ANNALS OF GEOPHYSICS, 68, 4, S448, 2025; doi:10.4401/ag-9325
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Aspects of Large Earthquakes in Taiwan

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Article history: received March 3, 2025; accepted June 28, 2025

Abstract

Large earthquakes ($M_s \geq 7$) cause severe damage across vast areas, extending for tens to hundreds of kilometers. Despite their lower frequency compared to smaller events, it is important to characterize them due to their devastating effect. For forty-nine $M_s \geq 7$ earthquakes from 1906 to 2024 in the Taiwan region, the moment magnitude, M_w, is smaller than M_s. The whole region is divided into six seismic zones based on regional tectonics. The spatial distribution of epicenters shows that most of the events occurred in the zone near the eastern costal line and offshore eastern Taiwan and only a few inland events happened on two zones in western Taiwan. The time series of earthquakes in six seismic zones show irregular recurrence behavior with aperiodicity. For the whole region, the time series may be separated into three intervals. The average inter-occurrence time between two sequent events in a time interval increases from the first time interval to the third one: 404.24 days (1.11 years), 845.30 days (2.32 years), and 2369.88 days (6.49 years), respectively, for the first, second, and the third time intervals. The average inter-occurrence time from for the whole time period is 895.7 days (2.45 years). The existence of a weak memory effect in the time series might be due to the presence of local stress transfer for some groups of events. The earthquake occurrences are the most active in April, September, and December, and the least active in May and August. The difference in seismic activities between the local daytime and local night-time is small, thus indicating small effects on generation of large earthquakes caused by solar and lunar tides.

Keywords: Earthquake; Location; Magnitude; Spatial Distribution; Time Series; Tidal Effect

1. Introduction

High seismicity (e.g. Hsu, 1971; Wang, 1998; Wang and Shin, 1998) in the Taiwan region (from 118°E to 125°E and 19°N to 26°N) has been caused by strong and complex regional tectonics of arc-continental collisions in the region (e.g. Hsu, 1971; Tsai et al., 1977; Wu, 1978; Tsai, 1986). The studies on large earthquakes are particularly significant for regional tectonics and seismic risk mitigation. From numerous literatures, Wang and Kuo (1995) first compiled a catalogue including forty-four $M_s \geq 7$ earthquakes during 1900-1995 and then Wang (2024) updated their catalogue to include five events which occurred during 1996-2024. Totally, there are forty-nine $M_s \geq 7$ earthquakes in the Taiwan region during 1900-2024. Included also is the seismic-moment magnitude, M_w, for each event. The most destructive events were the April 20, 1935 Hsinchu-Taichung M_s7.2 earthquake (cf. Miyamura, 1985) and the September 20, 1999 M_s7.7 Chi-Chi earthquake (cf. Ma et al., 1999). Of course, there were many historical earthquakes in the region (e.g. Tsai, 1985; Hsu, 1971, 1983). Nevertheless, historical earthquakes will not be taken

into account in this study, because there are high uncertainties of their locations and magnitudes. From the 49 large earthquakes, we will explore several problems as mentioned below.

Based on regional tectonics, we divide the whole region into six seismic zones. In order to understand regional seismicity of large earthquakes, it is significant to investigate the epicentral distributions and time series of earthquakes in the six seismic zones and the whole region. The variation in inter-occurrence times between two sequent events of the whole region will be investigated for exploring earthquake recurrences.

For $M_L \geq 2.5$ earthquakes with focal depths ≤ 30 km, Hsu et al. (2021) reported that in western Taiwan, the seismicity rate is the highest in February-April and the lowest values in July-September, exhibiting a direct correlation with annual water unloading; while in eastern Taiwan, shallow earthquakes (<18 km) are anti-correlated with water unloading. Hence, it is significant to evaluate the number of forty-nine large events in an individual month of a calendar year to examine the distribution of earthquake occurrences in 12 months.

The tidal effects on seismic activities due to the solar and lunar tides have long been a significant topic of seismology. Some earlier studies can be seen in Aki (1956). Numerous researchers claimed that they found positive correlations between seismicity with solar and lunar periodicities (e.g. Shimshoni, 1971; Shlien, 1972; Heaton, 1975, 1982; Glasby and Kasahara, 2001, 2002; Tanaka, 2010; Delorey et al., 2017). Delorey et al. (2017) detailedly described the mechanisms of tidal triggering of earthquakes, including earthquakes occurring at volcanoes and those happening in ocean basins. They addressed that Earth tides made by the gravitational pull of the sun and moon on the Earth, thus yielding periodic stresses. Such stresses are related to the rotation of the Earth relative to the sun and moon, including semi-diurnal (~12h) and diurnal (~24h). In addition, the rotation of the moon around the Earth results in a longer-period modulation (fortnightly, ~14.7days). Such tides impart both normal and shear stresses on fault surfaces in the upper crust. This will influence seismicity. They also addressed that tides trigger earthquakes at volcanoes (e.g. Emter, 1997) and ocean tides (e.g. Stroup et al., 2007) may trigger earthquakes in ocean basins. Their description is very significant for this study, because there are both inland and offshore earthquakes. Lin et al. (2003) and Chen et al. (2012) studied the possible relation of earthquake clustering to lunar phases in Taiwan. Of course, some others took the opposite viewpoint (e.g. Knopoff, 1964, 1970; Knopoff and Gardner, 1972; Vidale et al., 1998). Hence, it is significant to explore the possible tidal effect on large earthquakes in the six seismic zones of Taiwan. For this purpose, we evaluate the numbers of earthquakes in the local daytime (ldt) from 6 a.m. to 18 p.m. and the local night-time (lnt) from 18 p.m. to 6 a.m. next day for the whole region and six seismic zones and then study the possible differences on the two numbers.

In this study, based on 49 large earthquakes with $M_S \geq 7$, the difference between M_S and M_W will be first examined. The epicentral distribution and time series of earthquakes in six seismic zones and the whole region, the variation in inter-occurrence time between two earthquakes in the whole region, the numbers of earthquakes in twelve months of a calendar year, and the distributions of earthquakes in local daytime and local night-time are investigated. In addition, the possible tidal effect on earthquake occurrences are discussed.

2. Data

Wang and Kuo (1995) compiled a catalog of 44 earthquakes with $M_S \geq 7$ happened in the Taiwan region during 1906-1986 from several domestic and international catalogs reported in different literature. In these catalogs, different magnitudes were used to quantify earthquakes. In order to explore the related problems as mentioned above, it is necessary to unify the magnitude scales reported in different catalogues to the commonly-used surface-wave magnitude, M_S. For pre-1967 earthquakes, the conversion equations between M_S and other magnitude scales inferred by Wang and Miyamura (1990) and Wang (1992) were applied to evaluate the value of M_S. For the post-1967 events, the values of M_S were taken directly from the Earthquake Determination Report by USGS. The focal depths (denoted by H) of some earthquakes in the catalog compiled by Wang and Kuo (1995) are unknown.

After Wang and Kuo (1995) compiled their catalog, five large earthquakes happened. The first earthquake is the September 20 (local time September 21), 1999 M_S7.7 Chi-Chi earthquake which caused serious damage in Taiwan. The second one is the March 31, 2002 M_S7.1 offshore Hualien earthquake which caused some damage in Taipei whose location is about 150 km far away from the epicenter (cf. Chen, 2003). The third one is the December 26, 2006 M_S7.1 Pingtung earthquake which was one of the 'doubles' with the second event having $M_S = 6.9$ occurred about 8 minutes after and 66 km away from it. The 'doublets' caused damage in the local area. The forth one is the September 18, 2022 $M_S = 7.4$ (or $M_W = 7.0$) Chihshang earthquake which caused minor damage in eastern Taiwan.

The fifth one is the April 2 (local time April 3), 2024 $M_s = 7.7$ (or $M_w = 7.4$) offshore Hualien earthquake which caused serious damage in Hualien and some areas.

For the purpose of comparison, it is significant to include the seismic moment magnitude, M_w, for each event in this study. Chen et al. (2004b) and Theunissen et al. (2010) measured or re-evaluated the values of M_w for large Taiwan earthquakes. Several authors (e.g. Lee et al., 1978; Li, 1983; Engdahl et al., 1998; Kao et al., 1998; Engdahl and Villaseňor, 2002; Wu et al., 2008; Hsu et al., 2012; Kanamori et al., 2012) relocated or revised the locations of some of the forty-nine events. Wang (2024) took their results to replace the original ones listed in Wang and Kuo (1995) and then re-compiled a complete catalogue for $M_s \geq 7$ Taiwan earthquakes during 1900-2024. He took both M_s and M_w in his catalog and also revised the focal depths of some events. Totally, forty-nine instrumentally-recorded earthquakes quantified with $M_s = 7.0$-8.1 or $M_w = 6.75$-7.5 occurred from 1900 to 2024 have been re-compiled in Wang's catalog. The occurrence dates, epicenters, focal depths, and magnitudes of the forty-nine earthquakes are listed in Table 1. The uncertainties of epicenters and focal depths are higher for pre-1967 earthquakes than for post-1967 ones.

However, the focal depths of several pre-1940 events are still unknown because of a lack of sufficient and reliable data for evaluations. The crust-upper mantle boundary with $v_p = 7.5$ km/s in the Taiwan region is mainly in the range 35–45 km as inferred by several groups of researchers (e.g. Rau and Wu, 1995; Ma et al., 1996; Kim et al., 2005; Wu et al., 2007; Kuo-Chen et al., 2012). Hence, an average depth of 40 km is here taken as a boundary to classify the events: a crustal event with $H \leq 40$ km and an upper-mantle or subduction zone event with $H > 40$ km. Results show that most $M_s \geq 7$ earthquakes are crustal events. In addition, the damage caused by the 49 earthquakes can be seen in Wang (2024).

Table 1. The earthquake data (date, epicentral location, focal depth, H, and magnitude, M_s and M_w) used in this study: 49 events numbered from 01 to 49. As displayed in Fig. 2, the seismic zones are: 'ORR' for the area, including Ilan, the Okinawa trough, the Ryukyu trench, and the Ryukyu arc; 'PSP' for the Philippine Sea Plate; 'EAP' for the Eurasian Plate; 'ECR for the eastern costal range; 'NPF' for the north western plain and foothill; and 'SPF' for the south western plain and foothill.

No.	Local Date	Hour/Minute (ldt or lnt)	Lat. (°N)	Long. (°E)	H (km)	M_s/M_w	Seismic Zone
01	19060619	19/22 (lnt)	20.0	122.0		7.1/6.8	EAP
02	19090415	03/53 (lnt)	25.0	121.5	75.0	7.1/6.8	PSP
03	19091121	15/39 (ldt)	24.4	121.8	10.0	7.1/6.8	ORR
04	19100412	08/22 (ldt)	25.1	122.9	200.0	8.1/7.5	PSP
05	19100617	14/30 (ldt)	21.0	121.0		7.1/6.8	EAP
06	19100901	08/45 (ldt)	21.0	122.0		7.1/6.8	EAP
07	19150106	07/26 (ldt)	24.4	123.2	160.0	7.1/6.8	PSP
08	19150229	02/19 (lnt)	23.6	123.5		7.5/7.1	ORR
09	19160326	07/52 (ldt)	24.0	124.0		7.2/6.9	ORR
10	19170704	08/38 (ldt)	25.0	123.0	20.0	7.4/7.0	ORR
'ldt' = local daytime; 'lnt' = local night-time.							

No.	Local Date	Hour/Minute (ldt or lnt)	Lat. (°N)	Long. (°E)	H (km)	M_s/M_w	Seismic Zone
11	19170704	13/36 (ldt)	25.0	123.0	30.0	7.0/6.75	ORR
12	19191220	03/33 (lnt)	22.5	121.4	24.0	7.2/6.9	ECR
13	19191220	04/37 (lnt)	22.5	121.4	35.0	7.1/6.8	ECR
14	19200605	12/21 (ldt)	24.0	122.0	35.0	8.1 /7.5	ORR
15	19210402	17/36 (ldt)	22.6	123.4	35.0	7.4/7.0	PSP
16	19220901	03/16 (lnt)	24.6	122.2	35.0	7.7/7.2	ORR
17	19220914	03/31 (lnt)	24.6	122.3	35.0	7.3/7.0	ORR
18	19250416	03/52 (lnt)	20.4	120.2		7.2/6.9	EAP
19	19350420	06/01 (ldt)	24.3	120.8	10.0	7.2/6.9	NPF
20	19350904	09/37 (ldt)	22.5	121.5	20.0	7.3/7.0	ECR
21	19360821	14/51 (ldt)	22.0	121.2	50.0	7.2/6.9	ECR
22	19371208	16/32 (ldt)	23.1	121.4		7.1/6.8	ECR
23	19380907	12/03 (ldt)	23.8	121.8	10.0	7.1/6.8	ECR
24	19381206	07/00 (ldt)	22.9	121.6	10.0	7.2/6.9	EAP
25	19411216	03/19 (lnt)	23.4	120.5	15.0	7.2/6.9	SPF
26	19470926	00/01 (lnt)	24.8	123.0	110.0	7.6/7.2	PSP
27	19511021	05/34 (lnt)	23.8	121.7	4.0	7.4/7.0	ECR
28	19511021	11/29 (ldt)	24.1	121.8	1.0	7.2/6.9	ECR
29	19511022	13/43 (ldt)	23.8	121.9	18.0	7.2/6.9	ECR
30	19511124	02/50 (lnt)	23.3	121.4	36.0	7.4/7.0	ECR
31	19570223	04/26 (lnt)	23.8	121.8	30.0	7.4/7.0	ECR
32	19580311	08/25 (ldt)	25.0	124.0	70	7.0/6.75	PSP
33	19590426	04/40 (lnt)	25.0	122.5	126.5	7.9/7.4	PSP
34	19630213	16/50 (ldt)	24.4	122.1	35.0	7.3 /7.2	ORR
‘ldt’ = local daytime; ‘lnt’ = local night-time.							

No.	Local Date	Hour/Minute (ldt or lnt)	Lat. (°N)	Long. (°E)	*H* (km)	M_s/M_w	Seismic Zone
35	19640118	20/04 (lnt)	23.2	120.6	33.0	7.0/6.75	SPF
36	19650517	01/19 (lnt)	22.5	121.3	21	7.0/6.75	ECR
37	19660312	00/31 (lnt)	24.1	122.6	28.9	7.9/7.5	ORR
38	19680226	05/05 (lnt)	22.7	121.3	24	7.1/6.8	ORR
39	19720125	10/06 (ldt)	22.5	122.3	10.1	7.4/7.0	PSP
40	19720125	11/41 (ldt)	23.0	122.3	40	7.2 /7.3	PSP
41	19720425	17/57 (ldt)	23.5	121.5	15.4	7.0 /6.75	ECR
42	19780723	22/42 (lnt)	22.2	121.3	6.3	7.3 /7.2	ECR
43	19781223	19/23 (lnt)	23.3	122.3	48.0	7.0 /7.0	PSP
44	19861115	05/20 (lnt)	23.9	121.6	34	7.8 /7.3	ECR
45	19990921	01/47 (lnt)	23.9	120.8	8	7.7 /7.6	NPF
46	20020331	14/53 (ldt)	24.1	122.1	16.5	7.1 /7.1	ORR
47	20061226	20/26 (lnt)	21.6	120.6	44.0	7.1 /7.1	EAP
48	20220918	14/44 (ldt)	23.1	121.2	7.8	7.4/7.0	ECR
49	20240403	07/58 (ldt)	23.8	121.7	15.4	7.8/7.37	ECR
'ldt' = local daytime; 'lnt' = local night-time.							

3. Seismic Zonation Based on Regional Tectonics

The Taiwan region is in the juncture of the Eurasian plate and the Philippine Sea plate (Hsu, 1971; Tsai et al., 1977; Wu, 1978; Tsai, 1986). A simplified regional tectonic map is displayed in Fig. 1. In eastern Taiwan, the Philippine Sea plate (PSP) moves, with a sliding rate of ~8.2 cm/year (Yu et al., 1997), northwestward to collide with the Eurasian plate (EAP). The PSP starts to subduct northwards from the Ryukyu trench (shown by a dashed line in Fig. 1) almost around the latitude of ~23.6°N and then underneath the EAP in northern Taiwan. The westernmost boundary of its Wadati-Benioff zone is denoted a dotted line in Fig. 1. The Ryukyu arc is to the east of Taiwan island. Meanwhile, the Okinawa trough has extended southwestward to Taiwan from Japan. In between the Ryukyu arc and the Ryukyu trench, the main geological structures are the Nanao basin, the Yaeyama ridge, and the Huatung basin. In the area to the south of latitude 23°N, the EAP moves from west to east and starts to subduct almost from longitude 120°E and then underneath the PSP. Hence, the Taiwan island itself, the PSP, EAP, Okinawa trough, Ryukyu arc, Nanao basin, Yaeyama ridge, Ryukyu trench, and Huatung basin are the major components of regional tectonics of arc-continental collision (e.g. Tsai et al., 1977; Wu, 1978; Teng and Wang, 1981; Eguchi and Uyeda, 1983; Tsai, 1986; Sibuet et al., 1987; Lallemand et al., 1997, 2001; Kao, 1998; Kao et al., 1998; Wang, 1989a; Lin,

2002; Wu et al., 2009; Chen et al., 2024). Strong and complex tectonics of arc-continental collisions has resulted in active orogeny with complicated geological structures and high seismicity in the region.

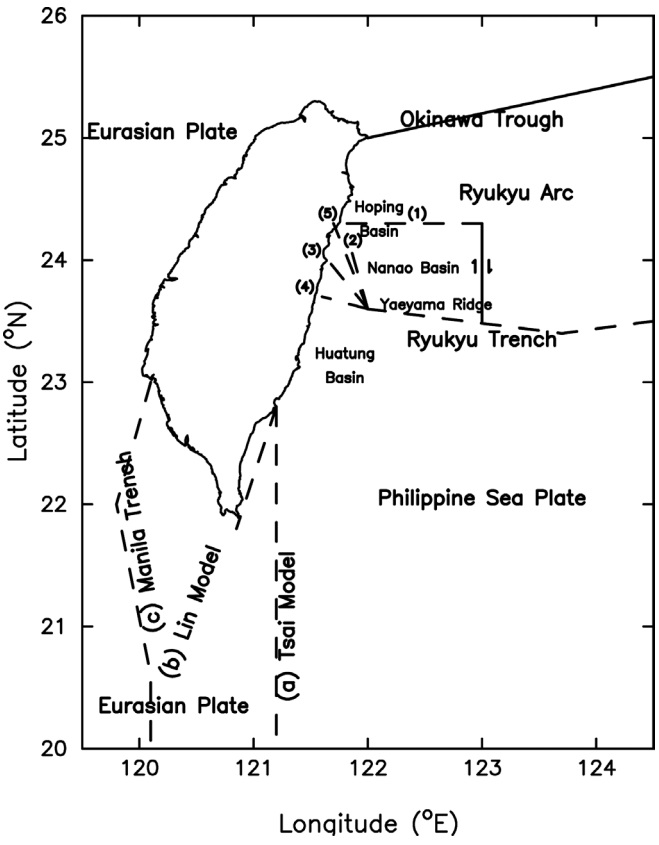

Figure 1. Regional tectonics. The dashed lines show the trenches. The numbers denote the models proposed by various authors.

There are two critical problems with regional tectonics. The first one is: How does the Ryukyu trench (represented by a dashed line in Fig. 1) approach and contact the Taiwan island? The second one is: Where is the trench where the Eurasian plate starts to subduct? For the first problem, essentially there are five models. Teng and Wang (1981) proposed that the westernmost segment of Ryukyu trench which is short has separated from the main one and moved to the north. The westernmost segment touches the Taiwan island and is linked to the main one by a strike-slip fault as shown by a thin solid line in Fig. 1. This model is denoted by (1) in Fig. 1. Eguchi and Uyeda (1983) assumed that the westernmost segment of Ryukyu trench turns to the northwest direction yet does not touch the Taiwan island as displayed by a dashed line in Fig. 1. This model is denoted by (2) in Fig. 1. Several authors (e.g. Kao, 1998; Kao et al., 1998; and Lin, 2002) considered that the westernmost segment of Ryukyu trench turns to the northwest direction and then touches the Taiwan island as displayed by (3) in Fig. 1. Wu et al. (2009) supposed that the westernmost end of Ryukyu trench touches the Taiwan island as displayed by a dashed line in Fig. 1. This model is noted by (4) in Fig. 1. Chen et al. (2024) assumed that the westernmost segment of Ryukyu trench turns to the northwest direction and then touches the Taiwan island as displayed by a dashed line in Fig. 1. This model is denoted by (5) in Fig. 1.

For the second problem, essentially there are three models to describe the trenches. Tsai (1986) assumed that the trench where the Eurasian starts to subduct is along the dashed line (a) in Fig. 1. Lin (2002) suggested that the trench where the Eurasian starts to subduct is along the dashed line (b) in Fig. 1. The eastern segment separates from the western segment, which is the Manila trench. Lallemand et al. (1997, 2001) showed that the Eurasian trench is just the Manila trench and almost along the dashed line (c) in Fig. 1.

Chen et al. (2024) proposed their Ryukyu trench model based on a detailed 3D velocity model inferred from a comprehensive data set. Hence, we divide the whole region into six seismic zones as shown in Fig. 2 based

on regional tectonics and their Ryukyu trench model. The six seismic zones are: the ORR zone, including Ilan, Okinawa trough, Ryukyu arc, Nanao basin, Yaeyama ridge, and Ryukyu trench; the PSP zone, i.e., the Philippine Sea Plate including the Huatung basin; the EAP zone, i.e., the Eurasian Plate; the ECR, i.e., the Eastern Coastal Range; the NPF, i.e., the northern part of Coastal Plain and Western Foothill; and the SPF zone, i.e., the southern part of Coastal Plain and Western Foothill. The NPF and SPF seismic zones are divided by a solid line as shown in Fig. 2. To the south of Taiwan, the area related to the Wadati-Benioff zone of the EAP is shown by two dashed lines which are normal to each other in Fig. 2.

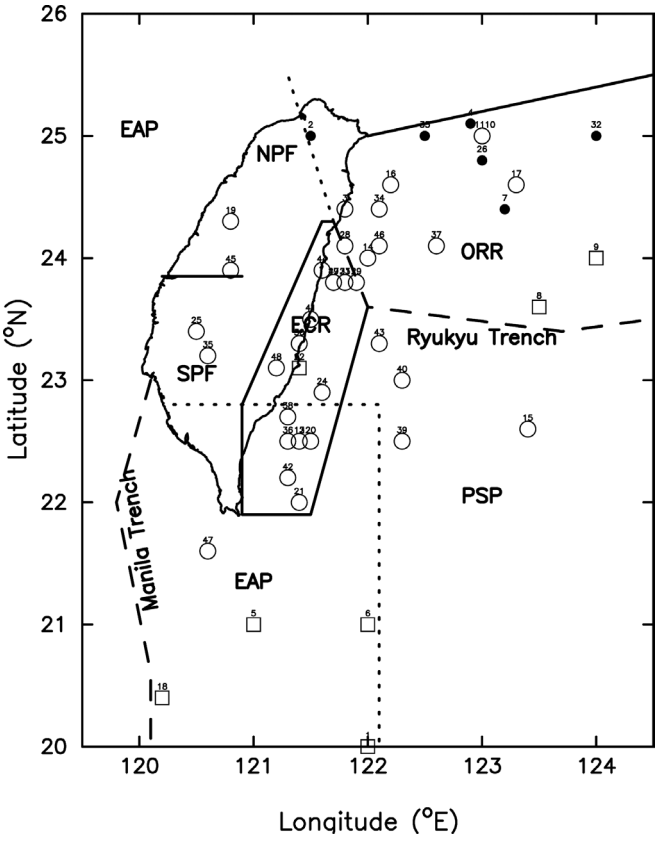

Figure 2. Epicenters of $M_S \geq 7$ earthquakes in the Taiwan region (from 118°E to 125°E and 20°N to 26°N): open circles for shallow events, solid circles for deep events, open squares for the events without focal depths, and open triangles for historical events. The seven seismic zones are: the ORR zone, including Okinawa trough, Ryukyu arc, Nanao basin, Yaeyama ridge, and Ryukyu trench; the PSP zone, i.e., the Philippine Sea plate; the EAP zone, i.e., the Eurasian plate; the ECR, i.e., the Eastern Coastal Range; the NTW zone, i.e., the northern Taiwan area; the NPF, i.e., the north part of Coastal Plain and Western Foothill; and the SPF zone, i.e., the south part of Coastal Plain and Western Foothill.

4. Results

4.1 Spatial Distribution of Earthquake Epicenters

The epicenters of forty-nine earthquakes in six seismic zones are plotted in Fig. 2 with different symbols: open circles for the events with $H \leq 40$, solid circles for those with $H > 40$ km, and open squares for those whose focal depths have not yet been estimated. Obviously most of events were located offshore in eastern Taiwan; while only a few of them occurred inland and in western Taiwan. The numbers and percentages of earthquakes in the whole area and in six seismic zones are listed in Table 2. The two values is the largest in the ECR zone and smallest in the NPF and SPF zones. The numbers of events are 11, 10, 6, 11, 18, 2, and 2, respectively, in the ORR, PSP, EAP, ECR, NPF, and SPN seismic zones.

Table 2. The numbers and percentages of earthquakes in six seismic zones and those in the local daytime (ldt) and the local night-time (lnt).

Area	Number (%)	ldt (%)	lnt (%)
Whole Area	49	26 (53.06%)	23 (46.94)
ORR: Okinawa Trough, Ryukyu Arc, and Ryukyu Trench	11 (22.45%)	7 (63.64%)	4 (36.36%)
PSP: Philippine Sea Plate	10 (20.41%)	6 (60.00%)	4 (40.00%)
EAP: Eurasian Plate	6 (12.24%)	3 (50.00%)	3 (50.00%)
ECR: Eastern Costal Range	18 (36.73%)	9 (50.00%)	9 (50.00%)
NPF: North Part of Western Costal Plain and Foothill	2 (4.08%)	1 (50.00%)	1 (50.00%)
SPF: South Part of Western Costal Plain and Foothill	2 (4.08%)	0 (0.00%)	2 (100.00%)

4.2 Time Series of Earthquakes

The time series of earthquakes in six seismic zones and the whole study area are displayed in Fig. 3. This figure clearly demonstrates different time series of earthquakes in the six seismic zones. It also shows that a few groups of earthquakes, for example the 1951 Hualien-Taitung earthquakes, had short inter-occurrence times to form a cluster such that the related line segments are much closed to one another and thus cannot be separated. On the other

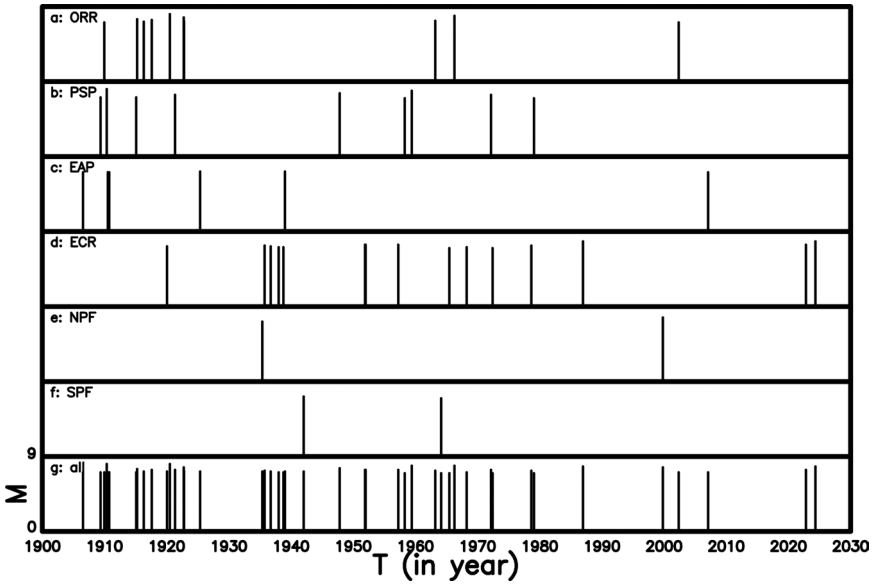

Figure 3. Time series of earthquakes in six seismic zones and the whole area: (a) for the ORR zone; (b) for the PSP zone; (c) for the EAP zone; (d) for the ECR zone; (e) for the NPF zone; (f) for the SPF zone; and (g) for the whole study area.

hand, the earthquakes with long inter-occurrence times separate very much. In addition, the degree of clustering remarkably decreases with increasing time in the time period of this study.

The inter-occurrence time between two sequent events versus the first event number is displayed in Fig. 4. In the time series, we may recognize three intervals: the first one from Event No. 1 in 1906 to Event No. 18 in 1925, the second one from Event No. 18 in 1925 to Event No. 41 in 1972, and the third one from Event No. 41 in 1972 to Event No. 49 in 2024. The average inter-occurrence times are 895.7 days (or 2.45 years), 404.24 days (or 1.11 years), 746.22 days (or 2.04 years), and 2369.88 days (or 6.49 years), respectively, for the whole time interval, the first, second, and the third time intervals. They are shown by a thin solid line for the whole time interval and three thin dotted lines for the three respective time intervals.

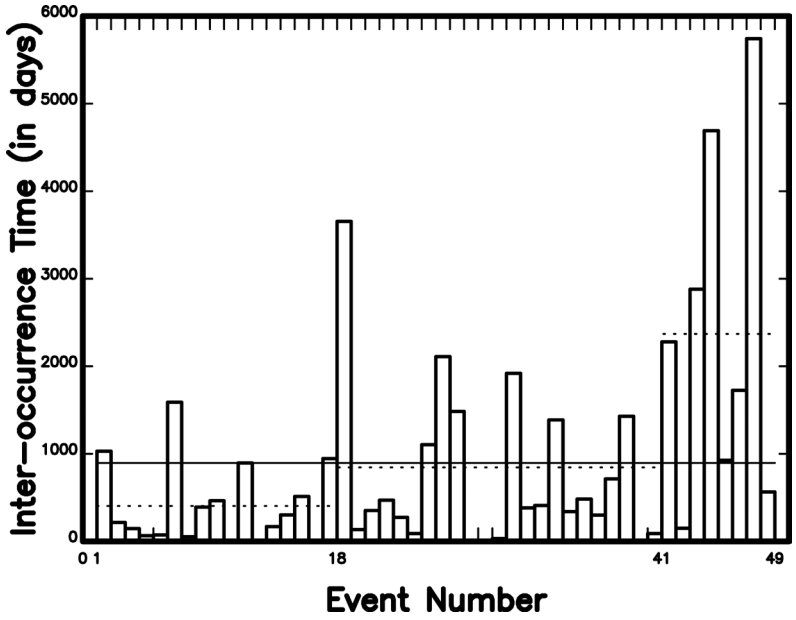

Figure 4. Time series of inter-occurrence time between two sequent earthquakes. The average inter-occurrence times are 895.7 days (2.45 years), 404.24 days (1.11 years), 845.30 days (2.32 years), and 2369.88 days (6.49 years), respectively, the first, second, and the third time intervals. They are shown by a thin solid line for the whole time interval and three thin dotted lines for the three respective time intervals.

4.3 Distribution of Events in Twelve Months

It is important to understand the distribution of events through the year. The numbers and percentages of events in January, February, March, April, May, June, July, August, September, October, November, and December are listed in Table 3. Results show that the occurrences of $M_s \geq 7$ earthquakes are the most active in April, September, and December, and the least active in May and August.

4.4 Distribution of Events in Local Daytime and Local Night-Time

The local daytime (ldt) and the local night-time (lnt) when an earthquake occurred are also listed in Table 1. The numbers and percentages of earthquakes in the ldt and the lnt for the whole area and for six seismic zones are listed in Table 2.

Table 3 shows the numbers and percentage of events in the ldt and the lnt in per month. Figure 5 displays the number of events in a single hour of a day. The distributions of numbers and percentage of events for twelve calendar months are quite irregular. Table 4 shows the number and percentage of events in respective 24 hours of a day.

Table 3. The numbers and percentage of events in the calendar months and the numbers of in the local day time (ldt) and the local night time (lnt).

Month	Number	%	ldt	lnt
January	4	8.16	3	1
February	4	8.16	1	3
March	4	8.16	3	1
April	8	16.33	5	3
May	1	2.04	0	1
June	3	6.12	2	1
July	3	6.12	2	1
August	1	2.04	1	0
September	8	16.33	4	4
October	3	6.12	2	1
November	3	6.12	0	3
December	7	14.29	2	5

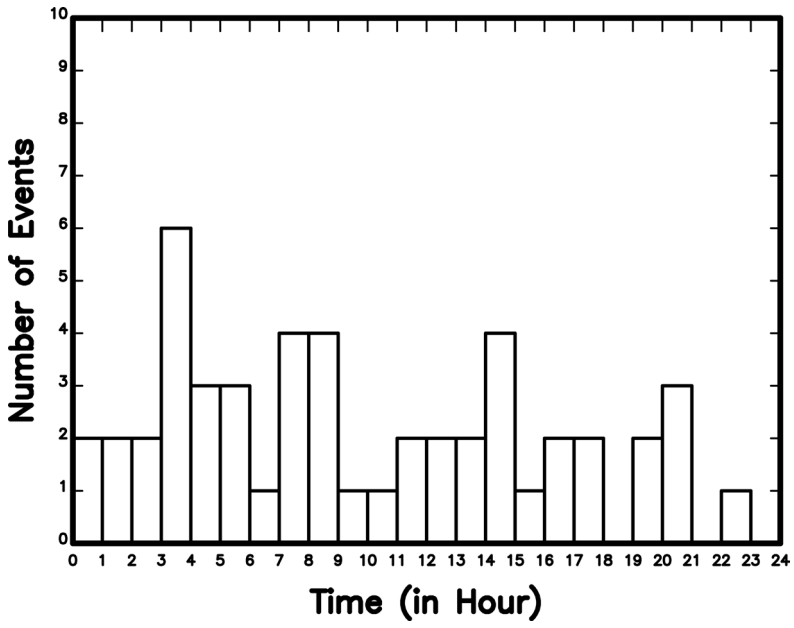

Figure 5. Time series of number of events occurring in respective 24 hours of 2 days.

Table 4. The number and percentage of events in an hour.

Hour	Number	%
00-01	2	4.08
01-02	2	4.08
02-03	2	4.08
03-04	6	12.2
04-05	3	6.12
05-06	3	6.12
06-07	1	2.04
07-08	4	8.16
08-09	4	8.16
09-10	1	2.04
10-11	1	2.04
11-12	2	4.08
12-13	2	4.08
13-14	2	4.08
14-15	4	8.16
15-16	1	2.04
16-17	2	4.08
17-18	2	4.08
18-19	0	0.00
19-20	2	4.08
20-21	3	6.12
21-22	0	0.00
22-23	1	2.04
23-24	0	0.00

Figure 6 demonstrates the distribution of the occurrence time per hour for the 49 large earthquakes. In the figure, an event occurred in the time range of 6^{hr}-18^{hr}, i.e., the day time, is denoted by an open circle, while an event occurred in the time range of 0^{hr}-6^{hr} or in that of 18^{hr}-24^{hr}, i.e., the night-time, is denoted by an solid circle.

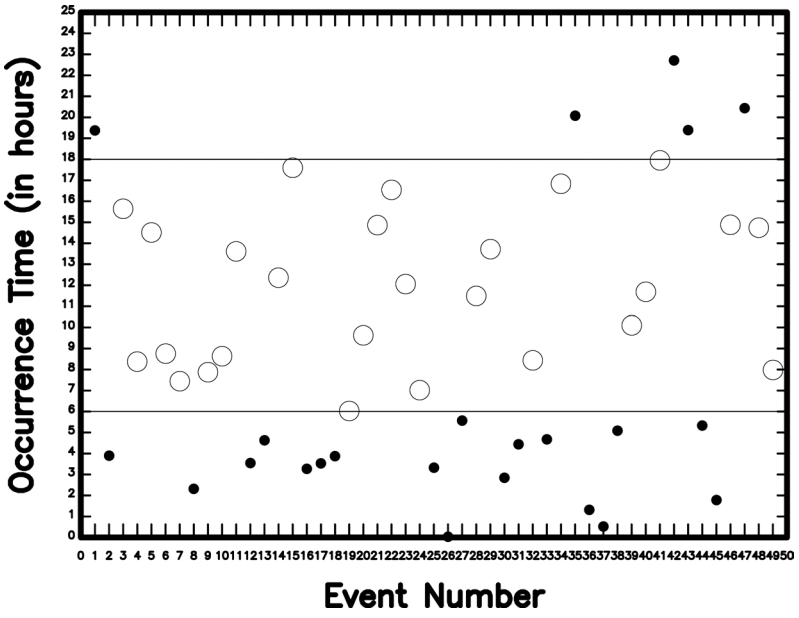

Figure 6. Time series of magnitudes of forty-nine $M_s \geq 7$ earthquakes from 1900 to date in Taiwan. (open circles for local day time and solid circles for local night time).

5. Discussion

5.1 Surface-wave Magnitude and Moment Magnitude

Since the early 1960's, M_s measured from the seismic waves with a period 20 ± 2 sec (Vanek et al., 1962) has been taken to quantify an earthquake. Due to saturation of seismic-wave amplitudes around 20 ± 2 sec, Aki (1972) argued "the inefficiency of M_s as a measure of the size of large earthquakes." In other word, the value of M_s can be underestimated for large earthquakes. In order to resolve the problem, Hanks and Kanamori (1979) defined the moment magnitude M_w, as:

$$M_w = (2/3) \log (M_o) - 10.7 \quad (1)$$

where M_o is the seismic moment (in dyne-cm). This equation was originally obtained based on M_s. In principle, M_w must be equal to M_s for large earthquakes.

Table 1 reveals $M_s > M_w$ for all events in study. For Taiwan earthquakes, Chen et al. (2007) studied the correlations between M_w and other magnitude scales. Their relationship between M_w and M_s is

$$M_w = 0.71 M_s + 1.78 \quad (2)$$

which is shown with a solid line in Fig. 7.

In addition to Eq. (2), Theunissen et al. (2010) also correlated M_w to M_s as:

$$M_w = 0.79 M_s + 1.29 \quad (3)$$

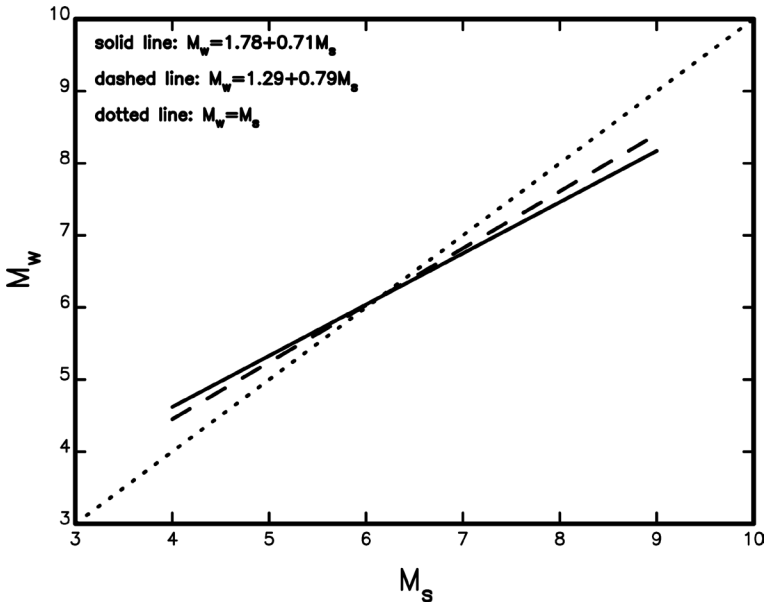

Figure 7. The relationships for the moment magnitude M_w and surface-wave magnitude M_s: the solid line for $M_w = 0.71M_s + 1.78$; dashed line for $M_w = 0.79M_s + 1.29$; and the dotted line for $M_w = M_s$.

which is displayed by a dashed line in Fig. 1 where a dotted line is plotted to show $M_w = M_s$. Figure 1 shows $M_s > M_w$ when M_s is larger than a particular M_s, i.e., M_{sp}, and $M_s < M_w$ when $M_s < M_{sp}$. The value of M_{sp} is 6.14 for the two relationships. For $M_s > M_{sp}$, the value of M_w evaluated from Eq. (2) is slightly smaller than that done from Eq. (3); while for $M_s < M_{sp}$, the value of M_w evaluated from Eq. (2) is slightly larger than that done from Eq. (3). Results suggest that the original idea of $M_w = M_s$ for large earthquakes does not seem to work for Taiwan earthquakes. From the definition of M_w, the reason causing the difference might be due to the measurement of M_o. We will explore the problem from two approaches as mentioned below.

The first approach is based on the global data for both global earthquakes and Taiwan's. For global earthquake with $5.0 \le M_s \le 6.7$, Purcaru and Berchember (1978) inferred the $\log(M_o) - M_s$ relationship as: $\log(M_o) = 1.50M_s + 16.1$ or $M_s = (2/3)\log(M_o) - 10.73$. This is similar to Eq. (1). For global earthquakes, Ekstrom and Dziewonski (1988) obtained the $\log(M_o) - M_s$ relationships as: (1) $\log(M_o) = 19.24 + M_s$ or $M_s = \log(M_o) - 19.24$ for $M_s \le 5.3$; (2) $\log(M_o) = 30.20 - (92.45 - 11.40M_s)1/2$ $M_s = 0.09[\log(M_o) - 30.20]1/2 - 8.11$ for $5.3 \le M_s \le 6.8$; and (3) $\log(M_o) = 16.14 + 1.5M_s$ or $M_s = (2/3)\log(M_o) - 10.76$ for $M_s \ge 6.8$. The $\log(M_o) - M_s$ relationships vary with magnitude ranges. Although the $\log(M_o) - M_s$ relationships for $M_s \le 6.8$ are different Eq. (1), that for $M_s \ge 6.8$ is similar to Eq. (1).

For the mid-plate earthquakes with $0.0 \le M_s \le 8.0$, Nuttli (1983) inferred $\log(M_o) = 1.0M_s + 18.85$ or $M_s = 1.0\log(M_o) - 18.85$. This $\log(M_o) - M_s$ relationships is different from Eq. (1). For the plate-margin earthquakes with $7.3 \le M_s \le 8.3$, Nuttli (1985) inferred $\log(M_o) = 1.45M_s + 16.35$ or $M_s = 0.69\log(M_o) - 11.28$ for $6.3 \le M_s \le 7.3$ and $\log(M_o) = 1.63M_s + 15.05$ or $M_s = 0.61\log(M_o) - 9.23$ for $7.3 \le M_s \le 8.3$. The first $\log(M_o) - M_s$ relationship is similar to Eq. (1), yet the second one not. Based on 25708 global earthquakes with $M_s \ge 4.5$ during 1976-2006 reported by the International Seismological Centre (ISC) and Global Centroid Moment Tensor (CMT), Das et al. (2019) and Das and Das (2025) inferred $\log(M_o) = 1.36M_s + 17.24$ or $M_s = 0.74\log(M_o) - 12.68$, This $\log(M_o) - M_s$ relationship is different from Eq. (1).

For 16 earthquakes with $5.0 \le M_s \le 6.7$ in Taiwan, Wang (1985) inferred the $\log(M_o) - M_s$ relationship: $\log(M_o) = 1.20M_s + 17.83$ or $M_s = 0.83\log(M_o) - 14.86$. For 201 Taiwan earthquakes with $4.2 \le M_s \le 7.8$ or 1.40×10^{23} dyne-cm $\le M_o \le 3.38\times10^{27}$ dyne-cm reported in the Global CMT catalog during 1976-2006, Chen et al. (2007) inferred the following $M_o - M_s$ relationships: $\log(M_o) = 1.07M_s + 18.72$ or $M_s = 0.93\log(M_o) - 17.50$. The $M_s - \log(M_o)$ relationships for Taiwan earthquakes are different from Eq. (1). Results seem to suggest that Eq. (1) does not work well for Taiwan earthquakes.

The second approach is to evaluate the values of M_w for Taiwan earthquakes from both the global data and Taiwan's. Chen et al. (2008) took the seismic moment (M_o) values of 79 earthquakes occurring in the Taiwan

region from two data sources: one from the catalog of the Global centroid-moment tensor (CMT) and the catalogue measured from the regional Broadband Array in Taiwan for Seismology (BATS) (Kao and Jian, 2001) for the period 1996-2005 and compared the values determined from the global and regional networks, respectively. M_{oG} and M_{oB} are used to denote the M_o values published in the Global CMT and regional BATS catalogues, respectively. Our results show $M_{wB} = (2/3)\log(M_{oB}) - 10.73$ and $M_{wG} = (2/3)\log(M_{oG}) - 10.73$. This leads to $M_{wB} - M_{wG} = (2/3)[\log(M_{oB}) - \log(M_{oG})] \approx -0.3$ from $\log(M_{oB}) = [1.01\log(M_{oG}) - 0.43] \pm 0.19$ when the standard deviations are ignored that M_{oB} linearly correlates with M_{oG} and that M_{oB} is, on average, approximately equal to $0.37M_{oG}$. This difference may be caused by the use of shorter period seismic waves in BATS for estimating M_{oB}. The moment magnitude evaluated from regional BATS seismograms is about 0.3 less than that estimated from global data. The previous results suggest that the value of M_o and also M_w is smaller for earthquakes occurring in Taiwan than for global ones.

5.2 Spatial Distribution of Earthquake Epicenters

Figure 3 shows that most of events were located offshore in east Taiwan; while only a few of them occurred inland in west Taiwan. Table 2 exhibits that the numbers of events in the ORR, PSP, EAP, ECR, NPF, and SPN seismic zones are 11, 10, 6, 11, 18, 2 and 2′, respectively. The number is the largest in the ECR seismic zone and the smallest in the NPF and SPF seismic zones. It seems reasonable that the ECR seismic zone is just in the area where the PSP collides the EAP. The PSP moves, with a sliding speed of 8.2 mm/year (Yu et al., 1997) to collide the EAP along the eastern coastal line. The tectonic stresses should be the strongest in this area. From the paleoseismicity data measured from the Chelungpu fault along which the 1999 Chi-Chi earthquake happened, Wang (2005) estimated the sliding rate of 4.95 mm/year. This remarkable difference in sliding rates yield a larger number of earthquakes in the ECR seismic zone than in western Taiwan.

Event Nos. 1, 5, and 6 whose focal depths have not yet known occurred within the Wadati-Benioff zone of the EAP. Event No. 18 whose focal depth has not yet known occurred on the Malina trench of the EAP. An intermediate-depth earthquake with $H = 48$ km, i.e., Event No. 43, occurred to the south of the Ryukyu arc and on the Huatung basin in the PSP. This event was located by the Taiwan Telemetered Seismographic Network (TTSN) (see Wang, 1989b). The uncertainties of locations evaluated by the TTSN for offshore earthquakes to the east of Taiwan are usually high. Since the crustal thickness of the sea area is shorter than the average value of 40 km, this event could be a shallow one rather than an intermediate-depth one.

There were six deep earthquakes, i.e., Nos. 2, 3, 7, 26, 32, and 33, occurred within the Wadati-Benioff zone of the PSP and are denoted by solid circles in Fig. 3. Among the six events, only No. 2, i.e., the 15 April 1909 Taipei earthquake (Wang et al., 2011; Kanamori et al., 2012), which occurred near the westernmost boundary (as represented by a dotted line) of the Wadati-Benioff zone of PSP and underneath northern Taiwan, was located to the west of longitude 122.0°E and underneath the Taiwan island. While other five deep earthquakes occurred offshore northern Taiwan to the east of this longitude and were underneath the Okinawa trough. As shown in Fig. 2, the Ryukyu trench starts to turn to northwest almost at the site (23.6°N, 122.0°E). From the seismicity pattern, Wang (1989) suggested that for the Wadati-Benioff zone, its western part to 122.2°E moves more northwardly than its eastern part to 122.25°E. His observation seems to meet the models displayed in Fig. 2. Since 1909, not any M_s 7 earthquakes has occurred in the area between the location of the 1909 Taipei earthquake and the longitude of 122.25°E.

An intermediate-depth earthquake, i.e., Event No. 43, occurred on the Huatung Basin within the PSP. This event was located by the Taiwan Telemetered Seismographic Network (TTSN) (see Wang, 1989b). The uncertainties of locations evaluated by the TTSN for offshore earthquakes to the east of Taiwan are usually high. Since the crustal thickness of the sea area is shorter than average value, i.e., 40 km, this event could be a shallow one rather than an intermediate-depth one. Three events, i.e., No. 1, No. 5, and No. 18, could occur in the Wadati-Benioff zone of EAP which has been subducting from west to east in southern Taiwan.

5.3 Time Series of Earthquakes

The time series of earthquakes in six seismic zones and the whole region are displayed in Fig. 4. This figure demonstrates irregular recurrence behavior, which is aperiodic as mentioned by numerous authors (e.g. Kagan and

Jackson, 1991; Goes, 1996; Chen et al., 2004c; Wang, 2003, 2005; Satake, 2015) for earthquakes in six seismic zones. We cannot see any correlation between earthquakes that occurred in two seismic zones.

The inter-occurrence time between two sequent events versus the event number is displayed in Fig. 5. As mentioned above, the variation in inter-occurrence time can be divided into three time intervals. The average inter-occurrence times are 895.7 days (or 2.45 years), 404.24 days (or 1.11 years), 845.30 days (or 2.32 years), and 2369.88 days (or 6.49 years), respectively, for the whole time interval, the first one, the second one, and the third one. The coefficient of variation (*CV*) is defined as the ratio of the standard deviation, s, to the mean μ,, i.e., $CV = \sigma/\mu$ (cf. Forkman, 2009). This value demonstrates the extent of variability in relation to the mean of the population. The values of μ have been shown previously. The values of σ are 1247.30 days, 177.33 days, 1024.56 days, and 2128.13 days, respectively, for the whole time interval, the first one, the second one, and the third one. Hence, the *CV* values are 1.393, 0.439, 0825, 0.898, respectively, for the whole time interval, the first one, the second one, and the third one. Results suggest that the extent of variability in relation to the mean of the population is the largest for the whole time interval, the secondly largest for the third time interval, the thirdly largest for the second one, and the smallest for the first one. Although the values of μ are very similar for the whole time interval and the second one, their values of σ are quite different. This indicates their variations are different. This suggests that the earthquake occurrences in the whole region are aperiodic because $CV > 1$, while the degree of aperiodicity increases from the first time interval to the third one. This again confirms irregular recurrence behavior of $M_s \geq 7.0$ earthquakes in Taiwan as mentioned above.

The average inter-occurrence times increase from the first time interval to the third one. The average inter-occurrence time for the whole time interval is longer those that for the first and second time intervals and shorter than that for the third time interval. This again reveals indirect evidence of irregular recurrence behavior with aperiodicity of the time series of earthquakes. Since the mechanisms to cause this phenomenon are not yet clear, more studies are necessary. Such irregular recurrence behavior with aperiodicity would reduce the possibility of long-term prediction or forecasting of $M_s \geq 7$ large earthquakes in Taiwan.

Wang (2024) recognized several special groups of events, i.e., 'doublets,' 'triplets,' and ''quadruplets,' under three criteria. First, the epicentral distance between two events is shorter than 110 km. Secondly, the inter-occurrence time between two events is shorter than 100 days. Thirdly, the difference in focal depths between two events is smaller than 40 km. Due to a small difference in the magnitudes between any two events in use, it is not necessary to set up a criterion for magnitude. From Table 1, there are five 'doublets,' i.e., Event Nos. 5 and 6, Event Nos. 10 and 11, Nos. 12 and 13, Event Nos. 16 and 17, and Event Nos. 20 and 21. Every pair of two events formed the "doublet." Three sequent earthquakes, i.e., Event Nos. 39, 40, and 41 which occurred offshore eastern Taiwan in 1972, formed the 'triplet.' Four sequential earthquakes, i.e., Event Nos. 27, 28, 29, and 30 which occurred offshore and near eastern Taiwan in 1951, formed the "quadruplet." They were the largest four events of the 1951 Hualien-Taitung earthquake sequence (e.g. Chen et al., 2008b). The formation of those kinds of groups of earthquakes may be due to stress transfer between different faults in a short time interval (e.g. Stein, 1999; King and Cocco, 2000; Wang et al., 2010, 2013). Chen et al. (2008b) studied in depth the stress transfer for the 1951 "quadruplet."

Although the epicentral distance between Event Nos. 7 and 8 is shorter than 110 km, they are not considered as the 'doublet.' This is due to a reason that Event No. 7 is a deep event and the focal depth of Event No. 8 is unknown. Their hypocentral distance might be longer than 110 km. Although several pairs of sequent earthquakes occurred, respectively, in an inter-occurrence time being shorter than 100 days, they are not considered to be the 'doublets' because the epicentral distance between two events of each pair was longer than 110 km. In fact, the Pingtung 'these' occurred in 2006 (cf. Ma and Liang, 2008; Chen et al., 2008a). Since the value of M_s for the second event is slightly smaller 7.0, only the first one, i.e., Event No. 47, is taken into account in this study.

Figure 2 reveals direct evidence of irregular recurrence behavior with aperiodicity of the earthquake sequence. Since the reasons to cause this phenomenon are not yet clear, more studies are necessary. Such irregular recurrence behavior with aperiodicity would reduce the possibility of long-term prediction or forecasting of $M_s \geq 7$ large earthquakes in Taiwan.

In order to explore long-term variation in earthquakes, earthquake prediction, and seismic risk estimates, it is significant to investigate the possibility of memory effect within a time series of earthquakes in a region. This kind of study is usually based on the frequency or probability distribution of inter-occurrence times of events. When every event of a time series of earthquakes is totally uncorrelated with others, such a time series is considered to be generated by a random process. The random distribution of point events is known as a Poisson process. Nevertheless, the presence of nests, swarms, and clusters in the spatial distribution and time series of earthquakes indicates the

possibility of function of the non-Poisson processes on earthquake occurrences (e.g. Gardner and Knopoff, 1974). When the swarms, foreshocks and aftershocks are removed, the sequence of mainshocks could be generated by a Poisson process without the memory effect.

A simple method to examine whether or not the memory effect operates in a time series of earthquakes in a region is to compare the exponential function and gamma function of the frequency distribution or probability distribution of inter-occurrence times of earthquakes. When the former is more appropriate than the latter to interpret the frequency distribution, the time series of earthquakes is mainly generated by the Poisson processes and thus the memory effect does not operate or is very weak. For the time series of first forty-four earthquakes, i.e., Event Nos. 1 to 44, Wang and Kuo (1998) studied the frequency distribution of inter-occurrence time between two events. Their results demonstrate that the exponential function is more appropriate than gamma function to describe the frequency distribution. This indicates that the time series of earthquakes with $M_s \geq 7$ was generated mainly by the Poisson processes. Wang (2014) investigated the memory effect in the time series of $M_s \geq 7$ Taiwan earthquakes through the fluctuation analysis. His results demonstrate that every two earthquakes of the series is short-term corrected, thus leading to a short-term memory effect rather than a long-term one. The presence of short-term correction must be due to the existence of 'doublets,' 'triplets,' and ''quadruplets' caused by stress transfer as mentioned before. His research result should work for the present time series of forty-seven events. This implicates impossibility or low possibility for forecasting a long-term trend of occurrences of $M_s \geq 7$ earthquakes in Taiwan.

5.4 Distribution of Events in Twelve Months

Table 3 shows the numbers and percentages of events per month. Results show that the occurrences of $M_s \geq 7$ earthquakes are the most active in April, September, and December, and the least active in May and August during 1906-2024. The reasons to cause such a distribution is not yet known and need more studies.

As mentioned above, for $M_L \geq 2.5$ earthquakes with focal depths ≤ 30 km, Hsu et al. (2021) reported that in western Taiwan, the seismicity rate is the highest in February-April and the lowest values in July-September, exhibiting a direct correlation with annual water unloading; while in eastern Taiwan, shallow earthquakes (<18 km) are anti-correlated with water unloading. They assumed that the elastic hydrological load cycle may be the primary driving mechanism for the observed synchronized modulation of earthquakes, as also evidenced by deep earthquakes in eastern Taiwan. From Table 3, the number of events in February-April, i.e., the wet season, is 16, while that in July-September, i.e., the dry season, is 12. Although the former is larger than the latter, the difference is not so large as mentioned by Hsu (2021) when looking at earthquakes with $M_s \geq 7$. Considering the seismicity in western Taiwan, i.e., seismic zones NPF and SPF in this study, from Table 1 there was one event in February-April, i.e., the wet season, and one in July-September, i.e., the dry season, in NPF. The former is equal to the latter. While there was one event in January and one in December in SPF. The two events did not occur in either the wet season or the dry season. Considering the seismicity in eastern Taiwan, i.e., seismic zone ECR in this study, from Table 1 the number of events in February-April, i.e., the wet season, is 4, while that in July-September, i.e., the dry season, is 5. The former is smaller than the latter with a difference of 1. Earthquake occurrences in ECR were the most active in October-December, because there were 12 events in this time interval.

Hsu et al. (2025) studied the relation of crustal stress changes with hydrological cycles. The effect of hydrological cycles on seismicity rate reveals the complex interplay between crustal stress conditions, faulting orientations, and earthquake nucleation. From the GNSS position time series in 2006-2021 across Taiwan, they suggested a prevailing NW-SE trending seasonal contraction and expansion of the Earth's crust in response to hydrological loading-unloading in SW Taiwan. This is consistent with the maximum annual water storage change inferred from hydrological data. In SW Taiwan there is a positive correlation between excess seismicity rate and reduced NW-SE compression and/or decreasing vertical loading. Hydrologically-induced contraction aligns with the tectonic compressive stress axis in the wet season (February-April), but this alignment does not yield more active seismicity during peak water storage. On the other hand, seismicity peaks during the dry months (July-September) coincides with the maximum uplift and water unloading. The hydrologically-induced changes of vertical stress or pressure caused are the major factor in triggering earthquakes, because the vertical stress amplitudes are 2~4 times greater than the horizontal stress changes in SW Taiwan. Considering SW Taiwan, i.e., seismic zone SPF in this study, there were only 2 events: one in January and the other in December. It does not seem that hydrologically-induced

contraction can be applied to interpret the occurrences of large earthquakes in Taiwan. Of course, this might be due to a small number of data set.

5.5 Distribution of Events in Local Daytime and Local Nigh-time

The effects of solar and lunar tides on seismicity have long been a debatable topic of seismology. Numerous researchers (e.g. Shimshoni, 1971; Shlien, 1972; Heaton, 1975, 1982; Glasby and Kasahara, 2001, 2002; Tanaka et al., 2002, 2004; Tanaka, 2010) claimed a positive correlation between seismicity with solar and lunar periodicities. On the other hand, some others (e.g. Knopoff, 1964, 1970; Knopoff and Gardner, 1972; Vidale et al., 1998) took the opposite viewpoint.

Table 2 shows the numbers of earthquakes in the ldt and the lnt for the whole area are, respectively, 26 with a percentage of 53.06% and 23 with a percentage of 46.94%. This shows that the number of large earthquakes is slightly bigger in the local day time than in the local night time, but the difference is small. In the ORR and PSP seismic zones, large earthquakes occurred slightly more highly in the ldt than in the lnt. In the EPA and ECR seismic zones, the possibility of occurrences of large earthquakes in the ldt is equal to that in the lnt. In the NPF and SPF seismic zones, $M_s \geq 7$ earthquakes occurred lower in the ldt than in the lnt.

Here, we consider the 1951 Taipei earthquake as an inland event, because it occurred just underneath northern Taiwan. From Table 2 we may have the three concluding points. First, in the sea area, including the ORR, PSP, and EAP seismic zones, 16 events occurred in the ldt and 10 in the lnt. The possibility of earthquake occurrences is higher in the ldt than in the lnt. Secondly, in the collision area, i.e., the ECR seismic zone, 9 events occurred in both ldt and lnt. In other word, the possibility of earthquake occurrences is the same in the ldt and in the lnt. In the inland area, i.e., the NPF and SPF seismic zones including the 1909 Taipei earthquake, 1 event occurred in the ldt and 4 events in the lnt. In other word, the possibility of earthquake occurrences is lower in the ldt than in the lnt.

Table 3 shows the numbers and percentage of events in the ldt and the lnt for twelve calendar months. Figure 6 displays the number of events in a single hour of a day. Since the distributions of numbers and percentage of events for twelve calendar months are quite irregular, we cannot identify a general rule to describe the distributions.

Table 4 shows the number and percentage of events in respective twenty-four hours of a day. The distributions of number and percentage are not regular. Nevertheless, the number and percentage in the time interval of 0^{hr}-6^{hr} are the highest and those in the time interval of 18^{hr}-24^{hr} are the lowest. This indicates that more earthquakes occurred from mid-night to early morning of next day than from evening to mid-night.

Figure 7 demonstrates the distribution of the occurrence time in a hour for 49 earthquakes. In the figure, an event occurred in the time interval of 6^{hr}-18^{hr}, i.e., the daytime, is denoted by an open circle, while an event occurred in the time interval of 0^{hr}-6^{hr} or in that of 18^{hr}-24^{hr}, i.e., the night-time, is denoted by an solid circle. Before Event No. 33, earthquakes occurred quite randomly in the time interval of 0^{hr}-18^{hr} and there was only one event happened in the time interval of 18^{hr}-24^{hr}. After Event No. 33, earthquakes occurred still quite randomly in the time interval of 0^{hr}-18^{hr}, yet the number of events slightly decreased; and the number of events slightly increased in the time interval of 18^{hr}-24^{hr}, in other word, more events occurred from evening to mid-night. Figures 6 and 7 also exhibit that large earthquakes in Taiwan occurred more easily in the time interval of 0^{hr}-18^{hr} than in that of 18^{hr}-24^{hr}.

There were some studies on this topic for Taiwan earthquakes. Wang and Kuo (1998) found a significant Poisson component in the frequency distribution of inter-occurrence times of $M_s \geq 7$ earthquakes in Taiwan, even though a weak memory effect exists (Wang, 2014) as mentioned above. This suggests that the tidal effect is not significant for triggering $M_s \geq 7$ earthquakes in this region. Lin et al. (2003) studied the possible relation of earthquake clustering to lunar phases in Taiwan. He found that significant clustering of earthquakes with $2.5 \leq M_L \leq 5.0$ (M_L = local magnitude) appears around lunar Day 14, with clustering around the full moon day being about 30% higher in frequency than that on other non-full moon days. The phenomena indicate that tidal forces caused by lunar attraction can indeed trigger some smaller earthquakes. On the other hand, a lack of any correlation between larger-sized earthquakes with $M_L > 5$ and lunar phases, thus indicating that larger earthquakes are barely induced by tidal forces, but predominantly by tectonic forces. They concluded that the lunar tide can indeed trigger some small earthquakes, while there is no tidal triggering effect for earthquakes of $M_L < 2.5$ or $M_L > 5$. Chen et al. (2012) explored the correlation between tidal effects and earthquakes with $M_L \geq 3$ that occurred near Taiwan during 1973 and 2008. Their results suggest that the lunar tidal force is likely a factor in triggering earthquakes. In California, USA, Delorey et al. (2017) analyzed 6941 earthquakes with M < 4.5 during 2012-2014 in and near the San Andreas

fault, From the results, they hypothesized that tidal triggering of earthquakes provide quantitative information regarding the fault's stress state and poroelastic properties. They found the complex interaction of semi-diurnal and fortnightly tidal periods exposes both stress threshold and critical state behavior. Hence, from the previous results we suggest that in addition to regional tectonic stresses, the solar and lunar tides would be a minor factor in influencing the occurrences of large earthquakes in Taiwan. The detailed mechanisms need further studies.

6. Conclusions

From forty-nine $M_s \geq 7$ Taiwan earthquakes from 1906 to 2024, we study several aspects of earthquakes of Taiwan into six seismic zones recognized from regional tectonics. The spatial distribution of epicenters shows that most of the events occurred in the area near the eastern costal line and offshore eastern Taiwan, and only a few inland events happened in western Taiwan. The numbers and percentages of earthquake are different in the sea area, conclusion area, and the inland area. The time series of earthquakes in six seismic zones show irregular recurrence behavior with aperiodicity. For the whole area, the inter-occurrence time between two sequent events in a time interval increases from the first time interval to the third one. The average inter-occurrence time from 1909 to 2024 is 2.45 years. There were several special groups of events, i.e., 'doublets,' 'triplets,' and ''quadruplets' due to stress transfer. The existence of a weak memory effect in the time series might be due to the presence of local stress transfer for these special groups of events. In the sea area, the possibility of earthquake occurrences is higher in the ldt than in the lnt. In the collision area, the possibility of earthquake occurrences is the same in the ldt and in the lnt. In the inland area, the possibility of earthquake occurrences is lower in the ldt than in the lnt. Totally, the difference in seismic activities between the local daytime and local night-time is small. This might indicate that there was only a small effect on generation of large earthquakes caused by solar and lunar tides.

Acknowledgments. I would like to express my deep thanks to two anonymous reviewers and Sector Editor for their valuable comments and suggestions that help me to substantially improve the manuscript. This work was partly sponsored by Institute of Earth Sciences, Academia Sinica, Taiwan, ROC.

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