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NOTES AND CORRESPONDENCE

The 15 April 1909 Taipei Earthquake

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ABSTRACT

In the very early morning at 03 h 53.7 m on 15 April 1909 (local time), a large earthquake occurred in northern Taiwan. In all, 9 persons were killed and 51 injured; 122 houses collapsed along with damage to another 1050 houses. This earthquake was one of the largest and most damaging events of the 20th century for the Taipei Metropolitan Area. The epicenter estimated by Hsu (1971) was determined to be 25°N, 121.53°E and its focal depth and earthquake magnitude evaluated by Gutenberg and Richter (1954) were ~80 km and $M_{GR} = 7.3$, respectively. The event took place underneath the Taipei Metropolitan Area and might be located at the western edge of the subduction zone of the Philippine Sea plate. In this study, the magnitudes of the earthquakes determined by others will also be described.

Key words: Damage, Hypocenter, Epicenter, Focal depth, Earthquake magnitude

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1. INTRODUCTION

Taiwan is situated along the collision boundary between the Philippine Sea plate and the Eurasian plate (Tsai et al. 1977; Wu 1978; Lin 2002). The former is moving northwestward with a speed of ~7 cm yr^{-1} (Seno 1977; Yu et al. 1997). The Philippine Sea plate has subducted underneath the Eurasian plate in northern Taiwan, where the Taipei Metropolitan Area (TMA) is located. The geological setting and related information of the TMA can be seen in Wang (2008). This collision causes high seismicity in Taiwan (Wang 1998). Since the TMA is the political, economic, and cultural center of Taiwan, seismic hazard evaluations in the area should be paid much attention by local earthquake scientists and engineers. The frequency-dependent site amplifications in the frequency range 1 - 50 Hz evaluated from well-logging data at 18 free-field strong motion stations in the TMA are all higher than 1 (Huang et al. 2009). This means that the ground motions generated by earthquakes will be amplified in the TMA, thus easily causing damage.

Wang (2008) found that three distant earthquakes, i.e., the 1986 M 7.8 Hualien offshore earthquake (Chen and Wang 1986, 1988), the 1999 M 7.6 Chi-Chi earthquake (Ma et al. 1999), and the 2002 M 7.1 Hualien offshore earthquake, all occurred far away from the TMA, but they caused damages in the area. However, before 1970, numerous large distant earthquakes, for instance the 1906 M 7.1 Meishan earthquake (Omori 1907; Cheng et al. 1999), the 1935 M 7.2 Hsinchu-Taichung earthquake (Miyamura 1985; Cheng et al. 1999), the 1941 M 7.1 Chungpu, Chiayi earthquake (Cheng et al. 1999), the 1951 M 7.6 Hualien earthquake (Su 1985; Cheng et al. 1999), and the 1972 M 7 Juisui earthquake (Chiang et al. 1986) did not cause remarkable damage in the area. What had caused the differences in damage between pre-1970 and post-1970 events? Observations show that the predominant frequencies of seismic waves generated by distant earthquakes are almost 0.5 - 1.0 Hz in the area (e.g., Wen and Peng 1998). This would result in damage to buildings with 10 - 20 floors. Before 1970, most buildings were lower than 4 floors, therefore, damage was minor. Since 1970, large numbers of high-rise buildings, ≥ 10 - 20 floors, have been constructed, and thus earthquake-induced damage has also increased, even though quality of construction has been substantially improved.

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Compared with other areas in Taiwan, seismicity in the TMA is in general low (Wang 1998, 2008; Wang et al. 2006). Although there were a few large events historically, there were no destructive events with M > 6 after 1909 (Wang et al. 2006). Recent studies concerning earthquakes in the TMA as mentioned in Wang (2008) are not sufficient for evaluating seismic hazards. To mitigate seismic risks in the area, it is necessary to investigate historical earthquakes either from documents or from old paper seismograms. Only historical documents of earthquake-induced damage are available prior to 1896 in Taiwan (Hsu 1983a). In 1897, the Japanese started seismological monitoring at Taihoku (Taipei) Meteorological Observatory and continued to install seismic stations around the island. A history about the construction of seismic network during the Japanese colonial period can be found in several works (Hsu 1961; Miyamura 1985; and Shin and Chang 2005). In all, Japanese seismologists constructed 17 stations, each equipped with three-component low-gain displacement seismometers. For all stations, the seismograms were recorded in an analog form. Since the end of the Second World War, this seismic network was transferred to the Taiwan Weather Bureau (now the Central Weather Bureau, CWB). Although instrument-recorded seismograms have been available since 1897, numerous early seismograms were lost.

Historically, several large and medium earthquakes occurred near or in the TMA (Hsu 1961, 1971; Wang 1998). The occurrence times, locations, magnitudes, and effects of M > 6 destructive earthquakes occurring in the area are listed in Table 1. The errors of the magnitudes of pre-1900 earthquakes are high. During the reign of Emperor Kanshi of the Ching Dynasty, an event occurred in April or May 1694 resulting in an earthquake-induced lake and destruction of aboriginal houses (Hsu 1983a, b). From historical documents on damages, the magnitude of this event was estimated to be 7 by Hsu (1983b) and Tsai (1985). Likewise, in the early morning (03 h 53.7 m) of 15 April 1909 (local time) a large earthquake occurred in northern Taiwan. This earthquake was one of the largest and most destructive events in the 20 century with regard to the TMA. Obviously, it is necessary to study this event for information which might help mitigate seismic risk in the area. The study of the event will also be useful for understanding regional tectonics.

Although seven seismic stations were installed at Taipei, Tainan, Peihu, offshore Keelung, Taichung, Taitung, and Hengchun before the occurrence of the 1909 Taipei earthquake, seismograms cannot be found now. Hence, it is impossible to study the earthquake using seismograms. In this study, an attempt is made to describe the damage, hypocenter (including epicenter and focal depth), earthquake magnitude, and related problems of the earthquake from several documents.

2. DAMAGE CAUSED BY THE 1909 TAIPEI EARTHQUAKE

During the earthquake, 9 persons were killed and 51 injured; 122 houses collapsed, and 1050 houses were dam-

Table 1. The M > 5 earthquakes occurred near the Taipei Metropolitan Area (after Wang 2008).

Time	Location	M	Effects
1659/10 - 11	Near Taipei		Aftershocks
1694/04 - 05	Near Taipei	7.0	Subsidence (Kanshi Lake) Damaged houses
1815/7/11	Near Taipei	6.5	Minor damage
1853/05 - 08	Tatungshan		Earthquake sound
1860/11 - 12	Near Taipei		Landslide
1865/11/06	Near Taipei	6.0	Landslide, death
1867/12/18	Offshore Keelung	7.0	Tsunami, surface ruptures, death
1881/12/08	Near Taipei		Minor damage
1909/04/15	25°N, 121.5°S h = 80 km	7.3	Death: 9; Injured: 51 Houses: Collapsed: 122 Damaged: 1050
1988/07/03	25.16°N, 121.57°S h = 5 km	5.3	Injured: 16

aged (Hsu 1971). From a local Japanese newspaper published in 1909, we can see that the damage caused by the event was distributed mainly in northwestern Taiwan, i.e., the Taipei City, the Taipei County (including Panchiou and Hsinchung), the Taoyuan County, and the Hsinchu County. Although 1172 houses were destroyed in different degrees of damage during the earthquake, the percentage of totally and partly collapsed houses was ~10%. The most damaged areas were Taipei City, Panchiou, and Hsinchung. The largest numbers of deaths and injuries were, respectively, in Taoyuan County and Taipei City. On the other hand, there was only minor damage in Ilan.

3. HYPOCENTER OF THE 1909 TAIPEI EARTHQUAKE

The hypocenter of the event, including epicenter (25°N, 123°E) and focal depth (~80 km), were first estimated by Gutenberg and Richter (1954) from limited global seismic data. Their results showed that the event was located offshore and to the northeast of Ilan. The epicenter is outside the area shown in Fig. 1. However, the epicenter was corrected to (25.0°N and 121.5°E) by Hsu (1971). As mentioned previously, the damage caused by the event was distributed mainly in northwestern Taiwan with only minor damage in Ilan. This spatial distribution of damage suggests that Hsu (1971) gave a more reasonable epicenter than Gutenberg and Richter (1954). Thus, the event was underneath the TMA rather than offshore eastern Taiwan. On the other hand, the focal depth estimated by Gutenberg and Richter (1954) has been used by others. Considering the focal depth, the event might be located at the western edge of the subduction zone of the Philippine Sea plate. Hence, the earthquake might not have any relationship to the shallow fault systems the TMA.

The epicenters of earthquakes occurring in the TMA during 1973 - 2009 are shown in Fig. 1: open circles for shallow (0 - 40 km) events in the crust and solid circles for deep (> 60 km) ones. The size of a circle denotes the magnitude of an event. Seismicity in a small area surrounding the epicenter of the 1909 Taipei earthquake (with a solid star) is quite low. As mentioned in Wang et al. (2006), shallow earthquakes mainly located in depth range from 0 - 10 km north of 25.1°N, and down to 35 km in depth for those south of 25.1°N. After 1988, no M ≥ 4 shallow event was located within this area.

The hypocentral distribution for M ≥ 4 earthquakes occurred during 1973 - 2009 is displayed in Fig. 2 where deep events show the existence of a subduction zone below the area. This zone is the Philippine Sea plate as proposed by Tsai et al. (1977), Wu (1978), and Lin (2002). The 1909 Taipei earthquake was located on the upper layer of the subduction zone. In some sense, the determination of focal depth by Gutenberg and Richter (1954) seems to be acceptable. It is also reasonable to assume that the event was thrust-faulting, even though now there are not enough seismic data to confirm this assumption.

4. EARTHQUAKE MAGNITUDE OF THE 1909 TAIPEI EARTHQUAKE

The earthquake magnitude of the 1909 Taipei earthquakes was evaluated by several groups of researchers. Results are described below.

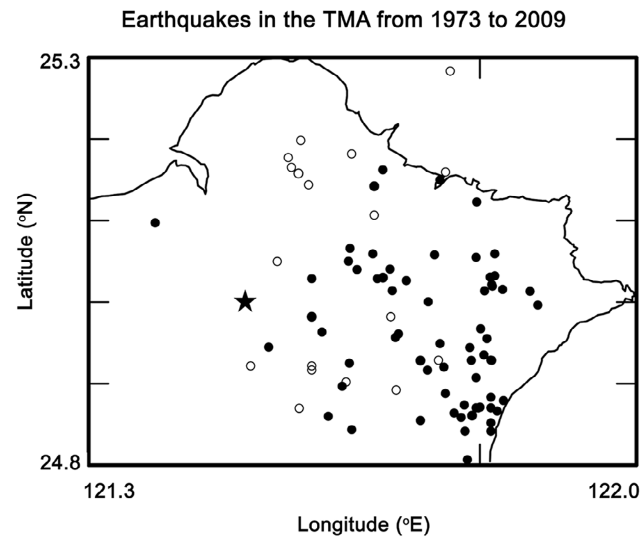

Fig. 1. The solid star denotes the epicenter of the 1909 Taipei earthquakes. Epicenters of earthquakes (4.0 ≤ M ≤ 5.7) during 1973 - 2009: open and solid circles for shallow (0 - 40 km) and deep (> 60 km) events, respectively.

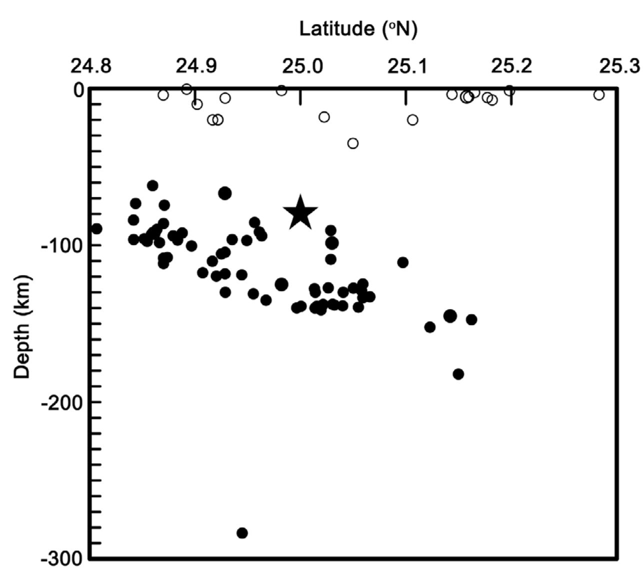

Fig. 2. Profile of earthquakes (shown in Fig. 1) along a specific longitude.

(1) M_{GR} and m_B

Gutenberg (1945a) defined the surface-wave magnitude in the form:

$$M_{GR} = \log A + 1.656 \log \Delta + 1.818 + C \quad (1)$$

where A is the vector sum of two horizontal maximum amplitudes with period around 20 sec in mm, Δ is the epicentral distance in degree, and C is the station correction. As only one component amplitude is available, A is the value of the maximum amplitude multiplied by 2 or 1.4. Gutenberg (1945b, c) also defined a medium-period body-wave magnitude, m_B, to quantify earthquakes based on the P and S waves in the form:

$$m_B = \log(A/T) + q(\Delta, h) \quad (2)$$

where T is the period related to the maximum amplitude A and q(Δ, h) is the correction term associated with epicentral distance (Δ) and focal depth (h). Based on Eqs. (1) and (2), Gutenberg and Richter evaluated the value of M_{GR} and m_B of the 1909 Taipei earthquake from limited global seismic data. The results, i.e., $M_{GR} = 7.3$ and $m_B = 7$, are given in "Seismicity of the Earth and Associated Phenomena" (Gutenberg and Richter 1954). Abe and Noguchi (1983) re-evaluated the value of m_B from the peak amplitudes of body-waves with a period of ~6 sec. Their value is 7.1 for the 1909 Taipei earthquake. The value of $M_{GR} = 7.3$ was used by Duda (1965), Hsu (1971), Lee et al. (1978), Bath and Duda (1979), and Abe (1981) in their respective earthquake catalogues.

(2) M_K

Kawasumi (1943) defined an earthquake magnitude, M_K, on the basis on the intensity value at a distance of 100 km. The intensity scale is the Japanese scale in 8 degrees from 0 to VII. From Japanese data, he obtained two formulas for conversion between the intensity of degree I with a radius of perceptibility (R) and M_K. The formula for R > 100 km is

$$I = M_I + 2 \ln(100/R) - 0.00183(R - 100) \quad (3)$$

The value of M_K of the 1909 Taipei earthquake evaluated by Kawasumi (1951) from Eq. (3) was 6.9 because of R = 900 km. Wang et al. (1990) found that M_K was overestimated for Taiwan earthquakes when $M_K > 7$. Hence, $M_K = 6.9$ is acceptable.

(3) M_J

Tsuboi (1951) defined an earthquake magnitude, M_J, in the following form:

$$M_J = 1.73 \log(\Delta) + \log(A) - 0.83 \quad (4)$$

where A is either the larger value of the maximum amplitudes along two horizontal components or the composite value of the two maximum amplitudes in mm and Δ is the epicentral distance in km. This formula has used by the Japan's Central Meteorological Observatory (CMO) (now Japan Meteorological Agency, JMA) to quantify earthquakes occurring in Japan and Taiwan since 1954. From Eq. (4), Utsu (1982) obtained $M_J = 7.2$ for the 1909 Taipei earthquake. Kawasumi (1951) correlated M_J to M_K in the following expression:

$$M_J = 4.85 + 0.5\, M_K \quad (5)$$

The value of M_J for the 1909 Taipei earthquake from Eq. (5) was 8.3 and listed in the Annual Report of Earthquakes of CMO of 1951. Obviously, this magnitude value is quite high.

(4) M_s and m_b

Vanek et al. (1962) defined a new surface-wave magnitude (denoted by M_s) through the so-called "Prague-Moscow formula":

$$M_s = \log(A/T) + 1.66 \log \Delta + 3.3 \quad (6)$$

where A, T, and Δ are, respectively, the peak amplitude, the period related to A, and the epicentral distance in degrees. Since 1966, this formula has been accepted by the International Association of Seismology and Physics of Earth's Interior (IASPEI) to quantify earthquakes. In the practical calculations, only the peak amplitude with period of 20 ± 2 sec is used. M_s is now evaluated only from the maximum vertical amplitude, with a period from 18 to 22 sec, recorded by the World-Wide Standard Seismographic Network (WWSSN), which has been constructed since the early 1960's. Hence, it is impossible to evaluate the value of M_s of the 1909 Taipei earthquake from the seismograms of the WWSSN. However, Lienkaemper (1984) found that M_{GR} is larger than a simple average of all single-station M_s by 0.16 units of M_s on average. Hence, it is reasonable to consider M_s = ~7.1 for the 1909 Taipei earthquake as mentioned in Wang and Kuo (1995).

The short-period body-wave magnitude, m_b, is determined almost from the vertical P waves at a period of ~1 sec through Eq. (2). The difference between m_B and m_b has been studied by numerous groups of researchers. Among them, Abe (1981) observed that m_b is lower than m_B by about 0.4

- 1.1 units, and he also deduced a relation between the two magnitudes for $5.5 < m_B < 7.8$ in the form:

$$m_B = 1.5\ m_b - 2.2 \tag{7}$$

From this equation, the value of m_b for the 1909 Taipei earthquake is ~6.1. Obviously, the difference between M_s and m_b is larger than that between M_{GR} and m_B.

5. CONCLUSIONS

Since the damage caused by the event was distributed mainly in northwestern Taiwan and the highest damage occurred near Panchiao, the epicenter (25.0°N and 121.5°E) determined by Hsu (1971) is more acceptable than the epicenter (24°N, 123°E) estimated by Gutenberg and Richter (1954). Thus, the event was underneath the TMA rather than offshore. The focal depth (~80 km) and earthquake magnitude ($M_{GR} = 7.3$ and $m_B = 7$) evaluated by Gutenberg and Richter (1954) have been widely used by others. Considering the epicenter (25.0°N and 121.5°E) determined by Hsu (1971) and the focal depth estimated by Gutenberg and Richter (1954), the event might be located at the western edge of the subduction zone of the Philippine Sea plate. The value of m_B determined by Abe and Noguchi (1983) from the peak amplitudes of body-waves with a period of ~6 sec is 7.1. The intensity magnitude (M_K) evaluated by Kawasumi (1951) is 6.9. The magnitude (M_J) reported by Utsu (1982) is 7.2. The values of M_s and m_b evaluated, respectively, from M_{GR} and m_B are about 7.1 and 6.1, respectively. Of course, more quantitative study of this earthquake is desirable, using historical seismograms from Taiwan and other regions, e.g., Mainland China, Japan, Indonesia, and Europe.

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