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Moderate-Magnitude Seismicity Remotely Triggered in the Taiwan Region by Large Earthquakes around the Philippine Sea Plate

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Abstract Seismicity in the Taiwan region was studied before and after the 12 largest seismic events with body-wave magnitudes exceeding 6.5, occurring around the Philippine Sea plate in the 1973 to 1994 period. The total local seismicity rate involving events with magnitudes as small as 2.0 was not affected by remote large events. However, the number of local earthquakes with magnitude $M_L \geqq 4.5$ in the 15 days following a large event exceeded the number before it in 9 out of 12 cases studied. When earthquakes with $M_L \geqq 4.0$ were considered, then 10 cases showed an increase in seismic activity after the big event. This suggests a 75 to 83% probability of remote triggering.

Introduction

The triggering of earthquakes in populous areas by large, distant earthquakes has repeatedly been a subject of public speculation. In fact, the relationship between seismic activity in spatially isolated regions has been denied in professional seismological literature. However, the phenomenon was clearly demonstrated after the June 1992 Landers (California) earthquake that provoked a sudden increase in seismicity at distances of up to 1250 km from the epicenter (Hill *et al.*, 1993; Anderson *et al.*, 1994; Bodin and Gomberg, 1994; Gomberg and Bodin, 1994). The mechanism of the triggering effect remains largely unclear. The most commonly proposed explanation is that some effect of the low-frequency seismic waves from the mainshock destabilized the faults that were near failure (Anderson *et al.*, 1994). In the meantime, one unexplained observation is that most of the triggered seismicity took place in the western Great Basin area to the north of the epicenter, whereas no discernible triggering was observed along the active San Andreas fault at much closer distances (Hill *et al.*, 1993).

One way to study remote triggering is to retroactively examine the existing seismicity catalogs in the world's most active regions. In this study, the area of Taiwan was selected because it is characterized by brisk seismicity rates. Taiwan's regional catalog provides a good opportunity to study the differences in seismic activity before and after major seismic events that have occurred in the western Pacific region throughout the past two decades.

Seismotectonics and Database

The island of Taiwan is situated on a boundary between the convergent Philippine Sea and Eurasian plates (Fig. 1). At present, the Philippine Sea plate moves toward the Eurasian plate at a rate of 7.1 cm/yr along the N307° direction (Seno *et al.*, 1993). Due to the plate interaction, frequent seismicity and rapid crustal deformation are observed in Taiwan (e.g., Tsai, 1986; Yu and Chen, 1994).

In 1972, the Taiwan Telemetered Seismic Network (TTSN) with approximately 25 stations was installed on the island to monitor earthquakes in the area of 21 to 26° N latitude and 119 to 123° E longitude, and it remained in operation until February 1991. The standard error of epicentral determination from this network was less than 5 km (Wang, 1989). Since 1991, the Central Weather Bureau, Taiwan (CWB) has upgraded the TTSN network into the advanced Central Weather Bureau Seismological Network (CWBSN). The number of stations increased to 75, and each station had three-component seismometers. The data management system of the CWBSN has been developed according to the guidelines of the Incorporated Research Institutions for Seismology (IRIS) consortium in the United States. After undergoing quality control, the time series are archived on the mass-storage devices.

The TTSN catalog employs a duration magnitude scale. The magnitude cutoff is about 1.5, and the catalog completeness threshold over the region is about 2.0. On average, 380 events with duration magnitudes $\geqq$2.0 are located monthly. The currently operating CWBSN network uses a local magnitude scale, which is calculated from the simulated Wood–Anderson seismogram (Shin, 1993). Yeh *et al.* (1993) converted all the data available from the two networks to the same local magnitude scale.

Analysis and Results

To check the influence of the biggest earthquakes around the Philippine Sea plate on seismicity near Taiwan, the most significant events within the rectangular area be-

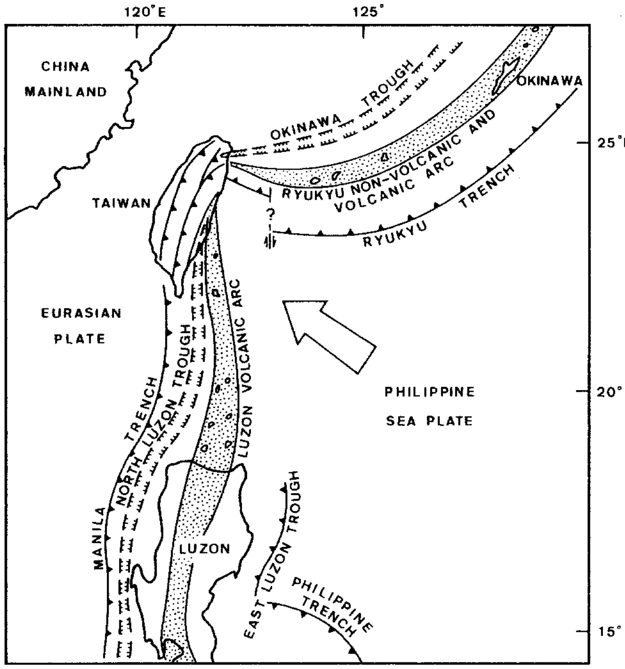

Figure 1. Plate-tectonics setting of Taiwan and the neighboring regions, showing the interaction of the Philippine Sea and Eurasian plates with the Ryukyu arc system, developed to the east and northeast of Taiwan, and the Luzon arc system extending to the south (after Ho, 1986).

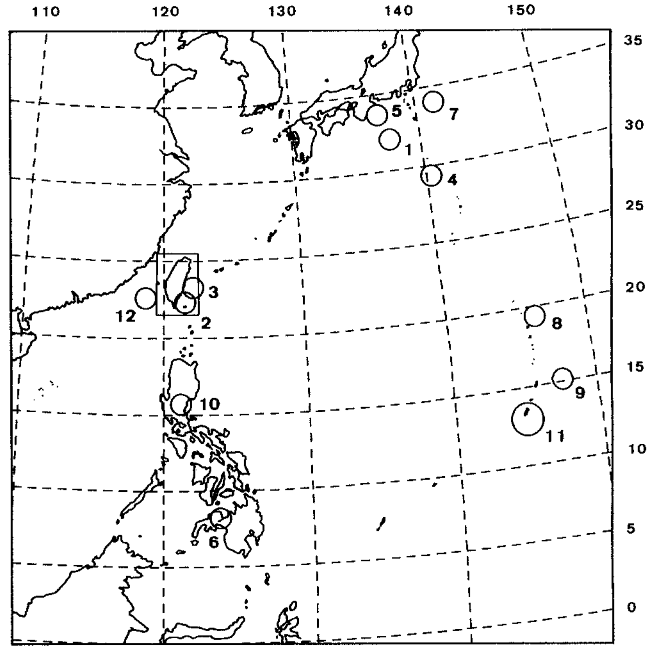

Figure 2. Epicenters of the largest earthquakes with $m_b \geqq 6.5$ occurring from 1973 to 1994 around the Philippine Sea plate. The circle size scales with the magnitude. Event numbers correspond to Table 1. The rectangular area shows the study area where seismicity was counted.

tween (5° N, 35° N) and (110° E, 150° E) were searched in the Preliminary Determination of Epicenters catalog (PDE). In the period from 1973 to 1994, 12 events with body-wave magnitudes $m_b \geqq 6.5$ occurred in the study area. The epicenters of these events are shown in Figure 2, and other parameters are listed in Table 1. The epicentral distances shown in the last column of Table 1 are related to the reference point at (24° N, 121° E) in Taiwan. Except for number 12, all events were interplate earthquakes located around the Philippine Sea plate. Events 2 and 3 were very close to Taiwan. Others were as far as 3000 km away from the island.

To test for the possibility of remote triggering, the 30-day cumulative seismicity was calculated from 15 days before to 15 days after each large event in Table 1. The interval of 15 days was inferred from the maximum delay in the appearance of triggered events as reported in the studies of the Landers phenomenon (Hill *et al.*, 1993; Anderson *et al.*, 1994). All the earthquakes with $M_L \geqq 2.0$ occurring within the local rectangular study area shown in Figure 2 were counted in the cumulative seismicity value. This local study area of 135,000 km^2 is defined by (21.5° N, 119.5° E) and (25.5° N, 122.5° E). The TTSN and CWBSN catalogs were used for the periods from 1973 to February 1991 and March 1991 to 1994, respectively.

It should be noted that the aftershocks of a big earthquake are related to the same causative fault and cannot be regarded as remotely triggered. Hence, for events 2 and 3, whose epicenters were within the local rectangle, the respective "source exclusion zones" were introduced, and all the earthquakes with epicenters within this zone were excluded from the analysis. Because these two events took place offshore, their exact fault dimensions are unknown. As established in the seismic hazard analysis for nuclear power plants in Taiwan (EIE, 1984), the relationship between the rupture length and the local magnitude indicates fault lengths

Table 1
Large Earthquakes Used in This Study

Event No.	Date (d m yr)	Origin time (hr:min)	Coordinates Lat.(°)	Long.(°)	Depth (km)	m_b	Δ* (km)
1	7 Mar 78	02:48	32.005	137.609	439	6.9	1859
2	23 Jul 78	14:42	22.282	121.512	17	6.5	197
3	23 Dec 78	11:23	23.247	122.075	33	6.6	138
4	6 Sep 82	01:47	29.325	140.360	175	6.5	2016
5	1 Jan 84	09:03	33.683	136.894	368	6.5	1886
6	5 Mar 84	03:33	08.147	123.762	649	6.5	1779
7	18 Sep 84	17:02	34.006	141.500	47	6.6	2285
8	16 Sep 86	18:20	19.376	146.301	47	6.5	2668
9	5 Apr 90	21:12	15.125	147.596	11	6.5	2959
10	16 Jul 90	07:26	15.679	121.172	25	6.5	921
11	8 Aug 93	08:34	12.982	144.801	59	7.1	2794
12	16 Sep 94	06:20	22.567	118.716	10	6.5	282

*Epicentral distances (Δ) are related to the referent point of (24° N, 121° E).

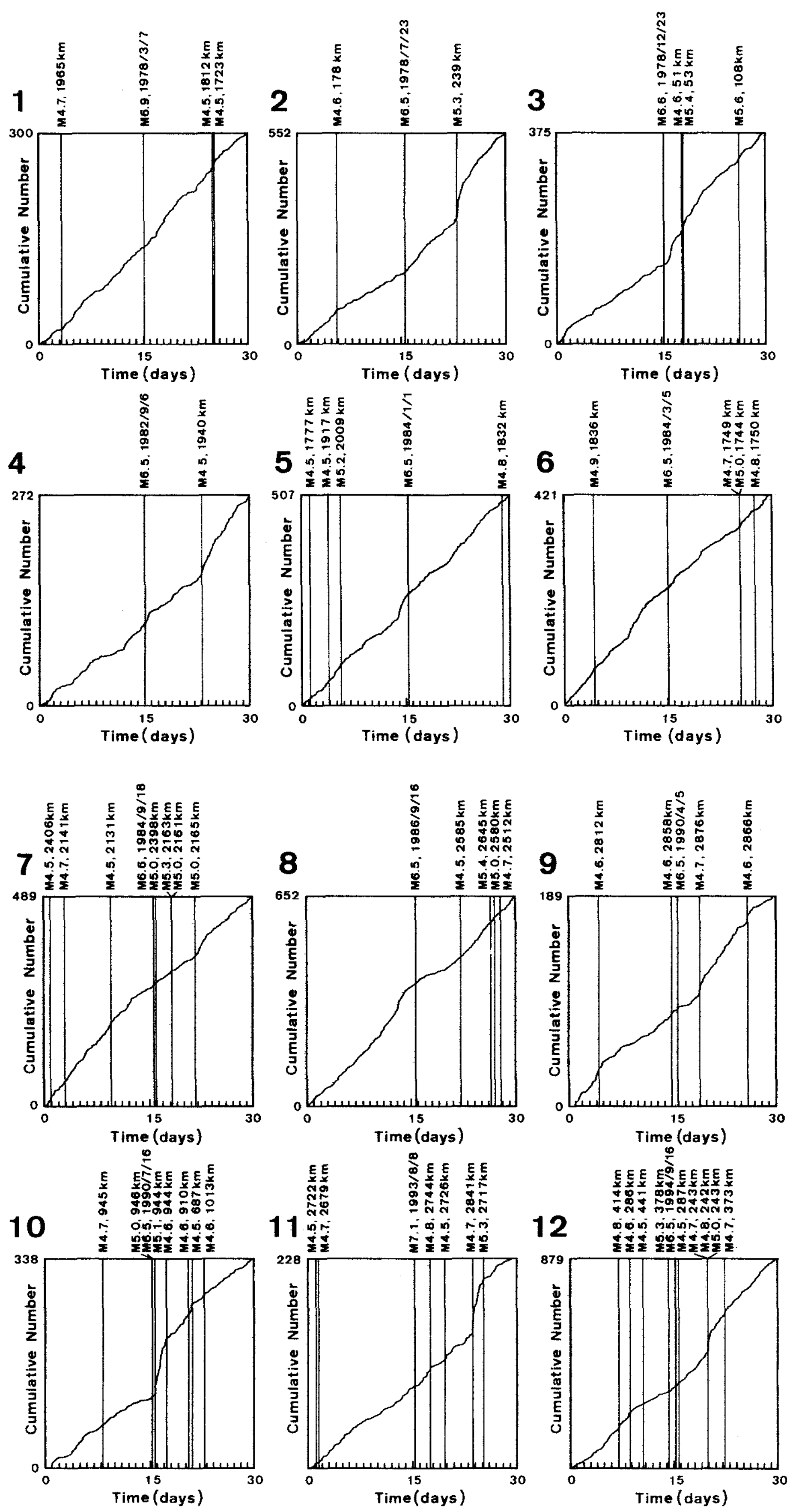

Figure 3. Seismicity in the 15 days before and after each big event. The vertical lines show the occurrence of $M_L \geqq 4.5$ earthquakes.

of about 15 and 26 km for events 2 and 3, based on their local magnitudes of 6.3 and 6.7, respectively. A "source exclusion zone" is then defined as a circle with a radius of 50 km around an epicenter.

As an additional statistic, the number of earthquakes with $M_L \geqq 4.5$ in the same time interval was examined. Figure 3 presents the cumulative regional seismicity curves for the local study area and for all 12 large reference earthquakes. The total cumulative number in the 30-day period varies from about 190 to 880. The origin time of the reference event is shown by the thick vertical line in the center of each plot. The thin lines indicate the origin times of $M_L \geqq 4.5$ quakes in the local Taiwan area. The numbers above them represent their magnitudes and distances from the reference event.

All the plots in Figure 3 show that the behavior of the overall cumulative seismicity is not affected by the big events. However, the opposite is valid when only $M_L \geqq 4.5$ earthquakes are considered. Table 2 summarizes the number of earthquakes in the 15-day period before and after each reference event. In 9 of the 12 cases, the number after the reference event exceeds the number before it by 1 to 4. Only events 2, 5, and 9 are exceptions. The results for $M_L \geqq 4.0$ seismicity are also listed in Table 2. In 10 of the 12 cases, the number of $M_L \geqq 4.0$ earthquakes recorded after the big event exceeds the number of those occurring before it by 1 to 7 (except events 5 and 7).

Table 2
Number of Earthquakes before and after the Big Events

	$M_L \geqq 4.5$			$M_L \geqq 4.0$		
Event No.	Earthquakes Before	Earthquakes After	Difference	Earthquakes Before	Earthquakes After	Difference
1	1	2	+1	2	4	+2
2	1	1	+0	4	10	+6
3	0	3	+3	2	5	+3
4	0	1	+1	0	7	+7
5	3	1	−2	8	7	−1
6	1	3	+2	4	6	+2
7	3	4	+1	10	6	−4
8	0	4	+4	4	6	+2
9	2	2	+0	6	7	+1
10	2	5	+3	6	9	+3
11	2	4	+2	9	13	+4
12	4	5	+1	7	12	+5

Discussion

Some of the additional earthquakes occurring after a big event could have been remotely triggered, whereas some of them may have been unrelated. There is no way to differentiate the triggered from the unrelated events. Hence, it can only be asserted that, in the average sense, more events occur after the big one than in the same time interval before it. By randomizing the data presented in Table 2, the probability of the observed increase in seismicity occurring by random chance can be estimated. From Table 2, a set of 24 numbers of earthquakes observed in 15-day periods (1, 2, 1, 1, 0, 3, etc. for the $M_L \geqq 4.5$ seismicity, and 2, 4, 4, 10, 2, 5, etc. for the $M_L \geqq 4.0$ seismicity) was randomly recorded into 12 "earthquakes before" and "earthquakes after" pairs. By doing this 10,000 times, it was determined how often N sequences showing an increase (more events in the "earthquakes after" pick) were found by chance. In this way, it was found that for the $M_L \geqq 4.5$ seismicity, $N \geqq 8$ occurs 6% of the time and $N \geqq 9$ sequences occurs only 2% of the time. For the $M_L \geqq 4.0$ seismicity, it was found that $N \geqq 8$ occurs 9% of the time, $N \geqq 9$ occurs 2% of the time, and $N \geqq 10$ can occur by chance just 0.5% of the time. Thus, with about 98% confidence in the first case and about 99.5% confidence in the second case, the hypothesis that what is observed is purely random must be rejected.

Conclusions

Regional seismicity catalogs in Taiwan were used to study the variations in local seismicity possibly associated with the 12 largest earthquakes occurring in the western Pacific region over a 22-year period. Cumulative local seismicity was counted over 15-day intervals before and after each large reference event. The local small-magnitude activity (between $M_L = 4.0$ and approximately 2.0) did not seem to respond to the occurrence of a very large event. However, in 9 of the 12 cases studied, the number of $M_L \geqq 4.5$ earthquakes recorded after the big event exceeded their number before it by 1 to 4. Similarly, 10 of the 12 cases exhibited an increase in the $M_L \geqq 4.0$ seismicity by 1 to 7. This suggests that the probability that a large earthquake causes an increase in remote moderate-magnitude seismicity is 75 to 83%. The probability of this occurring by random chance was shown to be negligible. The authors propose that this increased activity is a remote triggering effect, similar to that observed after the 1992 Landers (California) earthquake.

According to the data, the remote triggering effect may be observed, on average, up to the distances of 3000 km, i.e., the largest distances available in this study.

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References

Anderson, J. G., J. N. Brune, J. N. Louie, Y. Zeng, M. Savage, G. Yu, Q. Chen, and D. dePolo (1994). Seismicity in the western Great Basin apparently triggered by the Landers, California, earthquake, 28 June 1992, *Bull. Seism. Soc. Am.* **84,** 863–891.

Bodin, P. and J. Gomberg (1994). Triggered seismicity and deformation between the Landers, California, and Little Skull Mountain, Nevada, earthquakes, *Bull. Seism. Soc. Am.* **84,** 835–843.

EIE (1984). Seismic hazard analysis of Taiwan Power Company's nuclear power plant No. 2 at Kuosheng, Report to AEC, R.O.C., Eastern International Engineers, Inc.

Gomberg, J. and P. Bodin (1994). Triggering of the $M_s = 5.4$ Little Skull Mountain, Nevada, earthquake with dynamic strains, *Bull. Seism. Soc. Am.* **84,** 844–853.

Hill, D. P., P. A. Reasenberg, A. Michael, W. J. Arabasz, G. Beroza, J. N. Brune, D. Brumbaugh, R. Castro, S. Davis, D. dePolo, W. L. Ellsworth, J. Gomberg, S. Harmsen, L. House, S. M. Jackson, M. Johnston, L. Jones, R. Keller, S. Malone, L. Munguis, S. Nava, J. C. Pechmann, A. Sanford, R. W. Simpson, R. S. Smith, M. Stark, M. Stickney, A. Vidal, S. Walter, V. Wong, and J. Zollweg (1993). Seismicity in the western United States remotely triggered by the M 7.4 Landers, California, earthquake of June 28, 1992, *Science* **260,** 1617–1623.

Ho, C. S. (1986). A synthesis of the geologic evolution of Taiwan, *Mem. Geol. Soc. China* **7,** 15–29.

Preliminary Determination of Epicenters Monthly Listing (PDE), U.S. Department of the Interior/Geological Survey, National Earthquake Information Center.

Seno, T., S. Stein, and A. E. Gripp (1993). A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data, *J. Geophys. Res.* **98,** 17941–17948.

Shin, T. C. (1993). The calculation of local magnitude from the simulated Wood-Anderson seismograms of the short-period seismograms in the Taiwan area, *Terr. Atm. Ocean Sci.* **4,** no. 2, 155–170.

Tsai, Y. B. (1986). Seismotectonics of Taiwan, *Tectonophysics* **125,** 17–37.

Wang, J. H. (1989). The Taiwan telemetered seismographic network, *Phys. Earth Planet. Interiors* **58,** 9–18.

Yeh, Y. T., S. N. Cheng, C. Lee, C. C. Shin, and C. C. Chen (1993). Judgment of earthquake location and magnitude of several catalogues in the Taiwan region, Technical Report of the Seismology Center, Central Weather Bureau, Ministry of Transportation and Communications, Taiwan, R.O.C., V4-1, 1–23.

Yu, S. B. and H. Y. Chen (1994). Global positioning system measurements of crustal deformation in the Taiwan arc-continent collision zone, *Terr. Atm. Ocean Sci.* **5,** no. 4, 477–498.

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