Earth and Planetary Science
https://journals.nasspublishing.com/index.php/eps

REVIEW

A Catalogue of Historical and Instrumentally-Recorded $M_s \geq 7$ Earthquakes in Taiwan

Jeen-Hwa Wang

Institute of Earth Sciences, Academia Sinica, P.O. Box 1–55, Nangang, Taipei, Taiwan, China

Abstract: A catalogue of forty-nine instrumentally-recorded earthquakes with magnitudes ≥ 7 in Taiwan from 1906 to date is compiled from regional and international catalogues and literature. Included also are seven historical earthquakes that occurred from 1792 to 1867. The earthquake magnitude is the surface-wave magnitude, M_s. The moment magnitude, M_w, is also evaluated either from M_s or obtained from related documents. Except for one event, M_w is smaller than or equal to M_s. There are the 'doublets', 'triplets', and 'quadruplets' in these earthquakes. The spatial distribution of epicenters shows that most of the events occurred in offshore eastern Taiwan and only a few inland events happened in western Taiwan. The shortest inter-occurrence time between two consecutive events is less than 1 day; while the longest one is 5742 days between No. 47 event and No. 48 event. The inter-occurrence time somewhat increases with time. The time series of earthquakes shows irregular recurrence behavior with aperiodicity, fractality, and a weak memory effect. The damage produced by earthquakes is much higher from inland events (mainly in western Taiwan) than from offshore ones.

Keywords: Earthquake; Location; Magnitude; Spatial distribution; Time series; Damage

1. Introduction

The Taiwan region (from 118 °E to 125 °E and 19 °N to 26 °N) is at the juncture of the Eurasian plate and the Philippine Sea plate [1–4]. The Philippine Sea plate moves, with a sliding rate of about 8 cm/year [5], northwestward to collide with the Eurasian plate in eastern Taiwan. The former starts to subduct northwards almost from latitude ~24 °N and then underneath the latter in northern Taiwan. The western boundary of the subducted slab is almost along longitude 121.5 °E. Meanwhile, the Okinawa rough has extended southwestward to Taiwan. In the area to the south of latitude 23 °N, the Eurasian plate that moves from west to east starts to subduct almost from longitude 120 °E and then underneath the Philippine Sea plate. Strong and complex tectonics have resulted in active orogeny with

*Corresponding Author:
Jeen-Hwa Wang,
Institute of Earth Sciences, Academia Sinica, P.O. Box 1–55, Nangang, Taipei, Taiwan, China;
E-mail: jhwang@earth.sinica.edu.tw

Received: 26 March 2024; **Received in revised form:** 14 May 2024; **Accepted:** 28 May 2024; **Published:** 1 July 2024

Citation: Wang, J.H., 2024. A Catalogue of Historical and Instrumentally-Recorded $M_s \geq 7$ Earthquakes in Taiwan. *Earth and Planetary Science.* 3(2): 41–59. DOI: https://doi.org/10.36956/eps.v3i2.1061

DOI: https://doi.org/10.36956/eps.v3i2.1061

complicated geological structures, thus leading to high seismicity in the region.

Since Japanese installed the first seismograph at Taipei in 1897, there has been instrumentally-recorded earthquake data for seismological studies. Numerous authors [1,6,7–13] observed that the spatial distribution and temporal variation of earthquakes in the Taiwan region are both inhomogeneous and irregular. This is caused by complex geological structures and tectonics in the region.

It is significant and important to investigate the properties of spatial distribution and temporal variation of large earthquakes in Taiwan, not only for academic interests [9] but also for seismic risk mitigation [13,14]. To reach the goals, it is necessary first to compile a complete catalog of earthquakes with magnitudes being larger than a certain value. There are several catalogues of Taiwan earthquakes, including historical events before 1897 and instrumentally-recorded ones after 1897. According to Hsu [15], Hsu [16] reported twenty-seven historical earthquakes from 1644 to 1882 and Tsai [17] estimated the magnitude values (6.0–7.7) of eleven historical disastrous earthquakes from 1683 to 1895. Their catalogues are not complete for historical earthquakes and the magnitudes estimated by Tsai [18] have high uncertainties.

For instrumentally-recorded earthquakes, Hsu [6] reported the disastrous events from 1900 to 1960. Hsu [1] published the first catalogue of earthquakes with $M_H \geq 4$, where M_H is Hsu's magnitude [18,19], from 1936 to 1967. Seventy-four post-1936 $M_H \geq 5$ earthquakes are also included in Hsu's catalogue. Hsu [20] published a revised catalogue for $M_H \geq 4$ earthquakes from 1936 to 1979. Included also are some large earthquakes, i.e., documented historical events from 1644 to 1896 and instrumentally-recorded events from 1900 to 1936. Li [21] published a catalogue consisting of earthquakes with magnitudes ≥ 5. Cheng and Yeh [22] published a catalogue consisting of historical earthquakes from 1604 to 1897 and instrumentally-recorded $M_H \geq 4$ events from 1898 to 1988. Their catalogue is mainly composed of the events of Hsu's catalogue and those published in the catalogue of the Institute of Earth Sciences (IES), Academia Sinica. In their catalogue, the magnitude scales reported in the respective original catalogues have been transferred into the local magnitude, M_L, measured by the Central Weather Administration (CWA) [23] through the conversion formulas inferred by them. In addition, several international earthquake catalogues also include Taiwanese events. The details can be seen in Wang [19]. Wang and Kuo [24,25] collected the data for large earthquakes assigned by different magnitudes from both domestic and international catalogues. They transferred the different magnitude scales to the surface-wave magnitude, M_s, based on the conversion equations between M_s and other magnitude scales inferred by Wang and his co-author [19,20]. Wang and Kuo [24] compiled a catalogue including forty-four $M_s \geq 7$ earthquakes from 1900 to 1995. Cheng et al. [26] compiled a catalogue of disastrous earthquakes from 1736 to 2000. Chen and Tsai [27] compiled a catalog of earthquakes with $M_w \geq 5.5$ (where M_w is the moment magnitude as mentioned below) from 1900 to 2006.

Hanks and Kanamori [28] proposed a new magnitude scale, i.e., the moment magnitude M_w, to quantify earthquakes. For Taiwan earthquakes, Chen et al. [29] studied the correlations between M_w and other magnitude scales; while Theunissen et al. [30] correlated M_w to M_s. Several authors [30,31] measured or re-evaluated the values of M_w for Taiwan earthquakes. Theunissen et al. [30] compiled a catalogue of earthquakes with $M_w \geq 7$ from 1920 to 2006. Since Wang and Kuo [25] compiled their catalogue, five $M_s \geq 7$ earthquakes which will be described below have occurred in the Taiwan region. Hence, it is necessary to re-compile a new catalogue for $M_s \geq 7$ Taiwan earthquakes from 1900. For this new catalogue, the magnitude scales include both the surface-wave magnitude, M_s, and the moment magnitude, M_w.

In this article, we will mainly focus on six issues: (1) re-compilation of a catalogue of earthquakes with $M_s \geq 7$, including historical events and instrumentally-recorded ones, from Wang and Kuo [24] and other literature; (2) evaluations of the values of M_w for all events; (3) a comparison between M_s and M_w; (4) the spatial distribution of earthquakes; (5) the time series of earthquakes; and (6) earthquake-induced damage. In addition, we will also review and discuss previous studies (including fractality, the memory effect, and the factors influencing spatial distribution of damage) about the $M_w \geq 7$ earthquakes in Taiwan.

2. Data

2.1 Historical Earthquakes

From historical documents compiled by Hsu [16], several authors [1,6,16–18,31] studied historical earthquakes before 1897. The earthquake magnitudes were not estimated in the literature [1,6,16,17,31]. For historical earthquakes, the magnitudes cannot be determined because there were not any seismograms in Taiwan before 1897. Hence, Tsai tried to estimate the magnitude of an event just by comparing its spatial pattern of damage and that caused by a post-1900 event whose location was near the historical one. When the damage patterns of the two events are similar, he took the magnitude of the post-1900 event to be that of the historical one. Of course, there are some problems with this method. The number of buildings, building structures, etc. in the pre-1900 era should be different from those in the post-1900 era. These reasons will influence the estimation of the magnitude of a historical event. Nevertheless, he estimated the magnitude values of eleven historical earthquakes. Seven of them with $M_s \geq 7$ are taken into account in this study. These events are numbered by 'a', 'b', ..., and 'g' as listed in Table 1. Included also in the table is the damage, including the number of people killed, the number of injured, the number of houses collapsed, and the number of houses damaged, caused by the seven historical earthquakes. Cheng and his co-authors [23,26] also compiled numerous historical earthquakes with damage in their catalogues.

2.2 Instrumentally-Recorded Earthquakes

The instrumentally-recorded earthquakes in Taiwan have been reported since 1897 when Japanese installed the first seismometer at Taipei [9]. A simple history of seismic observations is described in Appendix. Since Gutenberg and Richter [32] proposed the surface-wave magnitude, M_{GR}, the magnitudes of global earthquakes, including Taiwan's larger-sized events, have been routinely determined by numerous governmental agencies, for example, the United States Geological Survey (USGS). The magnitude scales of Taiwanese earthquakes have been studied by numerous researchers. Kawasumi [33] first suggested the intensity magnitude of earthquakes in Japan and Taiwan. However, Wang and his coauthors [34] assumed that this magnitude is not appropriate for Taiwan earthquakes. The Japan Meteorological Agency (JMA, formerly Central Meteorological Observatory, CMO) routinely determined the magnitudes of earthquakes in Japan and some larger earthquakes in Taiwan based on the formula obtained by Tsuboi [35]: $M_J = \log A + 1.731\log\Delta - 0.83$ where A is either the larger value of the maximum amplitudes along two horizontal-component seismograms or the composite value of the two maximum amplitudes in μm and Δ is the epicentral distance in km. Hsu [1,21,36] determined the magnitudes of Taiwan earthquakes from 1934 to 1972 using the data observed by the Central Weather Bureau (CWB) (now the Central Weather Administration, CWA) based on the following formula: $M_H = \log A + 1.09\log\Delta + 0.50$. Clearly, M_H is different from M_J. Hsu did not determine the magnitudes of pre-1934 instrumentally-recorded earthquakes due to two reasons. The first reason is that the seismic stations were very few before 1934. The second one is that the pre-1934 old seismograms were not good enough and some of them were disturbed or lost during the Second World War. Hence, Hsu quantified the pre-1934 Taiwan earthquakes just by taking their magnitudes from other international catalogues, for example, the catalogue made by Duda [37].

The current surface-wave magnitude, M_s, is measured from the seismograms based on the Prague formula [38]: $M_s = \log(A/T) + 1.66\log(\Delta) + 3.3$ where A is the vector sum of the maximum amplitudes in microns with a period, T, at 20 ± 2 sec along two horizontal components, and Δ is the epicentral distance in degree.

Wang and Kuo [24] compiled a complete catalogue for earthquakes with magnitudes ≥ 7 from 1900 to 1986 based on several domestic catalogues [1,21,23,36] and international ones [37,39–47]. Wang and Kuo [24] collected the magnitude values reported in several catalogues for pre-1967 earthquakes and took the values of M_s directly from the Earthquake Determination Report by USGS for the post-1967 events. In order to unify the magnitude scales reported in different catalogues to the commonly-used surface-wave magnitude, M_s, for pre-1967 earthquakes, they applied the conversion equations between M_s and other magnitude scales inferred by Wang and his coauthor [19,20]. Hence, the resultant magnitude is equivalent to M_s. Forty-four $M_s \geq 7$ earthquakes reported by Wang and Kuo [24] are the base data of this study and listed in Table 1 where the events are counted from No. 1 to No. 44. A detailed description of some of the large earthquakes can be found in two articles [9,26].

After the publication of Wang and Kuo's catalogue [24], five $M_s \geq 7$ earthquakes happened in the Taiwan region. The five earthquakes are (1) the September 20 (local time September 21), 1999 M_s 7.7 Chi-Chi earthquake [48,49], (2) the March 31, 2002 M_s 7.1 offshore Hualien earthquake [50], (3) the December 26, 2006 M_s 7.1 Pingtung earthquake [51,52], (4) the September 18, 2022 M_w 7.0 or M_L 6.8 Chihshang earthquake [53], and (5) the April 2 (local time April 3), 2024 offshore Hualien earthquake [54]. The 1999 Chi-Chi earthquake caused serious damage in Taiwan. The 2002 offshore Hualien caused some damage in Taipei which is about 150 km far away from the epicenter [55]. The 2006 Pingtung earthquakes caused damage in the local area and were the "doublets" whose second event was M_s = 6.9 occurred about 8 minutes after the first one. The epicentral distance between the two events was 66 km. Hence, only the first event is considered in this study. The M_L 6.8 Chihshang earthquake occurred in eastern Taiwan on September 18, 2022. Its epicenter determined by the CWA from its seismological network is located at 23.137° N and 121.196° E with a focal depth of 7.8 km. The USGS only determined its moment magnitude of M_w = 7.0. Based on equation (3), its surface magnitude is M_s = 7.4. The 2024 M_L7.2 offshore Hualien earthquake caused serious damage in Hualien and some areas. Its epicenter determined by the CWA is located at 23.77 °N and 121.67 °E with a focal depth of 15.4 km and its local magnitude is M_L = 7.2 (see CWA). The USGS determined its moment magnitude of M_w = 7.4. The five earthquakes are numbered, respectively, as Nos. 45, 46, 47, 48, and 49 in Table 1. Hence, total of forty-nine instrumentally-recorded earthquakes with M_s = 7.0 – 8.1 occurred from 1900 to date. Related earthquake data are listed in Table 1.

Kanamori and his co-author [28,56] defined the moment magnitude, M_w, of an earthquake as equation (1):

$$M_w = (2/3)\log(M_o) - 10.7 \tag{1}$$

where M_o is the seismic moment with a unit of dyne-cm or Nt-m [57]. Theunissen and his co-authors [30] compiled a catalogue of twenty-six Taiwan earthquakes with $M_w \geq 7$ based in three ways: (1) to calculate the values of M_w from those of M_o which were measured by Chen and his co-authors [31]; (2) to take the values M_w directly from the global central moment tensor (GCMT) catalogue; and (3) to calculate the values of M_w from those of M_s which were reported by Wang and Kuo [24]. From the seismograms recorded at the global seismic network, Chen and his co-authors [31] evaluated the seismic moments for four large earthquakes: M_o = 100.0 × 10^{25} dyne-cm for the February 13, 1963 earthquake with M_s = 7.3; M_o = 486.0 × 10^{25} dyne-cm for the March 12, 1966 earthquake with M_s = 7.9; M_o = 134.0 × 10^{25} dyne-cm for the January 25, 1972 earthquake with M_s = 7.2; and M_o = 16.4 × 10^{25} dyne-cm for the April 24, 1972 earthquake with M_s = 7.0. Hence, based on equation (1), the values of M_w are 7.3 for the February 13, 1963 earthquake, 7.8 for the March 12, 1966 earthquake, 7.4 for the January 25, 1972 earthquake, and 6.8 for the April 24, 1972 earthquake. In addition, Theunissen and his co-authors [30] took the values of M_w = 7.2, 7.0, 7.3, 7.6, and 7.1, respectively, for the events with Nos. 42, 43, 44, 45, and 46 as listed in Table 1 from the GCMT catalogue. For the rest events, they calculated the values of M_w from those of M_s which were reported by Wang and Kuo [24] through the conversion equation between M_w and M_s inferred by them. These values are listed in Table 1. For other events, we calculated the values of M_w from those of M_s as listed in Wang and Kuo [24] based on equation (3) and results are also included in Table 1.

Obviously, the value of M_w for the April 24, 1972 earthquake is smaller than 7.0. However, Theunissen and his co-authors [30] reported M_w = 7.0 for this event based on the values of M_o measured by Chen and his co-authors [31]. We must examine the problem in an alternative way. Chen and his co-authors [29] inferred the conversion relationship between M_o and M_s as equation (2):

$$\log(M_o) = (1.07 \pm 0.04)M_s + (18.72 \pm 0.20) \tag{2}$$

A combination of equations (1) and (2) lead to $1.5(M_w + 10.7) = 1.07M_s + 18.72$ or equation (3)

$$M_w = 0.71M_s + 1.78 \tag{3}$$

From Table 1, the value of M_s for the April 24, 1972 earthquake is 7.0, thus leading to M_w = 6.8 based on equation (3). On the other hand, Theunissen and his co-authors [31] inferred the following M_w–M_s conversion equation (4):

$$M_w = 0.7925M_s + 1.2853 \pm 0.1860 \tag{4}$$

From this equation, M_w is 6.8 for this event. The two results confirm that the value of M_w for this event is 6.8 rather than 7.0. Hence, M_w = 7.0 for this event as reported by Theunissen and his co-authors [30] should be revised.

For the April 2, 2024, offshore Hualien earthquake, its value of M_w determined by the USGS is 7.37. Hence, the surface magnitude is M_s = 7.87 based on equation (3) and M_s = 7.68 based on equation (4). The average value is 7.82. Here, we take the value of 7.8 as the surface-wave magnitude to quantify this earthquake. According to this value, the 2024 offshore Hualien earthquake is slightly larger than the 1999 Chi-Chi earthquake.

Several authors [22,46,58–63] relocated or revised the locations of some of the forty-eight events. Their results have been here taken to replace the original ones as listed by Wang and Kuo [24]. However, the focal depths of several pre-1940 events are still unknown. The crust-upper mantle boundary with v_p = 7.5 km/s in the Taiwan region is mainly in the range of 35–45 km as inferred by several groups of researchers [64–68]. 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. The results show that $M_s \geq 7$ earthquakes are mainly crustal events.

There is a debatable problem concerning whether or not the March 17, 1906 Meishan earthquake [69,70] was an event with $M_s \geq 7$. Since 1900, this earthquake has been the most disastrous one in southwestern Taiwan [26]. It was located at (120.5 °E and 23.6 °N) and reported as 'shallow focal depth' by Hsu [1]. However, Gutenberg and Richter [39] and Wang and Kuo [24] did not include this earthquake in their catalogues. The magnitude values of this event reported by numerous researchers are $M_{DU} = 7.1$ [37], $M_H = 7.1$ [1,45,46], and $M_U = 7.1$ [47,48]. The magnitude values reported by the four groups of researchers are the same because the values reported by the last three groups were just taken from the first one. On the other hand, from old seismograms Abe and his coauthors [40–44] obtained $M_s = 6.8$ and $m_B = 6.9$ for this event. The revised value of M_s is smaller than 7. This is the reason why Wang and Kuo [25] did not include this event in their catalogue. Field geological surveys show that the Meishan fault is a strike-slip fault with a length of 25 km [71]. From the expression [72]: $\log(L_s) = (-3.55 \pm 0.37) + (0.74 \pm 0.05)M_s$ where L_s is the surface rupture length for strike-slip faults, the magnitude is $M_s = 6.7$ for $L_s = 25.0$ km. This estimated value is similar to $M_s = 6.8$ measured by Abe and his co-author [44]. Consequently, the magnitude of the event should be $M_s = 6.8$ which gives $M_H = 6.74$ based on the conversion equation: $M_s = (-0.95 \pm 0.31) + (1.15 \pm 0.05) M_H$ [20]. Hence, this earthquake is not included in the catalogue of this study because of $M_s < 7$.

3. Results

Table 1. The earthquake data (date, epicenter, focal depth, H, and magnitude, M_w and M_s): 7 historical events denoted by 'a' to 'g' and 49 recent events numbered from 01 to 49. M_w inside '( )' is calculated from M_s using equation (3); M_w inside '[ ]' is computed from M_o evaluated by Chen and his co-authors [31]; and M_w inside '< >' is taken from the GCMT catalogue. The value of M_s of No. 49 event was calculated from M_w. (Hazards: the number of deaths, the number of injuries; the number of houses collapsed, the number of houses damaged).

No	Date (Animal Year)	Lat. (°N) Long. (°E)	H (km)	M_s (M_w)	Deaths	Injuries	Collapse Houses	Damaged Houses	Remarks
a	17920809	23.6 120.5		7.1	617	781	24621		
b	18110317	23.8 121.8		7.5	21	16	41	14	
c	18151013	24.0 121.9		7.7	113	2	243		
d	18480212	24.1 120.5		7.1	1030	many	4220		
e	18620607	23.2 120.2		7.0	> 500	> 1000	> 500		
f	18671218	25.3 121.7		7.0	hundreds			many	
g	18821209	23.0 121.4		7.5	10			> 40	
01	19060619	20.0 122.0		7.1 (6.8)					
02	19090414	25.0 121.5	75.0	7.1 (6.8)	9	51	122	1050	
03	19091121	24.4 121.8	10.0	7.1 (6.8)		4	14	39	
04	19100412	25.1 122.9	200.0	8.1 (7.5)			13	59	
05	19100617	21.0 121.0		7.1 (6.8)					
06	19100901	21.0 122.0		7.1 (6.8)					

Table 1 continued

No	Date (Animal Year)	Lat. (°N) Long. (°E)	H (km)	M_s (M_w)	Deaths	Injuries	Collapse Houses	Damaged Houses	Remarks
07	19150105	24.4 123.2	160.0	7.1 (6.8)					
08	19150228	23.6 123.5		7.5 (7.1)					
09	19160325	24.0 124.0		7.2 (6.9)					
10	19170704	25.0 123.0	20.0	7.4 (7.0)					
11	19170704	25.0 123.0	30.0	7.0 (6.75)					
12	19191220	22.5 121.4	24.0	7.2 (6.9)					
13	19191220	22.5 121.4	35.0	7.1 (6.8)					
14	19200605	24.0 122.0	35.0	8.1 (7.5)	5	20	273	1275	
15	19210402	22.6 123.4	35.0	7.4 (7.0)					
16	19220901	24.6 122.2	35.0	7.7 (7.2)	5	7	14	161	
17	19220914	24.6 123.3	35.0	7.3 (7.0)		5	24	389	
18	19250416	20.4 120.2		7.2 (6.9)				minor	
19	19350420	24.3 120.8	10.0	7.2 (6.9)	3276	12053	17907	36781	faults, surface deformations, landsides, collapse of ground
20	19350904	22.5 121.5	20.0	7.3 (7.0)				114	
21	19360821	22.0 121.2	50.0	7.2 (6.9)		14	37	341	
22	19371208	23.1 121.4		7.1 (6.8)			7	140	
23	19380907	23.8 121.8	10.0	7.1 (6.8)				minor	
24	19381206	22.9 121.6	10.0	7.2 (6.9)					
25	19411216	23.4 120.5	15.0	7.2 (6.9)	358	733	4520	11086	landsides
26	19470926	24.8 123.0	110.0	7.6 (7.2)					
27	19511021	23.8 121.7	4.0	7.4 (7.0)	68	586		2382	fissures, landslides
28	19511021	24.1 121.8	1.0	7.2 (6.9)					
29	19511022	23.8 121.9	18.0	7.2 (6.9)					
30	19511124	23.3 121.4	36.0	7.4 (7.0)	20	326	1016	582	fissures, landslides
31	19570223	23.8 121.8	30.0	7.4 (7.0)	11	33	64	100	

Table 1 continued

No	Date (Animal Year)	Lat. (°N) Long. (°E)	H (km)	M_s (M_w)	Deaths	Injuries	Collapse Houses	Damaged Houses	Remarks
32	19580311	25.0 124.0	70	7.0 (6.75)					
33	19590426	25.0 122.5	126.5	7.9 (7.4)	18	71	1249	1449	
34	19630213	24.4 122.1	35.0	7.3 [7.2]	15	3	6	6	
35	19640118	23.2 120.6	33.0	7.0 (6.75)	106	650	10520	25818	
36	19650517	22.5 121.3	21	7.0 (6.75)					
37	19660312	24.1 122.6	28.9	7.9 [7.5]	7			minor	
38	19680226	22.7 121.3	24.0	7.1 (6.8)					
39	19720125	22.5 122.3	10.0	7.4 (7.0)					
40	19720125	23.0 122.3	40.0	7.2 [7.3]					
41	19720424	23.5 121.5	15.4	7.0 [6.75]	5	17	28	62	fissures, collapse of a large bridge and a tunnel
42	19780723	22.2 121.3	6.3	7.3 <7.2>				minor	
43	19781223	23.3 122.3	48.0	7.0 <7.0>	2	3		2	
44	19861114	23.9 121.6	34.0	7.8 <7.3>	15	44	1	few	
45	19990920	23.9 120.8	8.0	7.7 <7.6>	2489	12031	54406	51753	faults, fissures, landslides, liquefaction, collapse of bridges and water dams
46	20020331	24.1 122.1	16.5	7.1 <7.1>	5	1	1	160	
47	20061226	21.6 120.6	44.0	7.1 (7.1)	2	44	3		ruptures of submerged communications cables
48	20220918	23.1 121.2	7.8	7.4 <7.0>	1	79		many	landslides, damage of bridges
49	20240402	23.77 121.67	15.4	(7.8) 7.37	17	1155	5	> 1366	landslides, collapse of roads and bridges, local electric and gas supply system ruptured

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. The focal depths of some pre-1938 events cannot be estimated due to insufficient data. The epicenters of forty-nine instrumentally-recorded events and seven historical events are plotted in Figure 1 with different symbols: open red circles for the events with $H \leq 40$, solid red circles for those with $H > 40$ km, open green squares for those whose focal depths have not yet been estimated, and open blue triangles for seven historical events. The numbers from 1 to 40 for the events that occurred after 1900 and the indices from 'a' to 'f' for historic ones are also displayed inside each symbol.

Figure 2 shows the time series of earthquakes represented by M_s in the time domain (with a unit of day). The shortest inter-occurrence time between two events is less than 1 day; while the longest one which was between the No. 47 event and the No. 48 one is 5742 days. Since a few events occurred in a short time interval, the line segments representing them are close to one another and thus cannot be clearly separated. From Table 1, the year having the largest number of events is 1951.

The damage caused by some of the forty-nine earthquakes is compiled from numerous literature [1,6,14,16,17,21,26,29,31,54,73–75] and local governmental reports [76]. The results are listed in Table 1 in which there are the number of deaths, the number of injuries, the number of houses collapsed or seriously damaged, and the number of houses damaged.

4. Review of Previous Studies and Discussion

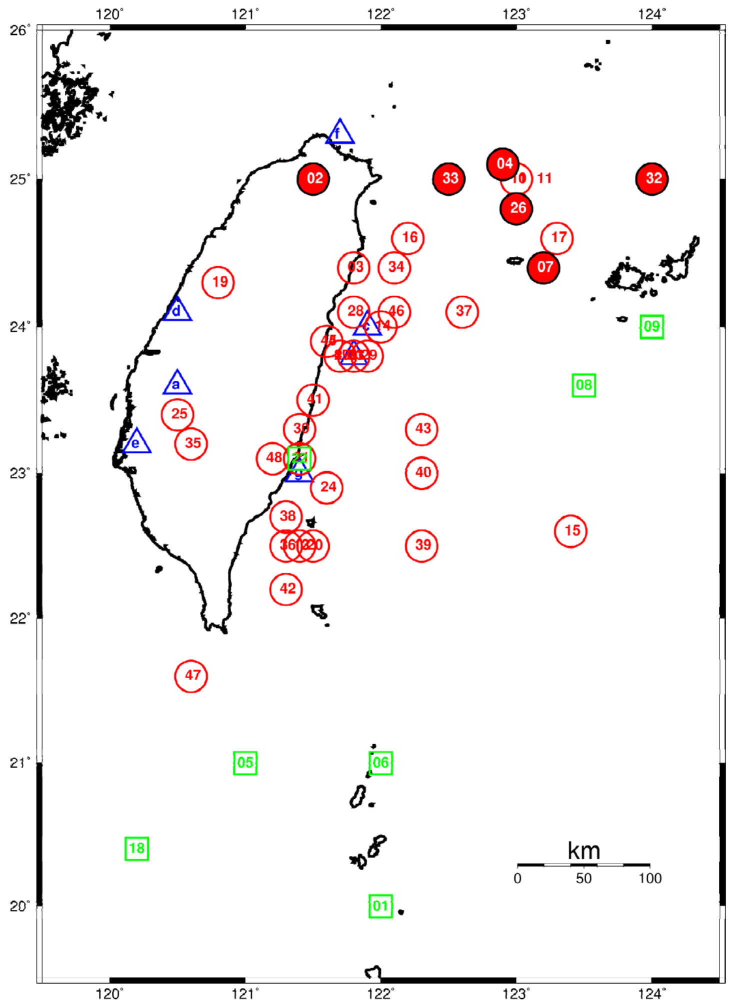

Figure 1. Epicenters of $M_s \geq 7$ earthquakes in the Taiwan region (from 118 °E to 125 °E and 20 °N to 26 °N): Open red circles for shallow events, solid red circles for deep events, open green squares for the events without focal depths, and open blue triangles for historical events.

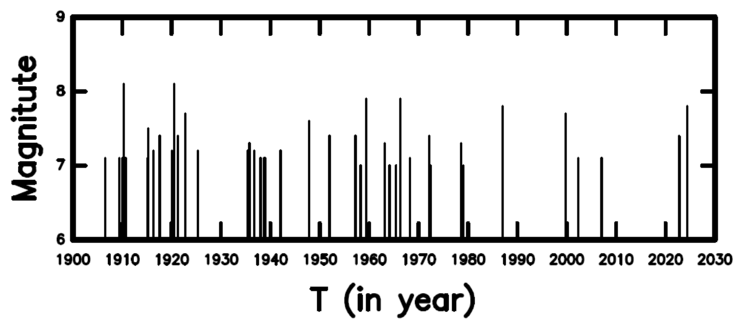

Figure 2. Time series of magnitudes of forty-nine instrumentally-reported $M_s \geq 7$ earthquakes from 1900 to date.

In the following, we will review the previous studies and discuss five topics: (1) M_w versus M_s for Taiwan earthquakes; (2) Mainshock problem; (3) Spatial distribution of earthquake epicenters; (4) Time series of earthquakes; and (5) Damage caused by earthquakes. The fourth topic includes four issues: (a) 'Is the time series of earthquakes periodic or aperiodic?'; (b) 'Is the time series of earthquakes fractal?'; (c) 'Does the memory effect exist in the time series of earthquakes?'; and (d) 'How are the occurrence times of earthquakes distributed in the twelve months of a calendar year?' The five topics are discussed below.

4.1 M_w Versus M_s for Taiwan Earthquakes

From Table 1, we can see that the values of M_w calculated from both equation (3) and the M_w–M_s relationship inferred by Theunissen and his co-authors [30] are smaller than those of M_s. The values of M_w calculated from those of M_o that was measured from global seismograms by Chen and his co-authors [31] are smaller than those of M_s for three events, i.e., Nos. 34, 37, and 41, and larger than that for an event numbered No. 40. Consequently, except for No. 40 the values of M_w either calculated from those of M_o or directly taken from the GCMT catalogue are all smaller than or equal to those of M_s. That M_w is not larger than M_s is a significant problem for Taiwan earthquakes.

From observations, Gutenberg and Richter [77] inferred the Gutenberg-Richter E_s–M_s relationship as the equation (5):

$$\log E_s = 1.5M_s + 11.8 \tag{5}$$

where E_s is the seismic radiation energy in ergs. The magnitude scale of the equation (5) was originally the Gutenberg-Richter surface-wave magnitude, M_{GR}, and at present is the commonly-used surface-wave magnitude, M_s. From the scaling law of displacement spectra of earthquake sources [78], the value of A may be saturated when the earthquake size is larger than a critical value. Hanks and Kanamori [28] emphasized that if M_s is saturated, E_s as calculated from equation (5) should be bounded for large earthquakes. This will yield underestimates of E_s for large earthquakes, especially for great ones.

Let ΔE be the strain energy of an earthquake which is the difference in the elastic strain energy before and after an earthquake. Hanks and Thatcher [79] first suggested that a magnitude scale based directly on an estimate of ΔE would prevent the problem of characterizing earthquake source strength from magnitude saturation due to narrow-band time domain amplitude measurements. The seismic radiation energy, E_s, is equal to $\eta\Delta E$, which η is the seismic efficiency and is commonly smaller than or equal to 1 [56,80–81]. When the stress drop is complete during an earthquake rupture, Kanamori [56] proposed a way to measure ΔE from the seismic moment based on the relation, see equation (6):

$$\Delta E = (\Delta\sigma/2\mu)M_o \tag{6}$$

where $\Delta\sigma$ is the earthquake stress drop and μ is the shear modulus. In this situation, ΔE equals E_s because of $\eta = 1$. For shallow earthquakes whose stress drops are almost constant in the range of 20–60 bars or (2–6) × 10^7 dyne/cm^2 [28,56,82,83], equation (6) may be reduced to be equation (7):

$$E_s = \Delta E = 2 \times 10^{-4}\, M_o \tag{7}$$

because of $\mu = (3–6) \times 10^{11}$ dyne/cm^2 [56]. Hanks and Kanamori [28] proposed that if E_s is evaluated directly from equation (7), it may be placed on the left-hand side of equation (5) to determine a non-saturated magnitude, i.e., the moment magnitude, M_w, as described by equation (1). Hence, M_w is based directly on the seismic moment, M_o, of an earthquake source. equation (1) coincides with the M_o–M_s relationship [84]: $\log(M_o) = 1.5M_s + (16.1 \pm 0.1)$ for earthquakes with $5.0 \le M_s \le 7.5$. This assumes that M_w is quite similar to M_s for a number of earthquakes with $M_s < 8$. But for $M_w > 8$ the value of M_s would be saturated and could not increase with earthquake size. Under this physical basis, M_w should be almost equal to M_s for $M_w < 8$ and larger than M_s for $M_w \ge 8$.

However, Table 1 shows the opposite result that M_w is smaller than M_s for most of the earthquakes in this study. This problem can first be examined by equation (3) and equation (4). The two relations lead to $M_w < M_s$ for $M_s > 6.1$. This means that the equality of $M_w = M_s$ as addressed by Kanamori and his co-author [28,56] does not exist for both shallow and deep earthquakes with $M_s > 6.1$ in Taiwan. Except for two events, i.e., Nos. 04 and 14 with $M_s = 8.1$, the saturation problem of measuring M_s from seismograms as mentioned above essentially does not exist for Taiwan earthquakes. This seems to suggest that the surface-wave magnitude, M_s, is more appropriate than the moment magnitude, M_w, to quantify large earthquakes with $7.0 \le M_s \le 8.1$ in Taiwan. The main reason for yielding larger M_s than M_w could be the difference between the displacement spectra of Taiwan earthquakes and theoretical ones. The value of M_s is determined from the amplitudes of surface waves at 20 ± 2 seconds; while that of M_o is done from the amplitudes of long-period surface waves and normal modes, geodetic data, or geological data [85]. The scaling law of displacement spectra of earthquake sources [74] reveals the changes in spectral amplitude with earthquake size. This will influence the measure of M_o. Chen and his co-authors [86] showed that the seismic moments of Taiwan earthquakes evaluated from a regional broadband array are in general smaller than those reported in the GCMT catalogue. This is due to the reason that the displacement amplitudes at shorter periods used for determining M_o by the regional broadband array are smaller than those at longer periods used in the GCMT catalogue. Clearly, the displacement amplitude or the related wave period is an important factor in influencing the evaluated value of M_o. From the scaling law of source displacements proposed by Aki [79], the displacement amplitudes at different periods are almost the same when the periods are longer than the corner period. This theoretical result might be inconsistent with observations of the Taiwan earthquakes. A simple way to explore the difference between M_s and M_w is to examine the possible differences in displacement amplitudes at distinct periods of Taiwan earthquakes. Since the number of Taiwan earthquakes whose displacement spectra are available is still small at present, this problem will be studied in the future.

4.2 Mainshock Problem

Based on Table 1, it is natural to ask whether or not all large earthquakes in the study are mainshocks. According to Båth's law [87,88], the magnitude of largest the aftershock is about 1.2 smaller than that of the mainshock. For Taiwan earthquakes, Chen and Wang [89] found that the magnitude difference, δM_s, between the mainshock and the largest aftershock slightly increases with the mainshock magnitude, M_s, and varies from 0.1 to 2.2, with two values of 0.3 and 0.9, which has the largest number of events. The mean value of δM_s is 0.83 ± 0.46. The differences of occurrence time and epicenter between the mainshock and the largest aftershock do not clearly correlate to M_s as well as δM_s. Hence, an $M \geq 8$ earthquake could be followed by one or few $M \geq 7$ aftershocks; while an $M \geq 7$ earthquake would will be followed by one or few $M \geq 6$ aftershocks. Only two $M_s \geq 8$ earthquakes occurred in Taiwan and no $M_s \geq 7$ aftershocks followed the two mainshocks. Since the events with $M_s < 7$ are not considered in this study, all $M_s \geq 7$ earthquakes in Table 1 are the mainshocks. The largest number of events occurring in one year is 4 in 1951.

Table 1 shows the existence of several special pairs of events. For each pair, the epicenters of two events are close to each other, the epicentral distance between them is shorter than a certain value, the inter-occurrence time between them is short, and the difference in their magnitudes is very small. We consider three criteria for selecting a pair. First, the epicentral distance is shorter than 110 km. The reason to take 110 km as a criterion is based on the fault length of the 1999 M_s7.6 Chi-Chi, Taiwan, earthquake. The fault length was about 100 km [50]. Since the uncertainty of earthquake location was high before 1967 as mentioned above, I take 110 km, which is about a degree of latitude or longitude, instead of 100 km to be the threshold epicentral distance. Secondly, the inter-occurrence time is shorter than 100 days. Chen and Wang [89] found that for $M \geq 5$ earthquakes in Taiwan, the largest difference between the occurrence time of a mainshock and that of its largest aftershock is about 100 days. Hence, I take 100 days to be the criterion of inter-occurrence time. 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, we can see five types of events, i.e., Nos. 5 and 6, Nos. 10 and 11, Nos. 12 and 13, Nos. 16 and 17, and Nos. 20 and 21. The two earthquakes of each pair form the "doublet." Three sequential earthquakes, i.e., Nos. 39, 40, and 41, which occurred offshore eastern Taiwan in 1972, form the 'triplet.' They were the largest three events of the 1972 Ruisui earthquake sequence [50]. Four sequential earthquakes, i.e., Nos. 27, 28, 29, and 30 which occurred offshore eastern Taiwan in 1951, form the "quadruplet." They were the largest four events of the 1951 Hualien-Taitung earthquake sequence [90,91]. Each event of 'doublets,' 'triplets,' and 'quadruplets' is considered to be a separate one in this study. Although the epicentral distance between No. 7 and No. 8 is shorter than 110 km, they are not considered as a 'doublet.' This is due to a reason that No. 7 is a deep event and the focal point of 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 'doublet' occurred in 2006 [52]. Since the value of M_s for the second event is slightly smaller than 7.0, only the first one, i.e., No. 47, is taken into account in this study.

4.3 Spatial Distribution of Earthquake Epicenters

Figure 1 shows that most of the post-1900 events were located offshore in east Taiwan; while only a few of them occurred inland and in west Taiwan. Except for No. 2, i.e., the 15 April 1909 Taipei earthquake [63,92], five deep earthquakes that occurred in northern Taiwan were within the northward subducted slab of the Philippine Sea plate and two deep events that happened in southern Taiwan were within the eastward subducted slab of the Eurasian plate. An intermediate-depth earthquake, i.e., Event No. 43, occurred in the Huatung Basin within the Philippine Sea plate. This event was conducted by the Taiwan Telemetered Seismographic Network (TTSN) [93]. 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., Nos. 1, 5, and 18, could occur in the slab of the Eurasian plate which has subducted from west to east in southern Taiwan.

Among the seven historical earthquakes, three inland events occurred in western Taiwan, one offshore event in northern Taiwan, and three events in or near the East Coastal Range. It is obvious that not any large event which occurred far away from Taiwan Island was reported by Tsai [4]. This is due to the lack of a report of damage observed on the island in the historical documents.

4.4 Time Series of Earthquakes

Periodicity or Aperiodicity

Numerous researchers addressed irregular recurrence behavior, thus being aperiodic, for earthquakes in different tectonic provinces. Some examples are shown below. Based on seven instrumentally-recorded earthquake catalogues, Kagan and Jackson [94] found irregular recurrence behavior for earthquakes. Goes [95] analyzed 52 time series of complete historical and paleoseismic earthquakes with magnitudes ≥7 in the Middle American Trench, Alaska, Chile, Japan, and the San Andreas fault, California. Results show irregular recurrence behavior for the time series of earthquakes in the study. Numerous authors [96–98] reported irregular recurrence behavior of paleoseismic earthquakes on the Chelungpu fault along which the 1999 M_s7.6 Chi-Chi earthquake ruptured. From geological and historical evidence, Satake [99] addressed irregular recurrence behavior of Japanese earthquakes.

Figure 2 clearly demonstrates that like the previous studies the time series of $M_s \geq 7$ large Taiwan earthquakes has irregular recurrence behavior, thus being aperiodic. The figure also shows that some earthquakes with short inter-occurrence times form a cluster and those with long inter-occurrence times separate very well. This seems to agree with the assumption proposed by Davis and his co-authors [100]. Their assumption is that the longer it has been since the last earthquake, the longer the expected time till the next. In addition, the degree of clustering remarkably decreases with increasing time. Figure 3 displays the inter-occurrence time between two consecutive events versus the event number. The inter-occurrence time almost increases with time and its time variation can be divided into three time intervals: the first one from No. 1 to No. 17, the second from No. 18 to No. 40, and the third one from No. 41 to No.49. The average inter-occurrence time is 895.7 days, 404.2 days, 746.2 days, and 2369.9 days, respectively, for the whole time interval, the first one, the second one, and the third one. The average inter-occurrence times obviously increases with time. The average inter- occurrence time for the whole time interval is longer than that for the first time interval and shorter than those for the second and third time intervals. This reveals indirect evidence of irregular recurrence behavior with aperiodicity of the earthquake sequence. Since the reasons for 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 ≥7 large earthquakes in Taiwan.

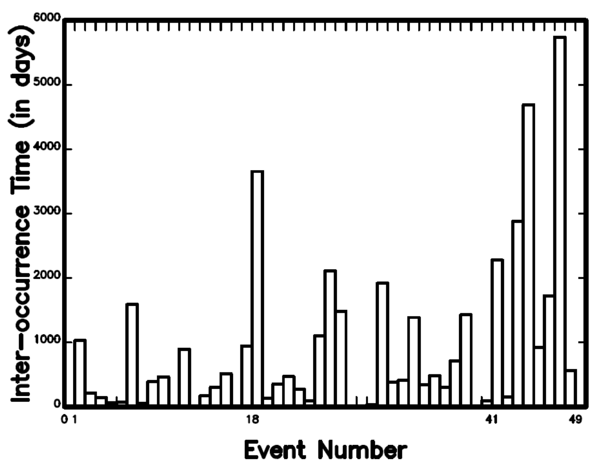

Figure 3. The inter-occurrence time (in days) between two consecutive events from No. 1 to No. 49.

Fractality

Self-similarity or scale-invariance is a fundamental property of natural phenomena or objects. In the 1950's, a mathematician Benoit B. Mandelbrot proposed the concept of fractal geometry with fractal dimension to describe the self-similar or scale-invariant natural phenomena [101]. Since he [102] measured the fractal dimensions for geophysical problems, fractal geometry has been widely applied to seismology [103]. For Taiwan earthquakes, fractal geometry has been used to describe earthquake phenomena, including the time series and spatial distributions of earthquakes [104–109].

For the time series of forty-four earthquakes from No. 1 to No. 44, Wang [110] measured its multifractal dimensions. His results show the existence of multifractality in the time series of M_s ≥7 earthquakes in the Taiwan region. This conclusion should be held for the present time series of forty-nine earthquakes.

Memory Effect

In order to understand long-term variation in earthquakes, earthquake prediction, and seismic risk estimates, it is necessary and important to explore the 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. It is very common to consider that in a time series of earthquakes, an event is totally uncorrelated to others. In other words, such a time series is 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 importance of the non-Poisson process on earthquake occurrences [111]. 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 for interpreting 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 weak. The detailed discussion of this problem can be seen by Wang and Kuo [25].

For the time series of forty-four earthquakes from No. 1 to No. 44, Wang and Kuo [25] studied the frequency distribution of inter-occurrence time between two events. Their results demonstrate that although the exponential function and gamma function can both describe the frequency distribution, the former is more appropriate than the latter. This indicates that the time series of earthquakes with M_s ≥7 was generated mainly by the Poisson processes. Wang [112] investigated the memory effect in the time series of forty-seven M_s ≥ 7 Taiwan earthquakes from No. 1 to No. 47 in this study through the fluctuation analysis. His results demonstrate that every two earthquakes of the time series is short-term corrected, thus leading to the existence of a short-term memory effect rather than a long-term one for M_s ≥ 7 Taiwan earthquakes. This implicates impossibility or low possibility of forecasting a long-term trend of occurrences of M_s ≥ 7 earthquakes in the Taiwan region.

Distributions of Events in Twelve Months

There are twelve months in a calendar year. It is important to understand the distribution of events in an individual month of a calendar 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 2. Results show that the occurrences of M_s ≥7 earthquakes are the most active in April and September, secondly active in December, and the least active in May and August in the past more than one hundred years.

Table 2. The number and percentage of events in terms of the month.

Month	Number	%
January	4	8.16
February	4	8.16
March	4	8.16
April	8	16.33
May	1	2.04
June	3	6.12
July	3	6.12
August	1	2.04
September	8	16.33
October	3	6.12
November	3	6.12
December	7	14.39

4.5 Damage Caused by Earthquakes

The survey of damage caused by earthquakes is commonly one of the important seismological subjects, not only for scientific studies but also for the public and the government. Included also in Table 1 are the simple reports of damage caused by earthquakes, including the number of deaths, the number of injuries; the number of houses collapsed, and the number of houses damaged. Since some events happened offshore, they did not cause damage or only caused minor damage in the inland area. It can be seen that more damage was caused by the earthquakes which occurred in western Taiwan than that done by the events which happened in eastern Taiwan. Cheng and his co-authors [26] also addressed the same point, not only for larger-sized earthquakes but also for smaller-sized ones.

We compare the damage between one event, i.e., No. 02 or the 15 April 1909 Taipei earthquake, and four events, i.e., Nos. 04, 07, 32, and 33. The five events are all deep ones and occurred on the northward subducted slab of the Philippine Sea plate. The first one occurred inland and was beneath the Taipei area, while others happened offshore. Table 1 shows that the damage caused by the first event was much higher than the total damage done by others. Two deep events, i.e., No. 21 and No. 22 that occurred on the eastward subducted slab of the Eurasian plate, produced only minor damage. In addition, numerous earthquakes that happened near or to the east of the eastern coast produced only small damage or even did not cause damage. On the other hand, two inland earthquakes (i.e., No. 19 and No. 45) which was the 1935 M_s7.3 Hsinchu-Taichung earthquake [1,21,36,113–115] and the 1999 M_s7.6 Chi-Chi earthquake [14,76], respectively, were disastrous. The faults on which the two earthquakes ruptured are mostly in the areas where there are cities and large towns with high population densities and a large number of buildings and civil structures. Consequently, the two earthquakes caused serious damage, especially on the western side of central Taiwan. Hence, since 1900, the two earthquakes have been the most disastrous ones in Taiwan. In addition, numerous inland earthquakes with $M_s < 7$ also produced remarkable damage. We may compare the damage between the 1999 M_s7.7 Chi-Chi earthquake that occurred in western Taiwan and the 2024 M_s7.8 offshore Hualien earthquake that happened in eastern Taiwan. Although their magnitudes are similar, the damage caused by the former is much higher than that done by the latter (see Table 1). In comparison between the damage caused by the 2024 Hualien earthquake and that done by the October 1951 Hualien earthquake sequence having three $M_s > 7$, the damage is smaller for the former than for the latter. This may be due to improvements in building design and technology from 1951 to date.

Three major reasons might result in the difference in damage between the earthquakes occurring in western Taiwan and those in eastern Taiwan. First, numerous earthquakes occurring in eastern Taiwan are offshore and thus houses, buildings, and civil structures are far away from the epicentral area where ground motions are usually high. Secondly, the number of houses, buildings, and civil structures is, on average, much larger in western Taiwan than in eastern Taiwan. Thirdly, geological surveys show that the sedimentary layers are commonly much thicker in western Taiwan than in eastern Taiwan [116]. Meanwhile, the seismic-wave velocities in the shallow depths are lower in western Taiwan than in other areas [64-69]. Low-velocity sedimentary layers can yield nonlinear effects [117–122], including strong site amplification, liquefaction, etc., which may strengthen the surface ground motions, thus being able to yield more damage. These three reasons might result in higher damage in western Taiwan than in eastern Taiwan.

Numerous researchers [123–125] observed that the *Q*-values of seismic-wave attenuation in Taiwan are the smallest in western Taiwan. The smallest *Q*-value will yield the highest loss of energy of the seismic waves. This will make the seismic waves decay fastest for the smallest *Q*-value. Hence, the seismic waves will decay fastest in western Taiwan. This would be a significant factor in reducing seismic risks in the area, otherwise, the earthquake-induced damage could be higher than reported.

5. Conclusions

Forty-nine $M_s \geq 7$ instrumentally-recorded earthquakes that occurred in the Taiwan region from 1906 to 2024 are compiled by Wang and Kuo [24] and other literature. Included also are seven historical events whose magnitudes were estimated by Tsai [18]. The currently used moment magnitude, M_w, is also evaluated for each instrumentally-recorded event. The differences between M_s and M_w show $M_s \geq M_w$ almost for all events. This might be due to the reason that the amplitudes at long periods of several hundred seconds are smaller for observational displacement spectra than theoretical ones for Taiwan earthquakes. Several groups of earthquakes formed the 'doublets,' 'triplets,' and 'quadruplets.' The spatial distribution of earthquakes demonstrates that most of the events occurred near the coastal line or offshore in eastern Taiwan and only a few inland events happened in western Taiwan. The time series of earthquakes shows irregular recurrence behavior with aperiodicity and multifractality and it was generated by the Poisson processes with a weak memory effect. The shortest inter-occurrence time between two consecutive events is less than 1 day; while the longest one is 5742 days. The average inter-occurrence time somewhat increases with time. The occurrences of $M_s \geq 7$ earthquakes are the most active in April, September, the second most active in December, and the least active in May and August. The damage caused by inland earthquakes is much higher than that done by offshore ones. Numerous offshore events did not produce damage on the inland areas and thus they were not reported in historical documents. The damage caused by earthquakes occurring in western Taiwan is much higher than that done by those happening in eastern Taiwan.

Author Contributions

Wang J.H. is responsible for collecting the data from literature, making the calculations, plotting the figures, compiling the tables, and writing the manuscript.

Funding

This study is in part supported by the Institute of Earth Sciences, Academia Sinca, Taipei, Taiwan, ROC.

Acknowledgments

The author thanks four reviewers for their valuable comments and suggestions for helping me to substantially improve the article.

Data Availability Statement

Data will be made available on request.

Conflict of Interest

There are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Materials

The supporting information can be downloaded at: https://journals.nasspublishing.com/files/EPS-1061-Supplementary-Materials.pdf

References

[1] Hsu, M.T., 1971. Seismicity of Taiwan and some related problems. Bulletin of the International Institute of Seismology and Earthquake Engineering, Japan. 8, 41–160.

[2] Tsai, Y.B., Teng, T.L., Chiu, J.M., et al., 1977. Tectonic implications of the seismicity in the Taiwan region. Memoir of the Geological Society of China, 2, 13–41.

[3] Wu, F.T., 1978. Recent tectonics of Taiwan. Journal of Physics of the Earth. 2(Supplement), S265–S299.

[4] Tsai, Y.B., 1986. Seismotectonics of Taiwan. Tectonophysics. 125(1–3), 17–28, 31–37.

[5] Yu, S.B., Chen, H.Y., Kuo, L.C., et al., 1997. Velocity field of GPS stations in the Taiwan area. Tectonophysics. 274(1–3), 41–59.

[6] Hsu, M.T., 1961. Seismicity of Taiwan (Formosa). Bulletin of the Earthquake Research Institute, University of Tokyo, 39, 831–847. Available from: https://www.iitk.ac.in/nicee/wcee/article/vol%20I_III-116.pdf

[7] Wang, J.H., 1988. B values of shallow earthquakes in Taiwan. Bulletin of the Seismological Society of America. 78(3), 1243–1254.

[8] Wang, J.H., 1998. Studies of earthquake seismology in Taiwan during the 1897–1996 period. Journal of the Geological Society of China. 41, 291–336.

[9] Wang, C.Y., Shin, T.C., 1998. Illustrating 100 years of Taiwan seismicity. Terrestrial, Atmospheric and Oceanic Sciences. 9, 589–614.

[10] Wang, J.H., Tsai, Y.B., Chen, K.C., 1983. Some aspects of seismicity in Taiwan region. Bulletin of the Institute of Earth Sciences, Academia Sinica, Republic of China. 3, 87–104.

[11] Wang, J.H., Chen, K.C., Lee, T.Q., 1994. Depth distribution of shallow earthquakes in Taiwan. Journal of the Geological Society of China. 37, 125–142.

[12] Wang, J.H., Chen, K.C., Leu, P.L., et al., 2015. *b*-value observations in Taiwan: A review. Terrestrial, Atmospheric and Oceanic Sciences Journal. 26(5), 475–492.
DOI: https://doi.org/10.3319/TAO.2015.04.28.01(T)

[13] Wang, J.H., Wang, C.Y., Song, Q.C., et al., 2005. The 921 Chi-Chi major earthquake. Office of Inter-Ministry Science & Technology Program for Earthquake and Active-fault Research, National Science Council: Taipei, Taiwan. pp. 582. (in Chinese)

[14] Wang, J.H., 2008. Urban seismology in the Taipei metropolitan area: review and perspective. Terrestrial, Atmospheric and Oceanic Sciences. 19(3), 213–233.

[15] Hsu, H., 1983. Source materials on the history of natural disasters in Ching, Taiwan. National Science Council, Executive Yuan, 1983: Taipei, Taiwan. (in Chinese)

[16] Hsu, M.T., 1983. Estimation of earthquake magnitudes and seismic intensities of destructive earthquakes in the Ming and Ching Eras. Meteorological

Bulletin, Central Weather Bureau. 29, 1–18. (in Chinese)

[17] Tsai, Y.B., 1985. A study of disastrous earthquakes in Taiwan, 1683–1895. Bulletin of the Institute of Earth Sciences, Academia Sinica. 5, 1–44.

[18] Wang, J.H., Miyamura, S., 1990. Comparison of several instrumentally determined magnitude scales for Taiwan earthquakes (1900–1978). Proceedings of the Geological Society of China. 33(2), 89–109.

[19] Wang, J.H., 1992. Magnitude scales and their relations for Taiwan earthquakes: A review. Terrestrial, Atmospheric and Oceanic Sciences. 3, 449–468.

[20] Hsu, M.T., 1980. Earthquake catalog in Taiwan (from 1644 to 1979). Open-File Report, Bulletin NTU. Earthquake Engineering Center, National Taiwan University, Taipei. pp. 77.

[21] Li, P.H., 1983. The strong earthquake recorders of 1900 to 1972: Re-analysis and occurrence time, spatial distributions study in Taiwan area. Technical Report, Central Weather Bureau, pp. 49. (in Chinese)

[22] Cheng, S.N., Yeh, Y.T., 1989. Catalogue of Earthquakes in Taiwan from 1604 to 1988. Open-File Report, Institute of Earth Sciences, Academia Sinica, pp. 255. https://search.worldcat.org/zh-tw/title/Catalog-of-the-earthquakes-in-Taiwan-from-1604-to-1988/oclc/26330060 (in Chinese)

[23] Central Weather Administration (CWA). 2024. Available from: https://www.cwa.gov.tw/eng/

[24] Wang, J.H., Kuo, H.C., 1995. A catalogue of Ms7 Taiwan earthquakes (1900–1994). Journal of the Geological Society of China. 38, 95–106.

[25] Wang, J.H., Kuo, H.C., 1998. On the frequency distribution of inter-occurrence times of earthquakes. Journal of Seismology. 2, 351–358.

[26] Cheng, S.N., Yeh, Y.T., Shaw, N.C., Chiang, C.H., 2002. Establishment of Disaster Earthquake Catalog on GIS. Technical Report, Central Weather Bureau, 195–211. (in Chinese)

[27] Chen, K.P., Tsai, Y.B., 2008. A catalog of Taiwan earthquakes (1900–2006) with homogenized Mw magnitudes. Bulletin of the Seismological Society of America. 98(1), 483–489.
DOI: https://doi.org/10.1785/0120070136

[28] Hanks, T.C., Kanamori, H., 1979. A moment magnitude scale. Journal of Geophysical Research. 84, 2348–2350.

[29] Chen, K.C., Huang, W.G., Wang, J.H., 2007. Relationships among magnitudes and seismic moment of earthquakes in the Taiwan region. Terrestrial, Atmospheric and Oceanic Sciences. 18(5), 951–974.

[30] Theunissen, T., Font, Y., Lallemand, S., et al., 2010. The largest instrumentally recorded earthquake in Taiwan: Revised location and magnitude, and tectonic significance of the 1920 event. Geophysical Journal International. 183, 1119–1133.
DOI: https://doi.org/10.1111/j.1365-246X.2010.04813.x

[31] Chen, P.F., Ekstrom, G., Okal, A., 2004. Centroid moment tensor solutions for Taiwan earthquakes of the WWSSN era (1963–1975). Terrestrial, Atmospheric and Oceanic Sciences. 15(1), 61–73.

[32] Gutenberg, B., Richter, C.F., 1942. Earthquake magnitude, intensity, energy and acceleration. Bulletin of the Seismological Society of America. 32, 163–191.

[33] Kawasumi, H., 1943. Intensity and magnitude. Zisin (Journal of Seismology). 15, 6–12. Available from: https://www.jstage.jst.go.jp/browse/zisin (in Japanese)

[34] Wang, J.H., Miyamura, S., Yeh, Y.L., 1990. Kawasumi's intensity magnitude for Taiwan earthquakes. Proceedings of the National Science Council, Republic of China. 14, 203–210.

[35] Tsuboi, C., 1951. Determination of the Richter-Gutenberg's instrumental magnitudes of earthquakes occurring in and near Japan. Geophysical Notes, University of Tokyo, Japan, 4, 1–10.

[36] Hsu, M.T., 1985. Computation of magnitudes of earthquakes occurred in 1934 and 1935. Meteorological Bulletin, Central Weather Bureau. 31, 103–106. (in Chinese)

[37] Duda, S.J., 1965. Secular seismic energy release in the circum-Pacific belt. Tectonophysics. 2, 409–452.

[38] Abe, K., 1981. Magnitudes of large shallow earthquakes from 1904 to 1980. Physics of the Earth and Planetary Interiors. 27, 72–92.

[39] Abe, K., 1984. Complements to "Magnitudes of large shallow earthquakes from 1904 to 1980". Physics of the Earth and Planetary Interiors. 34, 17–23.

[40] Gutenberg, B., Richter, C.F., 1954. Seismicity of the earth and associated phenomena. Princeton University Press: Princeton.

[41] Kanamori, H., 1977. The energy release in great earthquakes. Journal of Geophysical Research. 82, 2981–2987.

[42] Abe, K., 1979. Size of great earthquakes of 1837–1974 inferred from tsunami data. Journal of Geophysical Research. 84, 1561–1568.

[43] Kanamori, H., 1983. Magnitude scale and quantification of earthquakes. Tectonophysics. 93, 185–199.

[44] Kanamori, H., Anderson, D.L., 1975. Theoretical basis of some empirical relations in seismology.

Bulletin of the Seismological Society of America. 65, 1073–1095.

[45] Lee, W.H.K., Wu, F.T., Wang, S.C., 1978. A catalog of instrumentally determined earthquakes in China (magnitude>6) compiled from various source. Bulletin of the Seismological Society of America. 68, 383–398.
DOI: https://doi.org/10.1785/BSSA0680020383

[46] Utsu, T., 1979. Seismicity of Japan from 1885 through 1925-A new catalog of earthquakes of M>6 felt in Japan and smaller earthquakes which caused damage in Japan. Bulletin of Earthquake Research Institute, Tokyo University, Japan, 54, 253–308.

[47] Okal, E.A., 1992. Use of mantle magnitudes for the reassessment of the seismic moment of historical earthquakes: The 1906 San Francisco earthquake. Pure and Applied Geophysics. 139, 17–57.

[48] Pacheco, J.F., Sykes, L.R., 1992. Seismic moment catalog of large shallow earthquakes, 1900 to 1989. Bulletin of the Seismological Society of America. 82, 1306–1349.

[49] Bath, M., 1981. Earthquake magnitude: Recent research and current trends. Earth-Science Reviews. 17, 315–398.

[50] Gutenberg, B., 1956. Energy ratio of earthquakes of different magnitude. Bulletin of the Seismological Society of America. 46, 53–55.

[51] Shi, Y., Bolt, B.A., 1982. The standard error of the magnitude-frequency b value. Bulletin of the Seismological Society of America. 72, 1677–1687.

[52] Helmstetter, A., Sornette, D., 2003. Predictability in the epidemic-type aftershock sequence model of interacting triggered seismicity. Journal of Geophysical Research: Solid Earth. 108(B10), 2482.
DOI: https://doi.org/10.1029/2003JB002485

[53] Aki, K., 1965. Maximum likelihood estimate of b in the formula log N = a-bM and its confidence limits. Bulletin of the Earthquake Research Institute, University of Tokyo. 43, 237–239.

[54] Lee, S. J., Liang, W. T., Kawakatsu, H., 2013. Real-time Moment Tensor monitoring system (RMT) applied for the Taiwan region. Available from: http://ir.sinica.edu.tw/handle/201000000A/49985

[55] Chen, K.C., 2003. Strong ground motion and damage in the Taipei basin from the Moho reflected seismic waves during the March 31, 2002, Hualien, Taiwan, earthquake. Geophysical Research Letters. 30(11).
DOI: https://doi.org/10.1029/2003GL017193

[56] Kanamori, H., 1977. The energy release in great earthquakes. Journal of Geophysical Research. 82, 2981–2987.

[57] Aki, K., 1966. Generation and propagation of G waves from the Niigata earthquake of June 16, 1964. Bulletin of the Earthquake Research Institute. 44, 23–72.

[58] Engdahl, E.R., Van Der Hilst, R.D., Buland, R.P., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bulletin of the Seismological Society of America. 88(3), 722–743.

[59] Engdahl, E.R., Villaseñor, A., 2002. Global seismicity: 1900–1999. International Handbook of Earthquake Engineering and Seismology. 81A, 665–689.

[60] Kao, H., Shen, S.J., Ma, K.F., 1998. Transition from oblique subduction to collision: earthquakes in the southernmost Ryukyu Arc-Taiwan region. Journal of Geophysical Research. 103(B4), 7211–7229.

[61] Wu, Y.M., Chang, C.H., Zhao, L., et al., 2008. A comprehensive relocation of earthquakes in Taiwan from 1991 to 2005. Bulletin of the Seismological Society of America. 98(3), 1471–1481.

[62] Hsu, Y.J., Ando, M., Yu, S.B., et al., 2012. The potential for a great earthquake along the southernmost Ryukyu subduction zone. Geophysical Research Letters. 39(14).
DOI: https://doi.org/10.1029/2012GL052764

[63] Kanamori, H., Lee, W.H.K., Ma, K.F., 2012. The 1909 Taipei earthquake—implication for seismic hazard in Taipei. Geophysical Journal International. 91(1), 126–146.
DOI: https://doi.org/10.1111/j.1365-246X.2012.05589.x

[64] Rau, R.J., Wu, F.T., 1995. Tomographic imaging of lithospheric structures under Taiwan. Earth and Planetary Science Letters. 133(3–4), 517–532.
DOI: https://doi.org/10.1016/0012-821X(95)00076-O

[65] Ma K.F., Wang, J.H., Zhao, D., 1996. Three-dimensional seismic velocity structure of the crustal and uppermost mantle beneath Taiwan. Journal of Physics of the Earth. 44, 85–105.

[66] Kim, K.H., Chiu, J.M., Pujo, J., et al., 2005. Three-dimensional Vp and Vs structural models associated with the active subduction and collision tectonics in the Taiwan region. Geophysical Journal International. 162, 204–220.

[67] Wu, Y.M., Chang, C.H., Zhao, L., et al., 2007. Seismic tomography of Taiwan: Improved constraints from a dense network of strong-motion stations. Journal of Geophysical Research. 112(B8).

DOI: https://doi.org/10.1029/2007JB004983

[68] Kuo-Chen, H., Wu, F.T., Roecker, S.W., 2012. Three-dimensional P velocity structures of the lithosphere beneath Taiwan from the analysis of TAIGER and related seismic data sets. Journal of Geophysical Research.117 B06306. DOI: https://doi.org/10.1029/2011JB009108

[69] Omori, F., 1907. Preliminary note of the Formosa earthquake of March 17, 1906. Bulletin of the Imperial Earthquake Investigation Committee Japan. 1(2), 54–69.

[70] Omori, F., 1909. Note on the propagation velocity of the Formosa earthquakes of 1906 and 1908. Bulletin of the Imperial Earthquake Investigation Committee Japan. 3, 47–60.

[71] Peng, C.W., Shih, R.C., Chang, H.C., et al., 2004. The Mei-Shan fault and its shear zones structure in the near surface. Central Geological Survey. 15(Special Issue), 85–98. Available from: https://hdl.handle.net/11296/9j3b57 (in Chinese)

[72] Wells, D.L., Coppersmith, K.J., 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America. 84, 974–1002.

[73] Chen, K.C., Wang, J.H., 1988. A study on aftershocks and focal mechanisms of two 1986 earthquakes in Hualien, Taiwan. Proceedings of the Geological Society of China. 31(12), 65–72.

[74] Huang, B.S., Huang, Y.L., Lee, S.J., et al., 2008. Initial rupture processes of the 2006 Pingtung earthquake from near source strong-motion records. Terrestrial, Atmospheric and Oceanic Sciences. 19(6), 547–554. DOI: https://doi.org/10.3319/TAO.2008.19.6.547(PT)

[75] Tsai, Y.B., Yu, T.M., Chao, H.L., et al., 2001. Spatial distribution and age dependence of human-fatality rates from the Chi-Chi, Taiwan, earthquake of 21 September 1999. Bulletin of the Seismological Society of America. 91(5), 1298–1309.

[76] Ruisui Township Chronicles, 2007. Ruisui Township Office: Hualien County, Taiwan. pp. 555. (in Chinese).

[77] Gutenberg, B., Richter, C.F., 1956. Magnitude and energy of earthquake. Annals of Geophysics. 9, 1–15.

[78] Aki, K., 1967. Scaling law of seismic spectrum. Journal of Geophysical Research. 72, 1217–1232.

[79] Hanks, T.C., Thatcher, W., 1972. A graphical representation of seismic source parameters. Journal of Geophysical Research. 77, 4393–4405.

[80] Wang, J.H., 2004. The seismic efficiency of the 1999 Chi-Chi, Taiwan. Earthquake. Geophysical Research Letters. 31, L10613. DOI: https://doi.org/10.1029/2004GL019417

[81] Wang, J.H., 2006. Energy release and heat generation during the 1999 Chi-Chi, Taiwan, earthquake. Journal of Geophysical Research. 111(B11). DOI: https://doi.org/10.1029/2005JB004018

[82] Wang, J.H., 2009. Effect of thermal pressurization on the radiation efficiency. Bulletin of the Seismological Society of America. 99(4), 2293–2304.

[83] Knopoff, L., 1958. Energy release in earthquakes. Geophysical Journal. 1, 44–52.

[84] Purcaru, G., Berckhemer, H., 1978. A magnitude scale for very large earthquakes. Tectonophysics. 49, 189–198.

[85] Kanamori, H., Brodsky, E.E., 2004. The physics of earthquakes. Reports on Progress in Physics. 67, 1429–1496.

[86] Chen, K.C., Liang, W.T., Liu, Y.H., et al., 2008. Seismic moments for Taiwan's earthquakes evaluated from a regional seismic network. Earth, Planets and Space. 60, 559–564.

[87] Richter, C.F., 1958. Elementary Seismology. Freeman: San Francisco. pp. 768.

[88] Båth, M., 1965. Lateral inhomogeneities in the upper mantle. Tectonophysics. 2, 483–514.

[89] Chen, K.C., Wang, J.H., 2012. Correlations between mainshocks and aftershocks for Taiwan earthquakes. Pure and Applied Geophysics. 169, 1217–1229.

[90] Cheng, S.N., Yeh, Y.T., Yu, M.S., 1996. The 1951 Taitung earthquakes in Taiwan. Journal of the Geological Society of China. 39(3), 267–285.

[91] Chen K.H., Toda, S., Rau, R.J., 2008. A leaping, triggered sequence along a segmented fault: The 1951 ML7.3 Hualien-Taitung earthquake sequence in eastern Taiwan. Journal of Geophysical Research. 113(B2). DOI: https://doi.org/10.1029/2007JB005048

[92] Wang, J.H., Chen, K.C., Lee, S.J., et al., 2011. The 15 April 1909 Taipei earthquake. Terrestrial, Atmospheric and Oceanic Sciences. 22(1), 91–96.

[93] Wang, J.H., 1989. The Taiwan telemetered seismographic network. Physics of the Earth and Planetary Interiors. 58, 9–18.

[94] Kagan, Y, Jackson, D.D., 1991. Long-term earthquake clustering. Geophysical Journal International. 104, 117–133.

[95] Goes, S.D.B., 1996. Irregular recurrence of large earthquakes: An analysis of historical and paleoseismic catalogs. Journal of Geophysical Research. 101(B3), 5739–5749.

[96] Chen, W.S., Lee K.J., Lee, L.S., et al., 2004. Paleoseismology of the Chelungpu fault during the past 1900 years. Quaternary International. 115–116, 167–176.

[97] Wang, J.H., 2003. A one-body model of the 1999 Chi-Chi, Taiwan, earthquake. Terrestrial, Atmospheric and Oceanic Sciences. 14(3), 335–342.

[98] Wang, J.H., 2005. Earthquakes rupturing the Chelungpu fault in Taiwan are time-predictable. Geophysical Research Letters. 32,(6). DOI: https://doi.org/10.1029/2004GL021884

[99] Satake, K., 2015. Geological and historical evidence of irregular recurrent earthquakes in Japan. Philosophical Transactions of the Royal Society A. 373(2053). DOI: https://doi.org/10.1098/rsta.2014.0375

[100] Davis, P.M., Jackson, D.D., Kagan, Y.Y., 1989. The longer it has been since the last earthquake, the longer the expected time till the next? Bulletin of the Seismological Society of America. 79, 1439–1456.

[101] Mandelbrot, B.B., 1983. The Fractal Geometry of Nature. W.H. Freeman: New York, USA. pp. 468.

[102] Mandelbrot, B.B., 1989. Multifractal measures, especially for the geophysicist. Pure and Applied Geophysics. 131, 5–42.

[103] Turcotte, D.L., 1997. Fractals and chaos in geology and geophysics. Cambridge University Press: Cambridge, UK. pp. 221.

[104] Wang, J.H., Lin, W.H., 1993. A fractal analysis of earthquakes in west Taiwan. Terrestrial, Atmospheric and Oceanic Sciences. 4, 457–462.

[105] Wang, J.H., Lee, C.W., 1995. Multifractal characterization of an earthquake sequence. Physica A: Statistical Mechanics and its Applications. 221, 152–158.

[106] Wang, J.H., Lee, C.W., 1996. Multifractal measures of earthquakes in west Taiwan. Pure and Applied Geophysics. 146, 131–145.

[107] Wang, J.H., Chen, K.C., Huang, W.G., et al., 2014. Multifractal measures of M ≥ 3 shallow earthquakes in the Taipei Metropolitan Area. Terrestrial, Atmospheric and Oceanic Sciences Journal. 25(1), 17–26. DOI: https://doi.org/10.3319/TAO.2013.09.09.01(T)

[108] Wang, J.H., Chen, K.C., Chen, K.C., et al., 2022. Multifractal measures of the 2021 earthquake swarm in Hualien, Taiwan. Terrestrial, Atmospheric and Oceanic Sciences. 33(11). DOI: https://doi.org/10.1007/s44195-022-00011-5

[109] Tang, Y.J., Chang, Y.F., Liou, T.S., et al., 2012. Evolution of the temporal multifractal scaling properties of the Chiayi earthquake (ML = 6.4), Taiwan. Tectonophysics. 546–547, 1–9.

[110] Wang, J.H., 1996. Multifractal measures of time series of Ms7 earthquakes in Taiwan. Journal of the Geological Society of China. 39, 117–123.

[111] Gardner, J.K., Knopoff, L., 1974. Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bulletin of the Seismological Society of America. 64, 1363–1367.

[112] Wang, J.H., 2014. Memory effect in M ≥7 earthquakes of Taiwan. Journal of Seismology. 18, 467–480. DOI: https://doi.org/10.1007/s10950-014-9420-9

[113] Central Meteorological Observatory of Japan, 1935. Report of the Shinchiku-Taichu Earthquake of April 21, 1935. Seismometrical Review. 9(1), 1–63. Available from: https://twgeoref.gsmma.gov.tw/GipOpenWeb/wSite/ct?xItem=116401&ctNode=289&mp=6 (in Japanese)

[114] Hsu, M.T., 1980. Destructive Earthquake in Taiwan—from 1644 to the Present Time Meteorology Bulletin, Central Weather Bureau, 36–48. Available from: https://www.cwa.gov.tw/V8/C/D/publication.html (in Chinese)

[115] Miyamura, S., 1985. The Hsinchu-Taichung, Taiwan, earthquake of April 20, 1935. Proceedings of the Seminar Commemorating the 50th Anniversary for Hsinchu-Taichung Earthquake of 1935. 18–44.

[116] Ho, C.S., 1988. An introduction to the geology of Taiwan: explanatory text of the geology map of Taiwan. Ministry of Economic Affairs Taiwan, Central Geological Survey: Taiwan. pp. 192.

[117] Boore, D.M., Joyner, W.B., 1997. Site amplifications for generic rock sites. Bulletin of the Seismological Society of America. 87, 327–341.

[118] Huang, M.W., Wang, J.H., Hsieh, H.H., et al., 2005. Frequency-dependent site amplifications evaluated from well-logging data in central Taiwan. Geophysical Research Letters. 32, L21302. DOI: https://doi.org/10.1029/2005GL023527

[119] Huang, M.W., Wang, J.H., Ma, K.F., et al., 2007. Frequency-dependent site amplifications with f0.01 Hz evaluated from the velocity and density models in Central Taiwan. Bulletin of the Seismological Society of America. 97(2), 624–637.

[120] Huang, M.W., Wang, J.H., Hsieh, H.H., et al., 2009. High frequency site amplification evaluated from borehole data in the Taipei Basin. Journal of Seismology. 13, 601–611.

[121] Guéguen, P., Bonilla, L.F., Douglas, J., 2019. Comparison of soil nonlinearity (in situ stress—strain relation and G/Gmax reduction) observed in strong-motion databases and modeled in ground-motion prediction equations. Bulletin of the Seismological Society of America. 109(1), 178–186.
DOI: https://doi.org/10.1785/0120180169

[122] Mason, H.B., Yeh, H., 2016. Sediment liquefaction: A pore-water pressure gradient viewpoint. Bulletin of the Seismological Society of America. 106(4), 1908–1913.

[123] Wang, J.H., 1993. Q values of Taiwan: a review. Journal of the Geological Society of China. 36, 15–24.

[124] Chen, K.C., Shin T.C., Wang J.H., 1989. Estimates of coda Q in Taiwan. Proceedings of the Geological Society of China. 32(4), 339–353.

[125] Wang, Y.J., Ma, K.F., Mouthereau, F., et al., 2010. Three-dimensional Qp- and Qs-tomography beneath Taiwan orogenic belt: Implications for tectonic and thermal structure. Geophysical Journal International. 180(2), 891–910.
DOI: https://doi.org/10.1111/j.1365-246X.2009.04459.x