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2014

Chan, C. H., & Wu, Y. M. (2014). Seismic behavior in central Taiwan: Response to stress evolution following the 1999 Mw 7.6 Chi-Chi earthquake. *Journal of Asian Earth Sciences*, 90, 101-106.

<https://hdl.handle.net/10356/104670>

<https://doi.org/10.1016/j.jseaes.2014.04.006>

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1 **Seismic behavior in central Taiwan: response to stress evolution following the**
2 **1999 M_w7.6 Chi-Chi earthquake**

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11 Key words: Chi-Chi earthquake, Coulomb stress change, afterslip, viscoelastic
12 relaxation, Taiwan.

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Abstract. Following the 1999 $M_w 7.6$ Chi-Chi earthquake, a large amount of seismicity occurred in the Nantou region of central Taiwan. Among the seismic activities, eight $M_w \geq 5.8$ earthquakes took place following the Chi-Chi earthquake, whereas only four earthquakes with comparable magnitudes took place from 1900 to 1998. Since the seismicity rate during the Chi-Chi postseismic period has never returned to the background level, such seismicity activation cannot simply be attributed to modified Omori's Law decay. In this work, we attempted to associate seismic activities with stress evolution. Based on our work, it appears that the spatial distribution of the consequent seismicity can be associated with increasing coseismic stress. On the contrary, the stress changes imparted by the afterslip; lower crust-upper mantle viscoelastic relaxation; and sequent events resulted in a stress drop in most of the study region. Understanding seismogenic mechanisms in terms of stress evolution would be beneficial to seismic hazard mitigation.

1. Introduction

Two large earthquakes struck the Nantou region of central Taiwan in 2013. A M_w 5.8 earthquake occurred on March 27th, 2013 (Figure 1). The Central Weather Bureau Seismic Network (CWBSN) observed the largest intensity of VI near the epicenter. The event resulted in one fatality, ninety-seven injuries, and loss of property. Two months later, on June 2nd, another earthquake of M_w 6.3 took place in the vicinity (Figure 1). The event caused a comparable intensity and led to a loss of property and human life. In addition to these two events in 2013, another six earthquakes with $M_w \geq 6.0$ took place in this region following the 1999 M_w 7.6 Chi-Chi earthquake (Figure 1). For the purpose of seismic hazard mitigation, it is crucial to determine seismogenic mechanisms in this region.

Seismic behaviors could be controlled by stress evolution. Ma et al. [2005] calculated the Coulomb stress change (ΔCFS) imparted by the Chi-Chi coseismic ruptures, and analyzed seismicity in Taiwan during the subsequent 53 months. They concluded that during this period the ΔCFS caused by the Chi-Chi earthquake dominated Taiwan seismic activities. Chan and Stein [2009] evaluated the stress evolution imparted by the afterslip, the viscoelastic relaxation, and consequent earthquakes during the postseismic period and determined that post-seismic stress changes play an important role on the influence of seismic behaviors in Taiwan. Such studies are critical for understanding the correlations between stress evolution with seismic activities during the first years of the postseismic period. The time period from the Chi-Chi earthquake to the 2013 Nantou earthquake sequence is approximately 13 years. The stress influenced by the Chi-Chi earthquake could still be controlling the 2013 Nantou earthquake sequence, and understanding the earthquake source mechanism is critical.

Therefore, in this study, we sought to associate seismic activity with stress evolution in central Taiwan. We first investigated the spatial-temporal distribution of seismicity. Then, the Δ CFS during the Chi-Chi coseismic and postseismic periods was evaluated. Through statistical comparisons, the mechanisms driving seismicity within the region are expected to become clearer.

2. Seismic activity

2.1 The CWBSN catalog

The Central Weather Bureau Seismic Network (CWBSN) has started monitoring seismic activity within Taiwan in the beginning of the 1990's [Wu et al., 2008]. Due to the change in recording mode from a triggered recording to a continuous one, the CWBSN has greatly enhanced earthquake-monitoring ability since 1993 [Wu and Chiao, 2006]. In order to comprehend the reliability of the catalog within the study region, the temporal distribution of the magnitude of completeness (M_c) was evaluated based on the maximum curvature approach [Wiemer and Wyss, 2000]. Earthquakes with focal depths ≤ 30 km during the period from 1993 to 2012 were considered. The M_c was kept as low as ≤ 2.0 for most of the periods (Figure 2b). The only exception took place following the Chi-Chi earthquake. A reduction in seismic detection ability can be attributed to seismicity bursts following a large earthquake. For the use of the catalog, a magnitude threshold of 2.0 was considered.

2.2 The spatial and temporal distribution of seismicity

The spatial distribution of seismicity in Nantou was determined. A higher rate was observed in the northwestern portion of the study region (Figure 1a). The profiles (Figures 1b to 1d) represent the distribution of seismicity with depth. An eastern dipping trend of seismicity corresponds to the focal mechanisms of large events. Most events take place at the depth between 8 and 30 km. The depth distribution of seismicity is summarized in Table 1. The focal depths of $M \geq 2.0$ earthquakes are generally between 5-30 km. Additionally, for events with a larger magnitude, lower seismicity ratios were observed at a depth less than 10 km.

In Figure 2a, the temporal evolution of the seismicity rate within the study region is presented in the form of a time series. A sudden rise in the seismicity rate following the Chi-Chi earthquake could be associated with a consequent aftershock sequence [Chang et al., 2000; 2007]. Since the seismicity rate during the Chi-Chi postseismic period has never returned to the background level (solid line prior to the Chi-Chi earthquake in Figure 2a), such a temporal trend cannot simply be explained by modified Omori's Law [Utsu, 1961], suggesting that the seismicity rate returns to background after a certain period.

3. The association of consequent earthquakes with the Chi-Chi coseismic stress change

Previous studies [e.g., Chan and Wu, 2012; Chan et al., 2012] have suggested that a positive Coulomb stress change (ΔCFS) encourages the occurrence of consequent events and a negative ΔCFS inhibits future seismicity. In the following, the relationship between the Chi-Chi coseismic stress change and the distribution of consequent earthquakes will be discussed. For this purpose, the procedure of the

99 ΔCFS calculation is introduced. The Chi-Chi coseismic ΔCFS on the focal
100 mechanisms of large earthquakes and within the Nantou region are then evaluated.

101

102 **3.1 The Coulomb stress change (ΔCFS) imparted by the Chi-Chi coseismic slip**

103 According to previous studies (Harris [1998] and references therein), the ΔCFS
104 can be represented, as follows:

$$105 \quad \Delta CFS = \Delta \tau + \mu' \Delta \sigma_n, \quad (1)$$

106 where $\Delta \tau$ is the change of the shear stress along the rupture direction on the receiver
107 fault; μ' is the apparent friction coefficient; and $\Delta \sigma_n$ is the change of the normal
108 stress perpendicular to the receiver fault (unclamping is positive). In order to estimate
109 ΔCFS , the COULOMB 3.3 program [Toda and Stein, 2002] is applied.

110 For the calculation of ΔCFS during the Chi-Chi coseismic period, a coseismic
111 slip model was required. Here, the Chi-Chi coseismic slip model by Johnson and
112 Segall [2004] was considered. The model obtains a four-plane fault geometry with a
113 sub-horizontal décollement at the depth of 7.7 km, and also explains GPS deformation.

114

115 **3.2 The stress resolved on the focal mechanisms of large earthquakes**

116 Based on various references, the source parameters of eight significant
117 earthquakes were obtained (Table 2). Although there are two conjugation planes for a
118 focal mechanism, based on the dipping trend of seismicity (Figures 1b and 1c), the
119 eastern dipping plane of each earthquake was assumed as the actual one of interest.

The Δ CFS on each focal plane was evaluated (Table 2). Seven of the eight (88%) events could be associated with the Chi-Chi coseismic stress increase, suggesting that the Chi-Chi promoted the rupture of seismotectonics within the Nantou region.

3.3 A comparison with the distribution of smaller events

The spatial distribution of the Chi-Chi coseismic Δ CFS was evaluated and indicated that the stress above the décollement (depth ≤ 7.7 km) was dropped; in contrast, the stress in most of the areas beneath the décollement was promoted (Figures 1b, 1c, and 1d). Such a result corresponds to the characteristic Δ CFS pattern for a ramp-décollement structure (Figure 4 of Chan and Stein [2009]). To quantify the Δ CFS distribution with depth, we calculated Δ CFS in each 1km * 1km * 1km cell. The proportions of the region with an increased Δ CFS at different depth bins are represented in Table 1, showing a Δ CFS increase in more than 50% of the regions at the depth between 10-25 km. By contrast, at a depth of 0-5 and 5-10 km the ratios of regions that are stress-promoted were significantly low (1% and 37%, respectively).

The Chi-Chi coseismic Δ CFS may well explain the spatial distribution of the seismicity (Figure 1). Few of the events were in the region with a Δ CFS drop. For the $M \geq 2.0$ events, only 23% were at a depth ≤ 10 km, whereas most of the regions were further from the next failure (Table 1). Note that these ratios were even lower for events with larger magnitudes (i.e., 18% and 7% for $M \geq 4.0$ and 5.0, respectively).

The relationship between the Δ CFS and the consequent earthquake was also statistically tested using the Molchan diagram [Molchan, 1990]. In this diagram, the “fraction of space occupied by alarm” indicated ratios of the study region with

a Δ CFS level equal to or higher than a threshold (defined as “alarm”). The “fraction of failure to predict” presents the ratios of consequent earthquakes having a lower Δ CFS level than the alarm. In other words, when the data points are distributed along the diagonal line, the distribution of target earthquakes are independent of the Δ CFS. A convex distribution suggests that the majority of the consequent earthquakes occurred within regions with a lower Δ CFS as compared to the entire area. Whereas, a concavity suggests that most of the consequent earthquakes were higher in the Δ CFS area. The Molchan diagram confirmed the relationship between the distributions of consequent seismicity and the Δ CFS (Figure 3). Additionally, a better correlation was obtained for larger earthquakes. Only 45% and 32% of seismicity with a magnitude $M \geq 2.0$ and 4.0, respectively, were found within the Δ CFS drop area that covers 55% of the entire study region.

4. Stress evolution during the Chi-Chi postseismic period

In the discussion above, we proved that Chi-Chi coseismic Δ CFS controls seismic activity within the study region. Next, we try to associate the seismicity with stress evolution during the postseismic period. We evaluate and discuss the stress imparted by some of the postseismic factors (i.e., afterslip, lower crust-upper mantle viscoelastic rebound, and earthquakes of the Nantou sequence).

To evaluate the Δ CFS by the afterslip, the model inferred by Yu et al. [2003] was introduced. The model fulfilled GPS observations during the first 15 months of the Chi-Chi postseismic period. The afterslip results in a Δ CFS drop in most parts of the Nantou region (Figure 4a). Additionally, seven of the eight significant events were

located within the stress drop region, suggesting that the seismic behaviors are not controlled by the afterslip. In addition, the occurrence of smaller events cannot be associated with afterslip triggering. Only 14% of the $M \geq 2.0$ events are within the region where stress is increased by afterslip.

For the calculation of stress evolution by viscoelastic relaxation, the rheology model inferred by Chan and Stein [2009] was implemented (Figure 3c of the reference). We evaluated the stress change 14 years after the 1999 Chi-Chi earthquake and found that stress status is further away from failure in almost the entire study region (Figure 4b). Furthermore, all of the significant events as well as 95% of the $M \geq 2.0$ ones were located within the stress drop region. The results suggest that seismic activity does not fulfill the viscoelastic rebound model.

In addition to the Chi-Chi earthquake, the events of the Nantou sequence may also alter the stress status and dominate the behaviors of consequent earthquakes. Since the ΔCFS s imparted by small earthquakes are trivial [Ma et al., 2005], we only evaluated ΔCFS using the eight significant events (Figure 4c). Calculation of the ΔCFS requires knowledge of the rupture parameters for source events (i.e., the geometry of the rupturing fault and the magnitude of the slip). The detailed slip dislocation models for the No. 1, 4, and 5 events were obtained by Chi and Dreger [2004]. For the remaining events, we adopted a homogenous slip model using the dimensions and average slips according to the scaling laws of Yen and Ma [2011]. Stress in half of the region is promoted, making it difficult to distinguish their correlation with seismicity patterns. 49% of the $M \geq 2.0$ postseismic events are located in the region where stress is enhanced by previous events. To further determine the interactions between significant events, the ΔCFS for each focal plane

using preceding events was calculated (Table 2). Only three of the seven events (43%) were found to be promoted.

5. Discussion and conclusion

5.1 Seismicity remains higher than background following the Chi-Chi earthquake

Previous studies (e.g., Chang et al. [2000] and references therein) have observed a large amount of aftershocks in the vicinity of the 1999 Chi-Chi rupture zone. Seismicity rates within parts of central Taiwan have returned at a background level several years following the Chi-Chi earthquake [Ma et al., 2005]. In this study, in contrast, we observed that the seismicity rate within the Nantou region remained higher than background (Figure 2). Additionally, in comparison to eight significant events since 1999 (annual rate: 0.57), only four earthquakes with $M \geq 6.0$ took place from 1900 to 1998 (annual rate: 0.04).

5.2 The role of coseismic stress change in controlling seismicity during postseismic period

The seismicity rate increase could be attributed to the Chi-Chi coseismic stress increase. The coseismic ΔCFS also explained the detailed distribution of seismicity along the depth (Figures 1b, 1c, and 1d). An increase in ΔCFS was calculated beneath the décollement (at a depth ≥ 10 km); whereas, the stress above was determined to be dropped. In comparison, 77% of $M \geq 2.0$ events were located at a

depth ≤ 10 km, whereas most were closer to the next failure (Table 1). That the fault(s) beneath the décollement [Yue et al., 2005] or the lower part of the Shuilikeng Fault [Camanni et al., 2013] have been activated following the Chi-Chi earthquake has been suggested. Additionally, these ratios are even higher for larger events (82% and 93% for $M \geq 4.0$ and 5.0, respectively). Using the Molchan diagram (Figure 3), the correlations between coseismic ΔCFS and consequent seismicity were confirmed. Additionally, seismicity with larger magnitudes had a better correlation (black dots in Figure 3). The phenomenon may be attributed to a more precise depth location for large events and/or more heterogeneous rupture mechanisms for small events.

5.3 The role of postseismic stress evolution in controlling seismicity during postseismic period

Contrary to the coseismic ΔCFS , the correlation between stress evolutions during the postseismic period with consequent seismicity was trivial. The stress changes imparted by afterslip; lower crust-upper mantle viscoelastic rebound; and the events of the Nantou sequence were evaluated (Figure 4). All of these factors were determined to result in a stress decrease in most of the Nantou region. Additionally, most of the events from 1999 and 2013 were found within the postseismic stress drop zone. The interactions between the significant events of the Nantou sequence were examined (Table 2). The results concluded that few (43%) of them were promoted by preceding events. Here, it should be noted that inaccuracy in the ΔCFS calculation may be attributed to the homogeneous slip dislocation models for No. 2, 3, 6, 7, and 8 events. The correlations between postseismic stress evolution and consequent seismicity were evaluated statistically through the Molchan diagram (Figure 5). The

stress change imparted by each of the postseismic factors represented negative correlation with distribution of the earthquakes (most of dots in the diagram are above the diagonal line).

It is been aware that time-dependent stress evolutions were not presented and discussed in detail in this study. The 15-month afterslip model of Yu et al. [2003] was implemented. According to the GPS observations, however, the afterslip posterior to this period is trivial [Yu et al., 2003]. Regarding visco-elastic rebound, although the magnitudes of stress change for various periods are different, but their patterns are similar (Figure 6). For all of the time periods, most of the events were located within the stress drop region.

5.4 The possible application of time-dependent probabilistic seismic hazard assessments

We concluded that the Chi-Chi coseismic ΔCFS dominated seismic activity within the Nantou region. If the rate-and-state friction model [Dieterich, 1994] is further implemented, spatial and temporal distributions of the seismicity rate can be quantified [e.g., Toda and Enescu, 2011; Chan et al., 2012]. The application of the rate-and-state friction model requires determination of corresponding parameters (e.g., a constitutive parameter of the model, aftershock duration, and tectonic shear stressing rate). It is beyond the scope of this study. Additionally, by considering ground motion attenuation behaviors from ground motion prediction equations or waveform simulations, time-dependent seismic hazards can be assessed [Chan et al.,

258 2013]. Such information provides important information for decision-makers and
259 public officials in respect to seismic hazard mitigation [McGuire, 2001].

260

261 **Acknowledgements**

262 Our work was supported by the National Science Council in Taiwan.

263

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 329

330 **Table Captions**

331 **Table 1**

332 The depth distributions for seismicity with different magnitude thresholds and
333 volumes of $\Delta\text{CFS} \geq 0.1$ bars.

334

335 **Table 2**

336 The earthquake parameters of the Nantou sequence and the corresponding ΔCFS
337 imparted by the Chi-Chi coseismic slip and preceding earthquake(s). The reference of
338 each earthquake parameter is presented.

339

340 **Figure Captions**

341 **Figure 1**

342 The maximum ΔCFS (a) at the depth of 10-20 km, (b) at the Latitude of 23.9-24.0°, (c)
343 at the Latitude of 23.8-23.9°, and (d) at the Latitude of 23.7-23.8° during the Chi-Chi
344 coseismic period. The corresponding seismicity that occurred following the Chi-Chi
345 earthquake is superimposed. The ratios of seismicity in the stress-increase regions are
346 shown. The series number of each earthquake is presented in Table 2.

347

348 **Figure 2**

349 (a) The number of $M \geq 2.0$ seismicity and (b) the magnitude of completeness, (M_c), as
350 a function of time within the study region. Note that due to the update of the seismic

network since 2012, the determined magnitudes are lower than the previously determined magnitudes.

Figure 3

A Molchan diagram - which investigates the correlation between the Chi-Chi coseismic Δ CFS and the consequent seismicity during September 1999 and May 2013. The various colors represent the seismicity with different magnitude thresholds.

Figure 4

The Δ CFS imparted by (a) the afterslip, (b) the viscoelastic relaxation, and (c) preceding events during the Chi-Chi postseismic period. The target depth for the Δ CFS calculation was 15 km. We confirmed that the Δ CFSs due to afterslip and viscoelastic relaxation were insensitive to depth. The series number of each earthquake and the corresponding Δ CFS imparted by the preceding earthquake(s) are presented in Table 2.

Figure 5

A Molchan diagram - which investigates the correlation between the Δ CFS by different factors and the consequent seismicity. The various colors represent the Δ CFS by varies factors.

372 **Figure 6**

373 The Δ CFS imparted by the viscoelastic relaxation for (a) 1 year, (b) 5 years, and (c)
374 13 years in the postseismic period. The seismicity during the corresponding periods is
375 superimposed. The series number of each earthquake and the corresponding Δ CFS
376 imparted by the preceding earthquake(s) are presented in Table 2.

Depth range (km)	After Chi-Chi seismicity			$\Delta\text{CFS} \geq 0.1$ bar
	M $\geq$ 2.0	M $\geq$ 4.0	M $\geq$ 5.0	
0-5	6%	3%	0%	1%
5-10	17%	15%	7%	37%
10-15	26%	41%	48%	65%
15-20	12%	16%	29%	59%
20-25	16%	13%	10%	59%
25-30	23%	12%	7%	48%

Table 1

No.	Date	Longitude	Latitude	Depth (km)	M _w	Strike	Dip	Rake	Reference	Chi-Chi ΔCFS, bars	Nantou seq. ΔCFS, bars
1	99/09/20	121.01	23.94	8	6.4	36	50	100	<i>Chi & Dreger (2004)</i>	0.30	----
2	99/09/20	121.06	23.85	24	6.1	209	85	139	<i>Yen (2002)</i>	0.05	-0.07
3	99/09/20	121.04	23.84	21	6.1	336	38	63	<i>Yen (2002)</i>	1.29	-12.62
4	99/09/22	121.08	23.81	10	6.2	318	22	64	<i>Chi & Dreger (2004)</i>	2.83	1.13
5	99/09/25	121.01	23.87	16	6.8	5	30	100	<i>Chi & Dreger (2004)</i>	3.14	-6.82
6	00/06/10	121.11	23.90	27	6.1	33	87	-114	BATS	-2.23	1.61
7	13/03/27	121.00	23.90	26	5.8	14	34	87	BATS	0.77	1.92
8	13/06/02	120.97	23.86	15	6.3	30	37	106	BATS	3.88	-3.32

Table 2

Figure 3

Figure 5