交通部中央氣象局

委託研究計畫期末成果報告

最大餘震規模預報模式之建立(II)

Forecast of the Largest Magnitude in Aftershock Sequence

計畫類別：□氣象　□海象　■地震

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政府研究計畫期末報告摘要資料表

計畫中文名稱	最大餘震規模預報模式之建立(II)		
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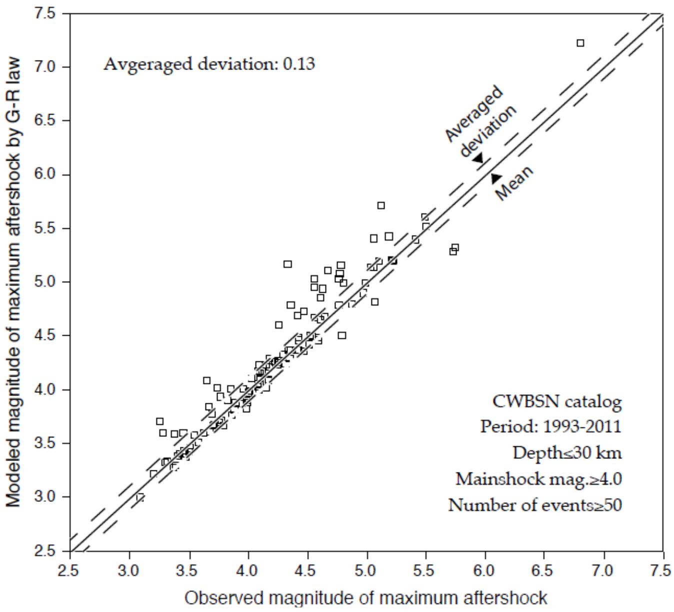
中英文關鍵詞	餘震、餘震規模、Gutenberg-Richter law、Omori’s law		
研究目的	迄今已有許多研究專注於大地震的前兆、預警分析，卻甚少有研究關注其餘震帶來的危害性。事實上，以 1999 年集集地震為例，在主震發生後一週內即有 12 個 $M_L \geq 6.0$ 的餘震發生，其中 $M_L \geq 6.5$ 的更高達 6 個。 由於些許建築物之結構已經遭受主震的破壞，更放大了餘震造成的地震損害。因此這些連續性的中、大規模餘震活動也是造成集集地震災情如此嚴重的原因之一。台灣地區位處高聚合速率之板塊邊界，擁有極高的地震活動度，歷來災害性地震序列的發生都造成難以估計的災損。因此，除主震的研究之外，若能同時分析並推估後續餘震可能之最大規模，將會使未來我們在防災、減災方面的工作更加完善。本研究之目的在於推算主震發生後每個時點可能發生的最		

	大餘震規模，進而建立預報系統；在主震發生後提供防災、減災工作的警訊，使人們有更多的反應時間與心理準備。
研究成果	本研究中，我們利用 Båth 定律、$1/\beta$，以及 Gutenberg-Richter relation 之統計經驗公式探討臺灣最大餘震。發現主震與餘震之規模差平均為 1.2，此結果符合 Båth 定律之經驗。然而，相對應之標準差卻相當顯著，顯示餘震規模可能不僅受控於主震規模。利用 Gutenberg-Richter relation 中之 b 值推導而得 $1/\beta$，可制約地震序列中最大餘震規模之下界。利用臺灣之地震目錄，顯示 66%之地震序列符合此一關係式。利用 Gutenberg-Richter relation 估計序列中最大地震規模，評估結果與觀測值之間誤差相當微小，顯示此關係式可成為餘震規模評估之重要指標。為了進一步估計餘震規模隨時間變化之趨勢，我們引用 Omori’s law 公式。透過此一方法，可評估最大餘震規模以及對應之時變趨勢。此結果可應用於大型地震震後即時地震災害的評估，並且有助於推動後續減災之工作。  **Figure 5** The comparison between observed and modeled magnitude of maximum aftershock in the sequence with number of events larger than 50. The models are based on the approach of the G-R law. The averaged deviation between observations and models for the 119 sequences

	is 0.13.
具體落實應用情形	如期完成計畫，並將技術轉移至氣象局地震測報中心。
計畫變更說明	（若有）
落後原因	（若有）
檢討與建議（變更或落後之因應對策）	

（以下接全文報告）

最大餘震規模預報模式之建立(II)

Forecast of the Largest Magnitude in Aftershock Sequence

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摘要

本研究中，我們利用 Båth 定律、$1/\beta$，以及 Gutenberg-Richter relation 之統計經驗公式探討臺灣最大餘震。發現主震與餘震之規模差平均為 1.2，此結果符合 Båth 定律之經驗。然而，相對應之標準差卻相當顯著，顯示餘震規模可能不僅受控於主震規模。利用 Gutenberg-Richter relation 中之 b 值推導而得$1/\beta$，可制約地震序列中最大餘震規模之下界。利用臺灣之地震目錄，顯示 66%之地震序列符合此一關係式。利用 Gutenberg-Richter relation 估計序列中最大地震規模，評估結果與觀測值之間誤差相當微小，顯示此關係式可成為餘震規模評估之重要指標。為了進一步估計餘震規模隨時間變化之趨勢，我們引用 Omori’s law 公式。透過此一方法，可評估最大餘震規模以及對應之時變趨勢。此結果可應用於大型地震震後即時地震災害的評估，並且有助於推動後續減災之工作。

Abstract

The Båth’s law, *b*-value of the Gutenberg-Richter law (G-R law) in the form of the $1/\beta$ relation, and the full form of the G-R law are introduced to model the maximum aftershock magnitude of the Taiwan region. The averaged difference of the magnitude between mainshock and maximum aftershock is about 1.20. It is consistent with the Båth’s law, but, with a large uncertainty. Large uncertainty implies the difference might be a variable controlled by other factors. Based on $1/\beta$, lower bound of the maximum

magnitude in an earthquake sequence could be estimated. In Taiwan region, 66 % of the earthquake sequences follow this relation. We further considered the G-R law for evaluating the maximum magnitudes of the earthquake sequences. The G-R law is a good index for maximum aftershock magnitude determination with a low uncertainty to fit between models and observations. In order to evaluate the decays of the aftershock magnitudes for different periods, the modified Omori's law is introduced. Through the approaches, the maximum magnitudes and temporal evolution of an earthquake sequence can be modeled. It might be of benefit for seismic hazards mitigation in the form of the rapid re-evaluation for short-term seismic hazards immediately following devastating earthquakes.

1. Introduction

Historical experiences have pointed out not only mainshock, but also consequent aftershocks may result in seismic hazards. For example, the M_w 6.3, February 21st, 2011 Christchurch, New Zealand, earthquake is regarded as an aftershock of the M_w 7.1, September 4th, 2010 Darfield mainshock (Chan et al., 2012). The Christchurch earthquake caused severe damage than the mainshock. Thus, understanding the behavior of aftershocks, in terms of magnitudes and temporal evolution is an important topic for seismic hazard mitigation.

Some of previous studies have investigated the maximum magnitudes of earthquake sequences. Båth (1965) concluded that the averaged difference $\overline{D_1}$ between the magnitude of the mainshock M_0 and the magnitude of the largest aftershock M_1 is

$$\overline{D_1} = 1.2 . \qquad (1)$$

This relation has been named as 'Båth's law. It becomes one of the most mentioned statistical characteristics in respect of earthquake sequences.

However, this relation does not in agreement with all of the results by consequent studies. Utsu (1969) pointed out that the $\overline{D_1}$ was larger than the expected value $1/\beta$, where β can be represented as

$$\beta = b \cdot \ln(10), \qquad (2)$$

where b is the b-value in the Gutenberg-Richter law (G-R law) (Gutenberg and Richter, 1954):

$$\log(N) = a - bM, \qquad (3)$$

where N is the number of event with magnitude larger than or equal to magnitude threshold M. According to the aftershock sequence in Japan, Utsu (1961; 1969) obtained a negative correlation between $\overline{D_1}$ and M_1, which is in disagreement with Bath's law. Up to now, the characteristic of maximum magnitude in an earthquake sequence remains controversial. In order to examine the feasibility of each model for maximum aftershock determination through comparison with observations, a high-quality catalog with a large number of events is desired.

Taiwan locates in a region where there is a high amount of seismic activity and a seismic network with good quality. Due to the interaction between the Eurasia and Philippine Sea Plates, the seismicity rate is high in the Taiwan region. The Central Weather Bureau Seismic Network (CWBSN) with a total of 75 stations started operation since the early of 1990s (Figure 1). The arrival times of P and S waves are selected manually for the determination of earthquake parameters, i.e. hypocenter and Richter local magnitude (M_L) (Shin, 1993). The CWBSN records approximately 20,000 events each year in a region of roughly 400 × 550 kilometers (*Wu et al*., 2008). Therefore, Taiwan can be a good candidate region for the examination the feasibility of each model for maximum aftershock determination.

In this study, we try to determine the behaviors of the maximum magnitudes in earthquake sequences in Taiwan. First, Båth's law (Båth, 1965) is introduced and the relationship between M_0 and M_1 is discussed. Then we try to model M_1 according to $1/\beta$, which can be regarded as lower bound of $\overline{D_1}$. The full form of the G-R law is further considered for calculating the maximum magnitudes in earthquake sequences. In addition, the temporal evolutions of the maximum aftershocks are discussed in this study. Four cases of the earthquake sequences are introduced and the feasibility of each model is evaluated in comparison with observations.

2. Earthquake catalog and clustering methodology

Catalog of the CWBSN is used in this study. In this study, we used clustering method to extract an earthquake sequence. Events with magnitude large than magnitude of completeness (M_c) of the mainshock epicenter region will be used for analysis. Spatial distribution of Mc and clustering methodology will be introduced in the following.

2.1 Spatial distribution of M_c

The CWBSN has greatly enhanced the earthquake monitoring capability in the beginning of 1990's (Wu and Chiao, 2006). To evaluate the reliability of the catalog, we calculated spatial distribution of M_c by using the maximum curvature approach (Wiemer and Wyss, 2000). We considered the catalog in the period from the beginning of 1993 to the end of 2011 for shallow earthquakes (with focal depth ≤ 30 km). We divided our study region into 0.2°×0.2° grids and searched for the events within a circle of 30 km in radius (Figure 1). The pattern of M_c simply reflects the density of the seismic stations. The station densities are the highest in the northern and southwestern Taiwan, where the M_c is as low as 1.5. The M_c for the inland region is generally less than 2.0, whereas the M_c in the offshore region is between 2.5 and 3.2 due to poor network coverage. The spatial distribution and magnitudes estimated in this study is consistent with those obtained from the Bayesian magnitude of completeness method (Mignan et al., 2011). To achieve reliable calculation, it is important that we re-evaluate M_c according to the catalog fulfill the same criterion of each calculation.

2.2 Clustering methodology

In order to extract earthquake clusters that events are related with one another in the catalog, the approach of spatiotemporal double-link cluster analysis (Wu and Chiao, 2006) is applied. This approach is modified from the single-link cluster analysis proposed by Davis and Frohlich (1991). We supposed an earthquake with magnitude larger than magnitude threshold of 4.0 be a potential candidate of mainshocks. An event is identified as an aftershock when its epicenter and occurrence time lay within the spatial and temporal windows of a mainshock. We set the spatial and temporal linking parameters of 5 km and 3 days, respectively, which are commonly used for earthquake clustering in Taiwan (Wu and Chiao 2006; Wu and Chen 2007; Wu et al. 2008a). Following the clustering approach, a total of 706 earthquake sequences were selected for analysis (Figure 2).

3. What factors may control maximum magnitude in a sequence?

According to the studied earthquake sequences (Figure 2), M_1 of each sequence is observed (horizontal component of Figure 3). The range of the corresponding M_1 is in between 0.0 (no consequent event) and 6.8 (which is the aftershock of the 1999 Chi-Chi earthquake). In the following, we try to fit the observation with several models to understand their behaviors.

3.1 Båth's law

According to the Båth's law, represented as equation (1), the difference between M_0 and M_1 was a constant. In order to test the feasibility of this law, the two parameters of each sequence are compared (Figure 3). The average of D_1 is 1.20, which corresponds to the conclusion of Båth (1965). It should be mentioned that the high standard deviation of 0.73 suggests the characteristics of some sequences may depart from Båth's law.

3.2 *b*-value

Based on the statement of Utsu (1969), $\overline{D_1}$ was larger than the expected value $1/\beta$. In order to examine the hypothesis, corresponding $1/\beta$ for each earthquake sequence is evaluated (Figure 4). Maximum likelihood estimation was used to calculate the *b*-value. Earthquake sequences with number of events larger than 50 were considered for this analysis in order to calculate the *b*-values. There are 66 % (79 of 119) of sequences have lower $1/\beta$ in comparison to D_1. Such result corresponds to the conclusion of Utsu (1969). Based on this approach, the upper bound of M_1 could be constrained.

3.3 The G-R law

In this study, the *b*-value and the G-R law (Gutenberg and Richter, 1954) are also introduced to determine the maximum aftershock magnitude in an earthquake sequence. We modeled the seismic behavior of the sequences according to the G-R law in the form of *a*- and *b*-value. We assume that M_1 is obtained when N equal to 1, i.e. $M_1 = \frac{a}{b}$. We compared the modeled M_1 with the observed ones for each sequence (Figure 5). The consistency between each other is confirmed by the relative low averaged deviation of 0.13.

4. Case studies on modeling the temporal evolution of aftershock magnitudes

Above three approaches have been proposed to model the maximum magnitudes in sequences. In the following we further evaluate their temporal distribution in a sequence. For the temporal evolution of seismicity rate $n(t)$ that decays with time *t*, we considered the modified Omori's law by Utsu (1961) and Utsu et al. (1995). It can be presented as:

$$n(t) = \frac{k}{(c+t)^p}, \qquad (4)$$

where *k*, *c*, and *p* are constants. In this study, the three parameters for each sequence were obtained by the best fit with observation. The total number of events N_1 after time t_1 is presented as:

$$N_1 = \int_{t_1}^{t_{end}} \frac{k}{(c+t)^p} dt, \quad (5)$$

where t_{end} is the time of the end of the sequence. We evaluated the ratio of N_1 to *N* for different periods and then modeled the decay of the maximum magnitudes by assuming a variable *a*-value and a fixed *b*-value in the G-R law.

Taking the 1999 Chi-Chi sequence as an example, the seismic behaviors of this sequence are modeled by the G-R law (Figure 6a) and the modified Omori's law (Figure 6b). According to the magnitude of the mainshock (M_L=7.3) and Båth's law, that D_1=1.2, the M_1 is expected to be 6.1; according to the *b*-value of 0.86 and the $1/\beta$ relation, the M_1 is expected to be smaller than 6.8; according to the modeled *a*- and *b*-values in the G-R law (6.26 and 0.86, respectively), the M_1 is expected to be 7.3 (Table 1). To compare with the observed M_1 (6.8), the $1/\beta$ relation performs the best model.

According to the date of the last event in the Chi-Chi sequence (May 5th, 2000), t_{end} is 151 days. Based on the modeled modified Omori's law (Figure 6b), N_1 can be evaluated as a function of t_1 according to equation (5). By assuming variable *a*-value and fixed *b*-value, the decay of M_1 can be evaluated. For example, when t_1= 50 days, N_1 becomes 1/7.24 times as that in the beginning of this sequence. The *a*-value becomes 6.26-log(7.24)=5.40. Considering the *b*-value of 0.86, the M_1 at this time is 1 unit smaller than that in the beginning. Based on this procedure, the temporal evolution of the M_1 according to other two approaches could be modeled (Figure 6c). To compare with the observation (thinnest line in Figure 6c), which represents the M_1 since each time point until the end of the sequence, it is found that all of the three approaches can model the trend of decay. For the statistical comparison in terms of averaged residual (Table 1), the model according to the $1/\beta$ relation has the best fit with observation. Through the same procedure, we modeled the M_1 behaviors for the other three earthquake sequences, i.e. the 1993 Dapu, 1994 Nanao, and 1998 Rueyli sequences (Figure 2) (Chan and Ma, 2004). The observed and modeled M_1, as well as residual for temporal evolution based on each model are presented (Table 1). It is found that either the G-R law or the $1/\beta$ relation has the best fit with observation, suggesting the feasibility of the models.

5. Discussion and Summary

5.1 Feasibility of the models for maximum magnitude in a sequence

In this study, Båth’s law, the $1/\beta$ relation, and the G-R law are introduced to model the maximum magnitude of earthquake sequences in Taiwan. All of the three approaches have demonstrated their feasibility within deviation ranges. By comparison the magnitudes between mainshock and maximum aftershock, an averaged difference of 1.20 between each other is obtained (Figure 3). It is consistent with the conclusion of Båth (1965). However, the corresponding large deviation of 0.73 implies the difference might be a variable controlled by other factors, such as the mainshock magnitude (Vere-Jones, 1969), $1/\beta$ (Utsu, 1961, 1969), or the total number of events in the sequence (Lombardi, 2002). Based on the *b*-value in the form of the $1/\beta$ relation, lower bound of the maximum magnitude in an earthquake sequence can be estimated (Figure 4). In the case of the earthquake sequences in Taiwan, 66 % of the earthquake sequences follow this relation, suggests its reliability. Based on this concept, the upper bound of the maximum magnitude could be constrained. However, corresponding lower bound remains controversial. The G-R law also provides evaluation of the maximum magnitude of earthquake sequences (Figure 5). According to the low deviation of 0.13 between models and observations, the G-R law can be an ideal index for maximum magnitude determination.

5.2 Difficulty for modeling occurrence of larger earthquakes.

Historical experiences have pointed that not only aftershocks may result in consequent seismic hazards, but also next larger earthquakes can further expand hazards. For example, a M_w7.4 earthquake took place off the Pacific coast of Tohoku, Japan on March 9th, 2011 (Nettles et al., 2011). Since the epicenter is away from land, the resulting damages are negligible. 51 hours after the earthquake on March 11th, an earthquake with M_w9.1 took place and resulted in disasters in Japan.

Although all of the three approaches provide information for possible magnitudes of aftershocks, they are difficult to evaluate the probability of consequent earthquakes with larger magnitudes, i.e. the first event becomes a foreshock. Based on the approaches of Båth's law and the $1/\beta$ relation, the maximum magnitude in a sequence is assumed to be smaller than the magnitude of the first event. Based on the G-R law, the modeled magnitude of a sequence could be larger than that of mainshock, when a large a-value or/and a small b-value are obtained. The foreshock-mainshock behaviors can also be modeled in the forms of physics-based or statistics-based approaches. For example, Chan et al. (2010; 2012) considered the Coulomb stress change imparted by earthquakes and the rate-and-state friction model to evaluate seismicity rate evolution. Based on this approach, the occurrence probabilities for different magnitudes can be estimated. Time-space Epidemic Type AfterShock model (as known as ETAS model by Kagan and Knopoff, 1981) can be another alternative. Based on this model, every earthquake is assumed as a mainshock, which can trigger consequence events that could be larger than the mainshock.

5.3 Possible application in a near real-time.

According to the approaches, the maximum magnitudes of an earthquake sequence and their temporal evolutions can be modeled. The results might be of benefit to decision-makers for seismic hazards mitigation. For example, the rapid re-evaluation for short-term seismic hazards immediately following devastating earthquakes could provide information on devastation estimations, emergency response, and/or victim sheltering. For this purpose, an approach that can be applied in a real-time or near real-time after occurrence of a large earthquake is desirable. The Båth's law could be applied immediately after earthquake, since it is assumed a constant magnitude difference between mainshock and maximum aftershock. The $1/\beta$ relation might also be applied in a real-time based on the assumption of temporal-stationary b-value. Practically, once a database for the spatial distribution of b-values has been established, the corresponding magnitude of maximum aftershock can be estimated right after occurrence of mainshock.

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Table 1 Source parameters for the mainshocks of the four sequences that considered for the discussion of temporal evolution. The observed and modeled M_1, as well as residual for temporal evolution based on the three approaches are also presented.

Earthquake		Dapu	Nanao	Rueyli	Chi-Chi
Origin time	Year	1993	1994	1998	1999
	Month	12	6	7	9
	Day	15	5	17	20
	Hour	21	1	4	17
	Minute	49	9	51	47
	Second	43.10	30.09	14.96	15.85
Location	Longitude (°)	120.52	121.83	120.66	120.81
	Latitude (°)	23.19	24.46	23.50	23.86
	Depth (km)	12.5	5.3	2.8	8.0
Mainshock magnitude (M_L)		5.7	6.5	6.2	7.3
Max. magnitude	Observation	4.6	5.1	4.5	6.8
	Båth	4.2 (-0.4)	4.2 (-0.9)	5.0 (+0.5)	6.1 (- 0.7)
	1/β	5.1 (+0.5)	5.1 (0.0)	5.8 (+1.3)	6.8 (0.0)
	G-R	4.9 (+0.3)	4.9 (-0.2)	4.4 (- 0.1)	7.2 (+0.5)
Residual for temporal evolution	Båth	0.87	0.30	0.51	0.43
	1/β	0.32	0.58	1.28	0.30
	G-R	0.32	0.24	0.26	0.72

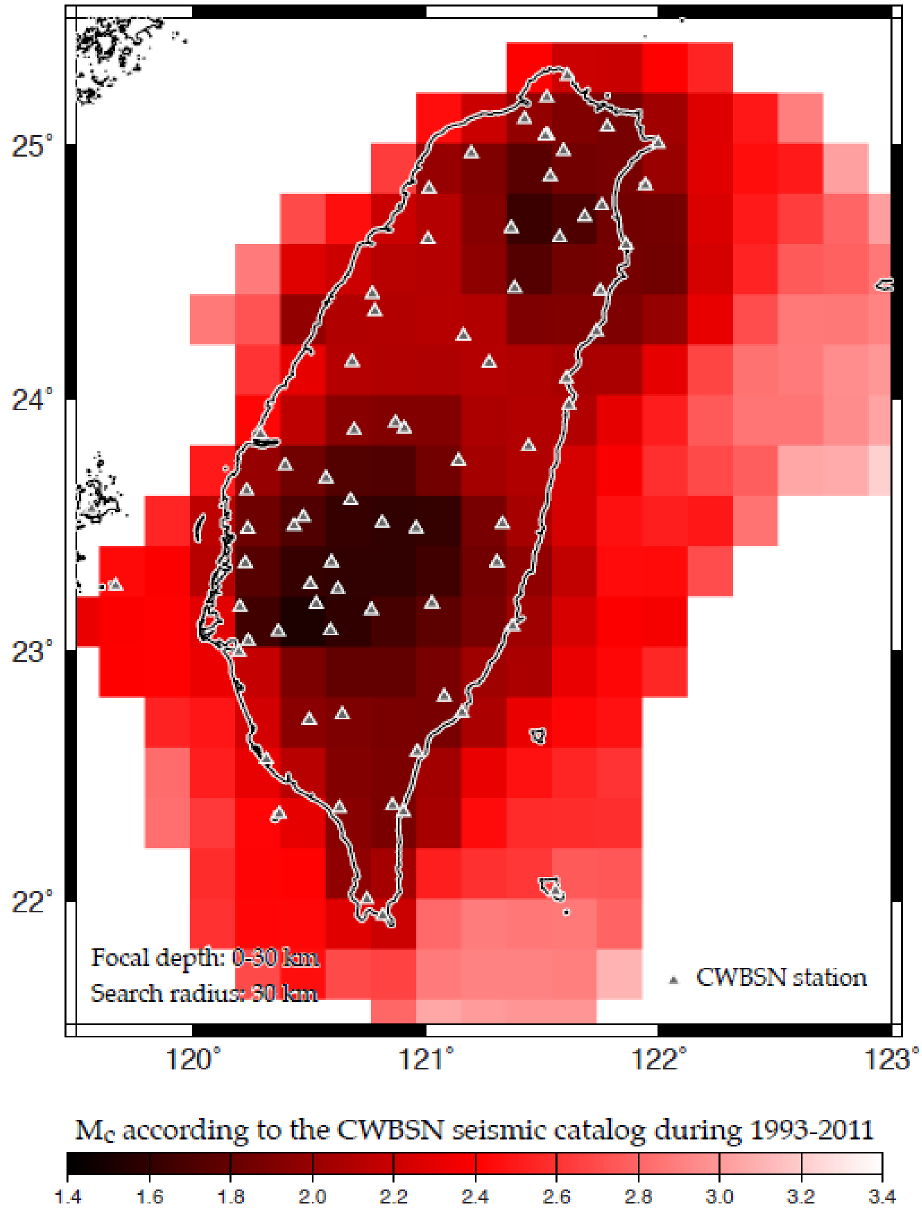

Figure 1 Spatial distribution of the magnitude completeness (M_c) according to the Central Weather Bureau Seismic Network (CWBSN) catalog. The triangles represent the locations of the CWBSN stations.

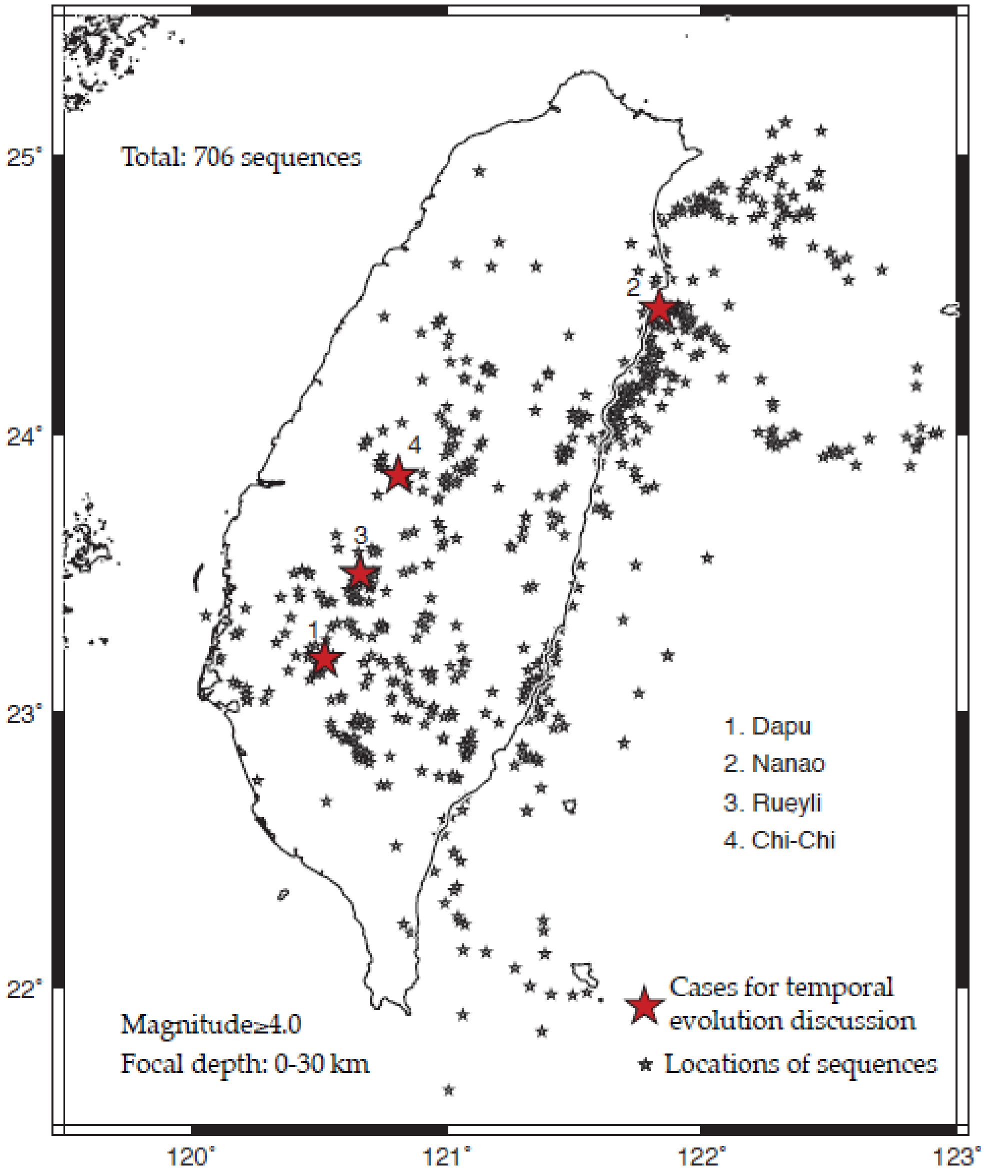

Figure 2 Distribution of the 706 investigated sequences in Taiwan selected by the approach of spatiotemporal double-link cluster analysis. The earthquakes with M_L greater or equal to 4.0 and focal depths less than 30 km during 1993 and 2011 are selected. The large stars represent the sequences for the discussion of temporal evolution.

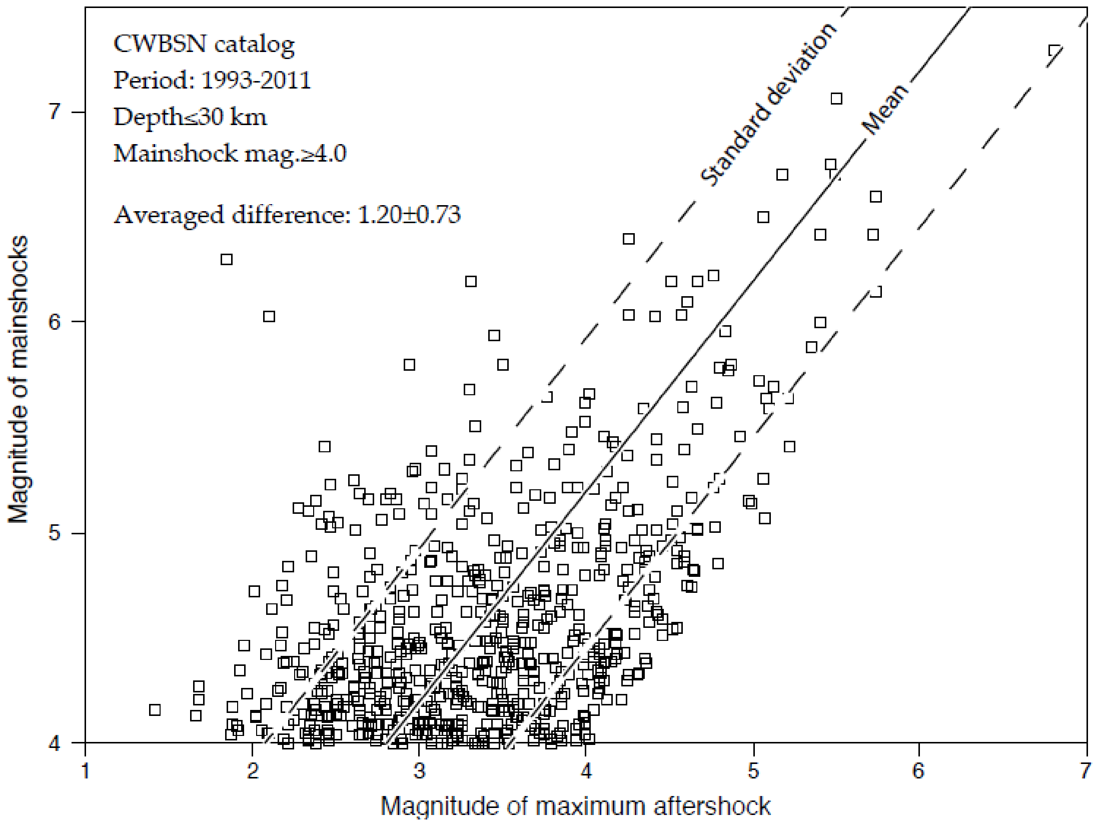

Figure 3 The comparison between magnitude of mainshock and that of maximum aftershock in each sequence. The average difference between each other is 1.20 with a standard deviation of 0.73.

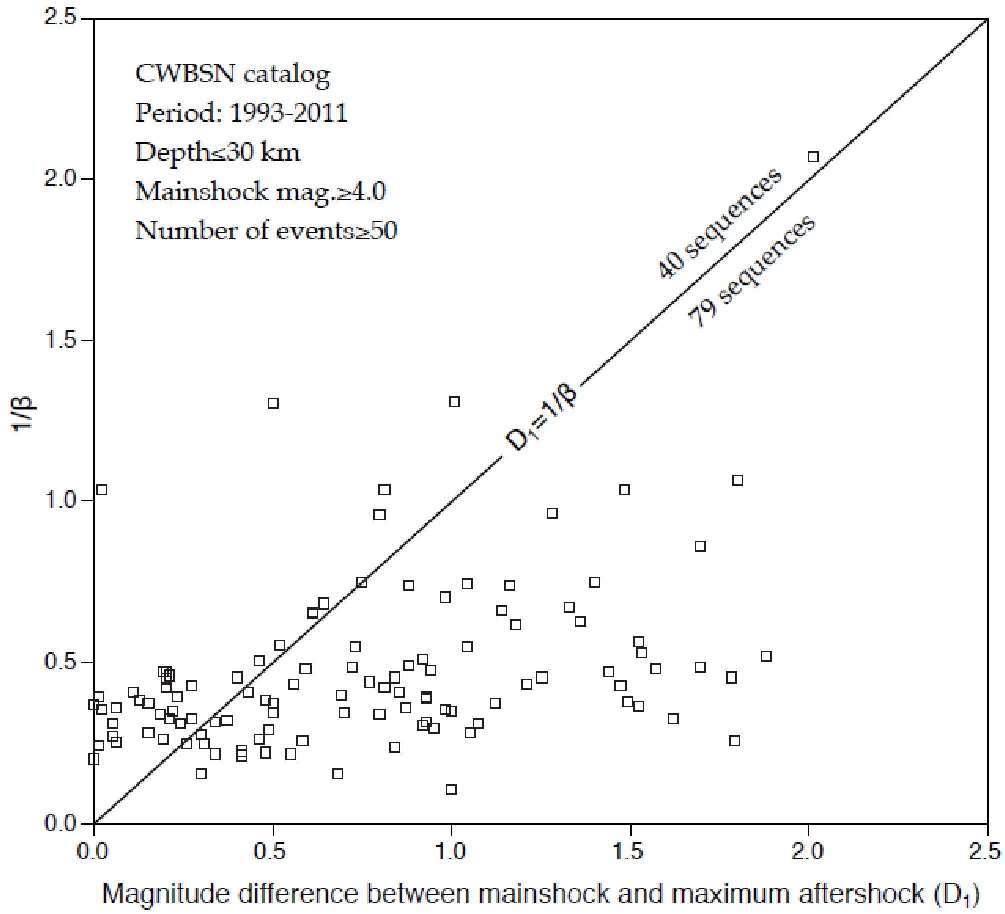

Figure 4 The comparison between $1/\beta$ and magnitude difference between mainshock and observed maximum aftershock (D_1) in the sequence with number of events larger than 50. There are 79 sequences have a smaller $1/\beta$ than D_1, whereas as only 40 ones have a larger $1/\beta$.

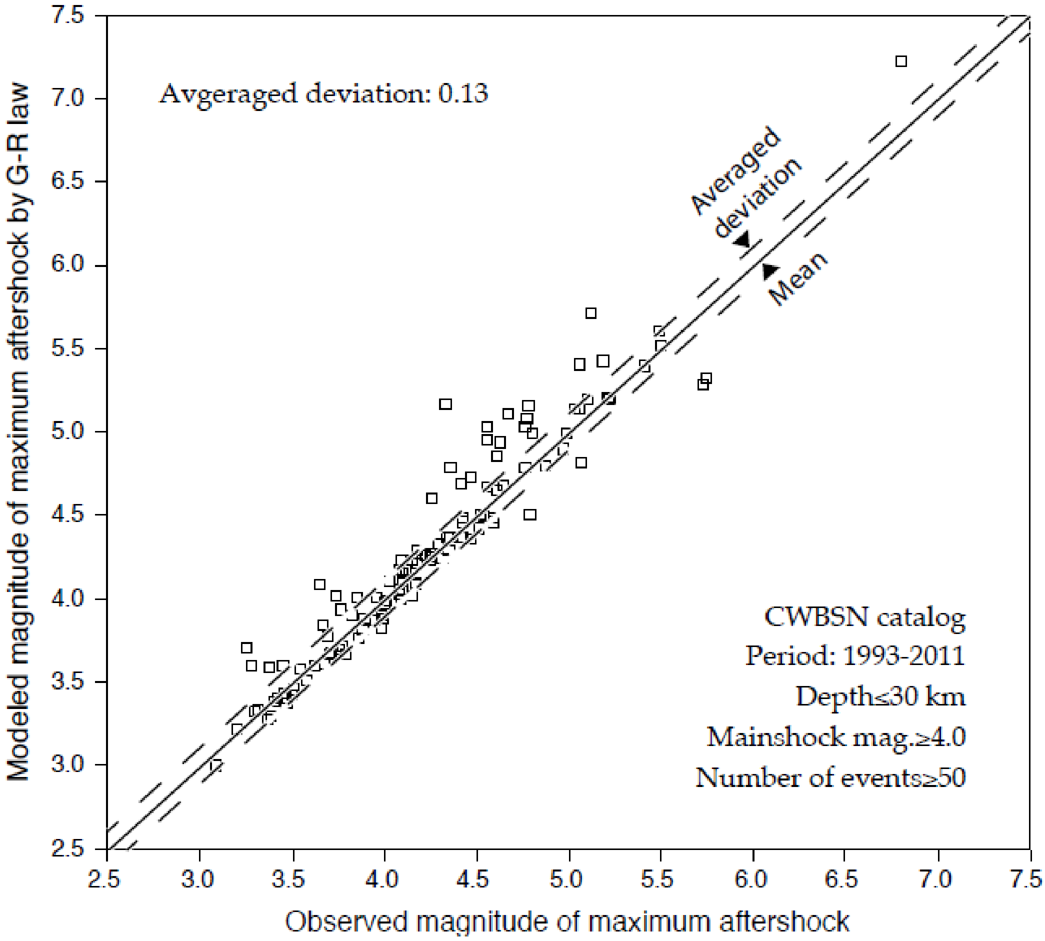

Figure 5 The comparison between observed and modeled magnitude of maximum aftershock in the sequence with number of events larger than 50. The models are based on the approach of the G-R law. The averaged deviation between observations and models for the 119 sequences is 0.13.

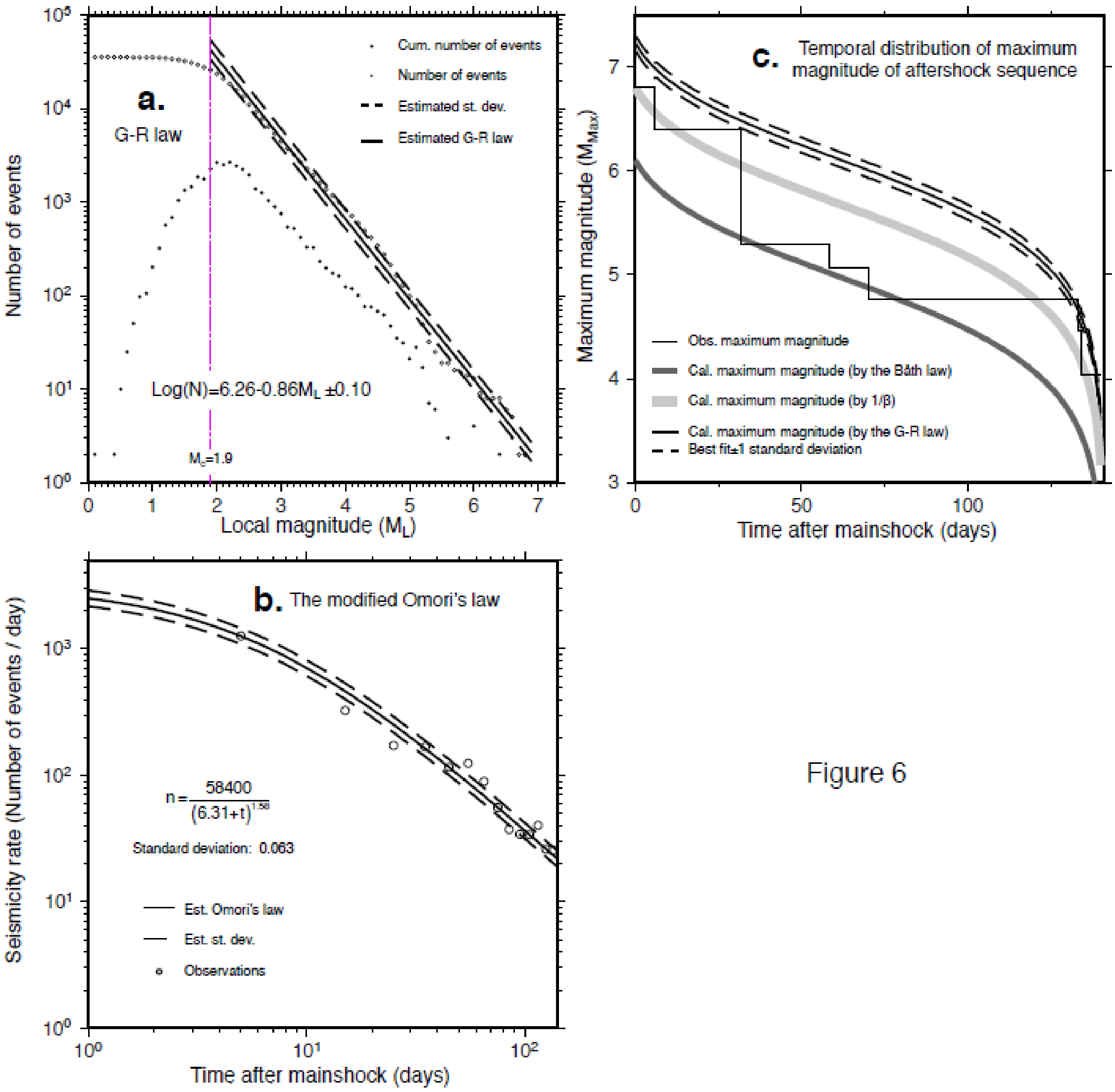

Figure 6 (a) Modeled G-R law, (b) modeled modified Omori's law and (c) observed and modeled temporal distribution of maximum magnitude of the 1999 Chi-Chi sequence. The residual for temporal evolution based on the three approaches are presented in Table 1.