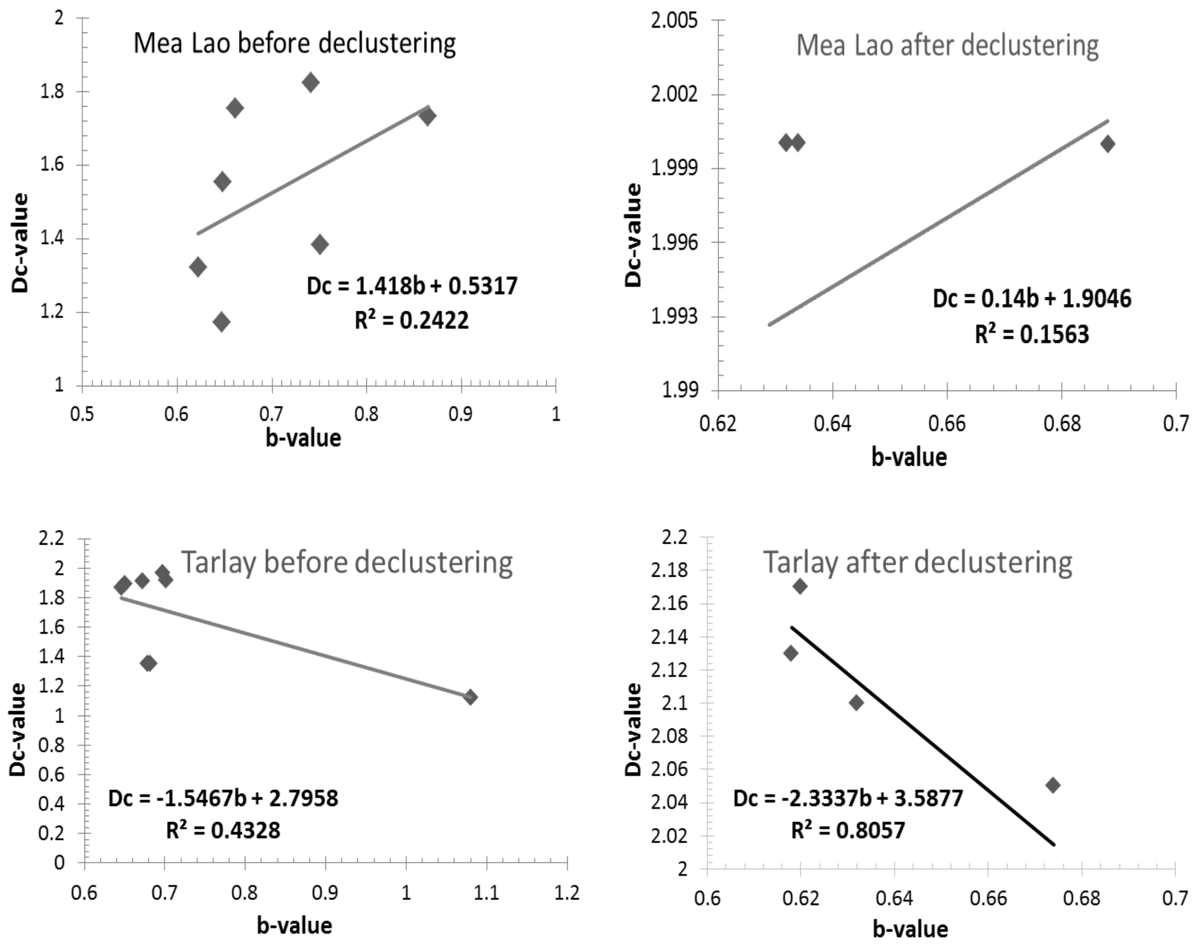

Figure 5. Empirical relationships between the b and Dc values analyzed from (a) Mea Lao before declustering, (b) Mea Lao after declustering, (c) Tarlay before declustering, and (d) Tarlay after declustering. The straight lines represent the linear regressions fitted with the observed data.

Regarding to the epicenter of the Tarlay earthquake, the relationship of the before-declustering dataset is Dc = −1.55b + 2.80 with R^2 = 0.43. Whereas the after-declustering dataset reveals the b-Dc relationship as Dc = −2.33b + 3.59 with R^2

= 0.81. In contrast to the Mae Lao earthquake, the b-Dc relationship of the Tarlay earthquakes expresses the negative linear correlation (Figures 5c and d). The negative correlation of Tarlay earthquake conforms to the previous works that reported the negative correlation at the region of seismogenic fault in Japan (Hirata, 1989) and the volcanic earthquake at Long Valley Caldera in California, USA (Barton et al., 1999).

6. Conclusion

In this study, the paramters of FMD (a and b values) and the fractal dimension (Dc value) were analyzed temporally at the epicenters of 2 well-known earthquake, i.e., Mae Lao and Tarlay earthquake. In addition in order to check the possibility of the utilized dataset, 2 earthquake dataset were employed, i.e., before- and after-declustering dataset. Based on the before-declustering dataset, the temporal variation of b value show fairly implication. Before both Mae Lao and Tarlay earthquakes were generated, b values were decrease continuously throughout 30 yr during 1985-2015 (Figures 4a and c). It imples that the tectonic stress were accumulated within 300-km radius from each earthquake epicenter. Meanwhile for Dc value, there are some fluctuation of the Dc value during 1985-2015. And also, there is significant drop of Dc value is noticeable during the short time period (i.e., 5-10 yr) before these earthquake studies were generated (Figures 4a and c). In constrast to the investigation using the before-declustering dataset, both b and Dc value analyzed from the after-declustering dataset do not show any meaningful variation of b and Dc in termpral. Consequently, we concluded that the before-declustering dataset can be used to analyzed temporally both b and Dc value that imply the earthquake precursor pior to any hazardeous earthquake posed.

Seismotectonically, b-Dc relationships reveal fairly correlation. However, each earthquake case study show different relation. Mae Lao earthquake indicate the positive relation while Tarlay earthquake express negative relation. Based mainly on the existing of 2 case study, we conclude preliminarily that althouth the hazardeous eartqhauke were generated in the same seismotectonic setting (i.e., intraplate earthquake source) the relation between b and Dc value may different. This may according to the different characteristic or activities of each fault zone. The Mae Lao earthquake generate by Phayao fault zone while Tarlay earthquake initiated by Namma Fault Zone. To further refine seismic activities (b value) and seismic pattern (Dc) value in cluding their relationship in this region, more detailed case studies of earthquake that generated in different seismogenic fault are indispensable.

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