Aspects of Large Taiwan Earthquakes and Their Aftershocks

CHAIN-THUSEY WANG¹ and JEEN-HWA WANG¹

(Manuscript received 1 May 1993, in final form 8 September 1993)

ABSTRACT

From the data of 31 large Taiwan earthquakes and their aftershocks published by Hsu (1971, 1980, and 1985) and reported in the Earthquake Data Report (EDR) by USGS, several aspects of mainshocks and their aftershocks are studied. Results show that the magnitude difference ($\Delta M$) between mainshock and the largest aftershock increases with mainshock magnitude (M). The linear relations of $\Delta M$ vs. M are different for two data sets. The difference of original times of main shock and the largest aftershock more or less decreases with magnitude of mainshock. The departure of the $M_a$-$m_b$ scaling of the mainshock from that of aftershocks is bigger for larger mainshocks than for smaller ones. The mainshock magnitude cannot be estimated from the logN-M relation from aftershocks and is actually larger than the maximum magnitude evaluated from the relation.

1. INTRODUCTION

Excluding swarms, almost all larger earthquakes are followed up by aftershocks. There is a close relation between the mainshock and aftershocks. Numerous properties of mainshock and aftershocks have been studied for the understanding of the physical relation between mainshock and aftershock and the possible transition process from mainshock to aftershocks. Omori (1896) first proposed a power law to describe the number of aftershocks with time: $n(t)=k/t^{P}$. This power law is called as Omori's law. Hereafter, Richter (1958) found that the difference in the surface-wave magnitude values of larger shallow-focus earthquakes and the largest aftershocks is about 1.2, and he named the rule as "Bath's law". The difference was found to depend on mainshock magnitude, time of occurrence, region and depth, being larger for deeper events (Bath, 1965, 1977; Utsu, 1969, 1970, and 1971; Vere-Jones, 1969; Gibowicz, 1973; Olsson, 1973; Purcaru, 1974; Okada, 1979; Papazachos, 1981; Papazachos and Comninakis, 1982; Lomnitz and Nava, 1983; Singh et al., 1983). It was also found that the finite magnitude difference significantly affects the shape of the recurrence curve for two earthquake populations of mainshocks and aftershocks, and the phenomenon of double

¹ Institute of Earth Sciences, Academia Sinica; P.O. Box 1-55, Nankang, Taipei, R.O.C.
population was demonstrated in the recurrence curves for earthquakes in the seismically active region (Bath, 1980, 1981, and 1983; Wesnousky et al., 1983; Singh et al., 1983). For large earthquakes \((M \geq 5.5)\) within the western Cordillera of the United States, Doser (1989) found that the average value of magnitude difference between mainshocks and their largest aftershocks is \(1.03 \pm 0.47\), and the difference somewhat decreases with increasing heat flow. The difference in time \((T)\) between mainshock and the largest aftershock in an earthquake sequence is also a significant parameter. For 59 Fennoscandian earthquake sequences, Bath (1984) reported that the frequency of earthquake sequence with \(T\) decreases with \(T\), and the average value is about \(7.0 \pm 6.3\) months. It is obvious that the standard deviation is quite large.

Tucker and Brune (1977) compared the \(m_b\) and \(M_s\) values of aftershocks of the 1971 February 9 San Fernando, California earthquake, and concluded that almost all data points of \(m_b\) vs. \(M_s\) lie within 1 standard deviation of the straight line with slope of 1. This means that the source properties of aftershocks of this earthquake show unique \(m_b\)-\(M_s\) scaling. The body-wave magnitude \((m_b)\) is determined from the amplitude of short-period \((\sim 1\) sec\) teleseismic P waves, and the surface wave magnitude \((M_s)\) from the amplitude of long-period \((\sim 20\) sec\) Rayleigh waves. Hence, the relation of the two magnitude scales is considered to be capable of showing the source scaling (Aki, 1967, 1972; Kanamori and Anderson, 1975) and plate tectonic characteristics (Nuttli, 1983a, b), and can be used for distinguishing nuclear explosions from earthquakes (Marshall and Basham, 1972).

Gutenberg and Richter (1944) first proposed the following relation:

\[
\log N = a - bM
\]

(1)

to correlate earthquake magnitude \(M\) to the cumulative number \((N)\) of events with magnitude greater than or equal to \(M\). This relation is commonly considered to be the typical of earthquakes in a broad region as suggested by Gutenberg and Richter (1944), and Ishimoto and Iida (1939), but also for earthquakes in a single fault or fault segment (Nur, 1978; Hanks, 1979; Andrews, 1980; von Seggern, 1980). Wesnousky et al. (1983) called this model the \(b\) value model. However, geological work by Allen (1968), Wallace (1970) and Matsuda (1977) shows a strongly dissimilar result that faults or fault segments generate earthquakes of a characteristic size that is a function of fault length and tectonic settings, and that those events and their foreshocks and aftershocks account for all seismic slip on a fault. Actually, numerous observations show that the maximum magnitude model holds for earthquakes occurring in a fault (Wesnousky et al., 1983; Singh, 1983; Schwartz and Coppersmith, 1984; Davison and Schulz, 1985). Wesnousky et al. (1983) called this model the maximum magnitude model. The maximum magnitude of an earthquake in a region, or a fault or a fault segment can be predicted from observed data through Eq. (1) for the \(b\) value model but not from the maximum magnitude model.

This work is made for studies on the difference in magnitude and occurrence time of mainshocks and the largest aftershocks, the \(M_s\)-\(m_b\) relations and the \(\log N\)-\(M\) relations for mainshocks and aftershocks for several large Taiwan earthquakes.

2. DATA

The data used consists of two sets: the first set is for the events, occurring in the period from 1901 to 1978, reported by Hsu (1971, 1980, 1985); and the second one is for the events, occurring from 1977 to 1991, from the Earthquake Data Report. The magnitude scale used
by Hsu (1971) is the Hsu's magnitude ($M_H$), and the magnitude scales used in the EDR are of two types: surface-wave magnitude ($M_s$) and body-wave magnitude ($m_b$). Wang (1992) stressed that although the $M_H$ was determined from the local seismic data, it is like the surface-wave magnitude ($M_s$).

From the data reported in the National Earthquake Information Service Catalogue, Tajima and Kanamori (1985) showed that the aftershock activity of a 1966 offshore Hualien, Taiwan earthquake was mainly in the 100 days after the mainshock occurrence and the linear size of the related aftershock area was about 50 km. From local seismic data published by the Central Weather Bureau, Chan (1985) reported that the aftershock activity of 1972 Juisui, Taiwan earthquake was mainly in the 100 days after the mainshock occurrence and the linear dimension of the aftershock area was about 50 km. A similar result can also be seen from the results by Chen and Wang (1984) for the 1983 Taipingshan, Taiwan earthquake. Hence, 100 days is considered to be a good interval for the selection of aftershocks. Since the uncertainty in determining the earthquake epicenter is larger from global data than from local data, the linear dimension of 50 km is also a good criterion for the choice of aftershocks. Under the two criteria, 13 mainshocks (No. 1-No. 13 in Table 1) with totally 39 aftershocks from 1906 to 1965 were selected from the first data set, and 18 mainshocks (No. 14-No. 31 in Table 1) with totally 78 aftershocks from 1977 to 1991 were selected from the second data set. The events for the first data set have $M_H$ values greater than 5.0 and those for the second data set have $M_s$ values larger than 4.0. For the 1951 Hualien, eastern Taiwan earthquake sequence, since two large aftershocks with the same magnitude values occurred on the same day and at nearly the same place, that earthquake sequence is not selected in this study.

The related source parameters of earthquakes used are listed in Table 1. The code "No" displays the earthquake sequence. The earthquake sequences from No. 1 to No. 13 belong to the first data set and those from No. 14 to No. 31 belong to the second one. The first event of each sequence is the mainshock. The largest aftershock is denoted by a symbol "*" in Table 1. For sequences No. 3 and No. 4, the largest aftershocks have magnitude values very close to those of their mainshocks, and values of difference in magnitude are 0.4 and 0.0, respectively. The localities of mainshocks are shown in Figure 1: The open cycles represent the mainshocks before 1965 (the first data set), and the solid cycles denote the mainshocks after 1977 (the second data set). Out of 31 mainshocks, 4 (13%) were located in western Taiwan and 27 (87%) in eastern Taiwan. It is noted that there was no earthquake in western Taiwan for the second data set.

3. RESULTS AND DISCUSSION

The data points of the difference in magnitude values ($\Delta M$) of the mainshock and the largest aftershock versus the magnitude (M) of the mainshock are shown in Figure 2. The data points for the first data set are shown by open circles and those for the second data set by solid circles. Essentially, the $\Delta M$ values of the first data set are smaller than those of the second data set. For the two data sets, the $\Delta M$ values increase with the magnitude of mainshock. Meanwhile, except for few data points, the data points of the two data sets are somewhat close to each other for $M < 6.5$, but separate for $M > 6.5$. It is noted that the $\Delta M$ value is not remarkably locality-dependent. The two lines shown in Figure 2 are the regression lines for the two data sets. The regression equations are:

$$\Delta M_H = (-1.377 \pm 0.910) + (0.279 \pm 0.137)M_H$$

(2)
Table 1. The earthquake data used in this study. The first event is the mainshock and the event denoted by a open star is the largest aftershock.

| No | Date       | Lat.  | Long.  | H(km) | $M_H$ | $m_b$ | $M_s$ |
|----|------------|-------|--------|-------|-------|-------|-------|
| 01 | 190603162242 | 23.500| 120.500 |       | 7.10  |       |       |
|    | 190603261129 | 23.500| 120.500 |       | 5.00  |       |       |
|    | 190604070053 | 23.500| 120.500 |       | 5.50  |       |       |
|    | 190604072240 | 23.500| 120.500 |       | 5.50  |       |       |
|    | 190604131918 | 23.500| 120.500 |       | 6.60  |       |       |
|    | 190604140752 | 23.500| 120.500 |       | 5.80  |       |       |
| 02 | 191701041655 | 23.900| 120.900 |       | 5.80  |       |       |
|    | 191701061808 | 23.900| 120.900 |       | 5.60  |       |       |
| 03 | 192209011916 | 24.600| 122.200 |       | 7.60  |       |       |
|    | 192209141931 | 24.600| 122.300 |       | 7.20  |       |       |
|    | 192210150747 | 24.500| 122.200 |       | 5.90  |       |       |
|    | 192212021146 | 24.600| 122.000 |       | 6.00  |       |       |
| 04 | 193012081610 | 23.300| 120.400 | 05.0  | 6.50  |       |       |
|    | 193012220808 | 23.300| 120.400 |       | 6.50  |       |       |
|    | 193012221219 | 23.300| 120.400 |       | 5.60  |       |       |
| 05 | 193101012352 | 23.500| 122.000 |       | 6.03  |       |       |
|    | 193102130041 | 24.100| 121.900 |       | 5.74  |       |       |
| 06 | 193504222001 | 24.300| 120.800 | 10.0  | 7.10  |       |       |
|    | 193504222226 | 24.700| 120.900 |       | 6.00  |       |       |
|    | 193505042302 | 24.500| 120.800 |       | 6.00  |       |       |
|    | 193507161619 | 24.400| 120.700 | 30.0  | 6.40  |       |       |
| 07 | 193712081633 | 23.100| 121.400 |       | 7.00  |       |       |
|    | 193712170932 | 22.800| 121.500 |       | 6.60  |       |       |
| 08 | 195710191829 | 23.700| 121.300 | 10.0  | 6.60  |       |       |
|    | 195801221829 | 23.600| 121.300 | 05.0  | 6.00  |       |       |
| 09 | 195908150857 | 21.700| 121.300 | 20.0  | 6.80  |       |       |
|    | 195908180034 | 22.100| 121.700 | 15.0  | 6.10  |       |       |
|    | 195909250237 | 22.100| 121.200 | 10.0  | 6.50  |       |       |
| 10 | 196104091535 | 23.800| 122.300 | 56.0  | 6.50  |       |       |
|    | 196105191637 | 23.300| 123.600 | 65.0  | 5.50  |       |       |
|    | 196109170842 | 23.700| 122.200 | 45.0  | 5.90  |       |       |
| 11 | 196302130850 | 23.800| 122.100 | 47.0  | 7.20  |       |       |
|    | 196303041338 | 24.600| 121.800 | 05.0  | 6.10  |       |       |
|    | 196303100025 | 24.500| 121.800 | 05.0  | 6.00  |       |       |
| 12 | 196304210438 | 23.900| 122.200 | 20.0  | 5.50  |       |       |
|    | 196304262345 | 23.900| 122.200 | 05.0  | 5.30  |       |       |
|    | 196305111749 | 23.900| 122.000 | 10.0  | 5.40  |       |       |
| 13 | 196504262215 | 21.200| 120.700 | 33.0  | 6.10  |       |       |
|    | 196505280516 | 21.000| 120.900 | 38.0  | 5.40  |       |       |

for the first data set and

$$
\Delta M_s = (-2.965 \pm 1.081) + (0.638 \pm 0.174) M_s
$$

for the second data set. The slope value of Eq. (3) is larger than that of Eq. (2). The two lines display a systematic difference in magnitude between the two data sets. Although Wang (1992) stated the similarity between $M_H$ and $M_s$, his conclusion might be not good enough for larger events because his data set has a small number of events with $M_s > 6.5$. Meanwhile, for the events with $M_s > 6.5$ used in his study, the $M_s$ values are greater than
Table 1. (Continued.)

| No | Date          | Lat.  | Long.  | H(km) | \(M_H\) | \(m_b\) | \(M_S\) |
|----|---------------|-------|--------|--------|---------|---------|---------|
| 14 | \(197707150212\) | 24.051 | 122.214 | 33.4 | 5.5 | 5.7 |
|    | \(\star 197712252233\) | 24.175 | 121.690 | 40.5 | 5.2 | 4.7 |
| 15 | \(197802080015\) | 24.146 | 122.663 | 39.9 | 5.5 | 5.7 |
|    | \(\star 197803142032\) | 24.072 | 122.638 | 42.7 | 5.5 | 5.4 |
| 16 | \(197807231442\) | 22.282 | 121.512 | 16.9 | 6.3 | 7.4 |
|    | \(\star 197807241141\) | 22.242 | 121.574 | 30.4 | 5.0 | 5.5 |
|    | \(197807242354\) | 22.135 | 121.437 | 18.0 | 5.0 | 5.4 |
|    | \(197807250416\) | 22.531 | 121.270 | 10.7 | 4.1 | 4.5 |
|    | \(197807251756\) | 22.346 | 121.391 | 27.6 | 5.2 | 4.8 |
|    | \(197807260334\) | 22.186 | 121.290 | 24.0 | 4.7 | 4.6 |
|    | \(197808071016\) | 22.576 | 121.342 | 33.0 | 5.4 | 4.6 |
| 17 | \(197812231123\) | 23.247 | 122.075 | 33.0 | 6.6 | 7.0 |
|    | \(\star 197812231503\) | 23.050 | 121.873 | 33.0 | 5.0 | 4.9 |
|    | \(\star 197812260749\) | 22.907 | 121.700 | 10.0 | 5.1 | 5.3 |
|    | \(197812271446\) | 23.245 | 122.159 | 33.0 | 4.9 | 4.2 |
| 18 | \(197912020525\) | 22.919 | 121.448 | 36.5 | 5.5 | 5.7 |
|    | \(\star 197912230946\) | 22.965 | 121.740 | 33.0 | 5.1 | 5.1 |
| 19 | \(198103021213\) | 22.894 | 121.453 | 23.5 | 5.5 | 5.9 |
|    | \(\star 198103272241\) | 22.981 | 121.662 | 26.0 | 4.6 | 4.6 |
|    | \(198109122332\) | 22.970 | 121.427 | 33.9 | 4.8 | 4.5 |
| 20 | \(198201231410\) | 23.900 | 121.707 | 17.0 | 5.6 | 5.9 |
|    | \(\star 198201271653\) | 23.790 | 121.588 | 35.5 | 5.0 | 4.7 |
| 21 | \(198306240906\) | 24.176 | 122.402 | 44.1 | 6.1 | 6.7 |
|    | \(\star 198306251940\) | 24.008 | 122.528 | 34.4 | 5.4 | 5.0 |
|    | \(198309072311\) | 24.032 | 122.327 | 33.0 | 5.5 | 5.7 |
|    | \(198309091701\) | 24.094 | 122.373 | 33.0 | 5.3 | 5.1 |
| 22 | \(\star 198309211920\) | 24.095 | 122.148 | 28.2 | 6.0 | 6.4 |
|    | \(\star 198309231229\) | 24.013 | 122.228 | 32.4 | 5.7 | 5.8 |
|    | \(198309250329\) | 23.937 | 122.266 | 33.0 | 5.1 | 4.0 |
|    | \(198310050329\) | 24.070 | 121.768 | 33.0 | 5.0 | 4.6 |
|    | \(198310072005\) | 23.969 | 122.584 | 33.0 | 5.1 | 4.7 |
|    | \(198401191112\) | 24.138 | 122.371 | 34.9 | 5.0 | 5.2 |
| 23 | \(198506121722\) | 24.585 | 122.078 | 27.9 | 5.2 | 5.8 |
|    | \(\star 198507101706\) | 24.199 | 121.745 | 35.0 | 4.8 | 4.1 |
| 24 | \(198508051300\) | 24.394 | 121.886 | 10.0 | 5.2 | 5.5 |
|    | \(\star 198509201501\) | 24.593 | 122.280 | 18.4 | 5.3 | 5.1 |

the \(M_H\) values. Hsu's magnitude was estimated from the peak amplitude value of local seismograms recorded by the old seismographs of the Central Weather Bureau (CWB, formerly Taiwan Weather Bureau) through the formulae calibrated based on surface-wave magnitude. The predominant period of the peak amplitude values is around 1 second. From the scaling law proposed by Aki (1967, 1972), the displacement amplitude value of 1 second period and that of 20 second period cannot increase with the same rate with the earthquake magnitude and the former is usually saturated as the magnitude is greater than 3. The saturation becomes very serious as the magnitude value is greater than 7. Hence, it is suggested that the magnitude values of the mainshocks of the first data set were under-estimated. The under-estimation might increase with magnitude. On the other hand, the peak amplitude of
Table 1. (Continued.)

| No | Date               | Lat.  | Long.   | H(km) | $M_H$ | $m_b$ | $M_S$ |
|----|--------------------|-------|---------|-------|-------|-------|-------|
| 25 | 1986052200525      | 24.125| 121.619 | 19.3  | 6.1   | 6.4   |       |
|    | 198605221747       | 23.934| 121.686 | 28.6  | 4.9   | 4.8   |       |
| *  | 198606041620       | 23.951| 121.739 | 20.1  | 5.1   | 5.3   |       |
| 26 | 198607301131       | 24.611| 121.782 | 33.0  | 5.6   | 5.6   |       |
|    | 198607311116       | 24.829| 122.761 | 33.0  | 5.1   | 5.2   |       |
| 27 | 198611142120       | 23.901| 121.574 | 33.8  | 6.3   | 7.8   |       |
|    | 198611142304       | 23.866| 121.711 | 33.0  | 6.1   | 6.3   |       |
|    | 198611150100       | 23.955| 121.839 | 28.0  | 5.1   | 5.4   |       |
|    | 198611150724       | 23.877| 121.677 | 33.0  | 5.5   | 5.8   |       |
|    | 198611151612       | 23.923| 122.039 | 33.0  | 4.9   | 4.9   |       |
|    | 198611180849       | 24.008| 121.787 | 33.0  | 5.1   | 5.2   |       |
|    | 198611260949       | 24.215| 121.858 | 32.5  | 4.8   | 4.5   |       |
|    | 198611300303       | 23.950| 121.960 | 33.5  | 5.1   | 4.2   |       |
| 28 | 198908212312       | 24.094| 122.478 | 42.8  | 5.6   | 6.3   |       |
|    | 198908222002       | 23.957| 122.610 | 37.9  | 4.9   | 5.0   |       |
|    | 198909061216       | 24.048| 122.562 | 23.8  | 4.2   | 4.5   |       |
|    | 198909061339       | 23.993| 122.569 | 32.8  | 5.0   | 4.3   |       |
| 29 | 199012131950       | 23.722| 121.627 | 10.0  | 5.9   | 6.3   |       |
|    | 199012132156       | 23.713| 121.673 | 10.0  | 5.3   | 5.1   |       |
|    | 199012132318       | 23.681| 121.625 | 10.0  | 5.4   | 5.7   |       |
|    | 199012132328       | 23.807| 121.678 | 10.0  | 5.7   | 5.4   |       |
|    | 199012140143       | 23.822| 121.716 | 10.0  | 5.1   | 4.9   |       |
|    | 199012140237       | 23.584| 121.677 | 10.0  | 5.1   | 4.9   |       |
|    | 199012140455       | 23.883| 121.758 | 10.0  | 4.6   | 4.4   |       |
|    | 199012180439       | 23.766| 121.772 | 10.0  | 5.0   | 4.8   |       |
|    | 199012190020       | 23.701| 121.579 | 10.0  | 5.2   | 5.3   |       |
|    | 199012192338       | 23.669| 121.606 | 10.0  | 5.3   | 5.2   |       |
| 30 | 199103260358       | 21.704| 121.789 | 17.7  | 5.8   | 6.3   |       |
|    | 199103260619       | 21.673| 121.826 | 19.4  | 5.2   | 5.1   |       |
|    | 199103260637       | 21.633| 121.714 | 10.0  | 4.4   | 3.9   |       |
| *  | 199103261024       | 21.867| 121.610 | 10.0  | 5.3   | 5.5   |       |
|    | 199103261240       | 21.653| 121.992 | 10.0  | 4.2   | 3.7   |       |
|    | 199103261343       | 21.607| 121.871 | 10.0  | 4.3   | 4.8   |       |
|    | 199103261420       | 22.175| 121.657 | 10.0  | 4.4   | 4.0   |       |
|    | 199103261830       | 21.870| 121.722 | 10.0  | 4.6   | 4.8   |       |
|    | 199104091004       | 21.548| 121.850 | 10.0  | 4.5   | 4.0   |       |
| 31 | 199109300944       | 22.535| 121.479 | 24.3  | 5.5   | 5.2   |       |
| *  | 199110120508       | 22.798| 121.536 | 7.7   | 5.1   | 4.8   |       |
|    | 199112051548       | 22.544| 121.450 | 16.5  | 4.6   | 4.7   |       |

the Rayleigh waves with period of around 20 seconds in the seismograms recorded on the world-wide stations is less saturated as the magnitude value is smaller than 8. Hence, the magnitude values of the mainshocks of the second data set, which are smaller than 8, could be estimated to some extent correctly. On the other hand, the magnitude value of the largest aftershock can be correlatively determined from both the long-period and the short-period signal because its value is not so large as that of the mainshock. Therefore, the difference in magnitude between the mainshock and the largest aftershock must be smaller for $M_H$ scale than for $M_S$ scale. This interprets the systematic difference in Eq. (2) and Eq. (3) and the data points shown in Figure 2.

The seismic energy $E$ relates to surface-wave magnitude ($M_S$) in the following form:
Fig. 1. Figure shows the localities of mainshocks listed in Table 1. The open circles represent the events of the first data set and the solid circles denote the events of the second one as described in the text. The number near the circles is the number of event listed in Table 1.

Fig. 2. Figure shows the data points of $\Delta M$ vs. $M$: the open circles for events of the first data set and the solid circles for events of the second data set. The two solid lines represent the regression lines of the two data, respectively.
\[ \log E = 11.8 + 1.5M_s \]  

(4)

by Gutenberg and Richter (1956). Let \( E_0 \) and \( E_a \) be the seismic energy of mainshock and the largest aftershock, respectively. Hence, \( \log(E_0/E_a) = 1.5\Delta M_s \). From Eq. (3), the \( \Delta M_s - M_s \) relation approximately has the form \( \Delta M_s \sim 2/3M_s \). Thus \( \log(E_0/E_a) \sim \Delta M_s \) or \( E_a/E_0 \sim 10^{1/M_s} \). This leads to the fact that the \( E_a/E_0 \) value decreases exponentially with the mainshock magnitude. The larger the mainshock magnitude is, the bigger the energy releases during the mainshock occurrence. Therefore, for large Taiwan earthquakes, the seismic energy of an earthquake sequence is mainly released from the mainshock. It is noted that for earthquakes within the western Cordillera of the United States, Doser (1989) reported a similar result.

The distributions of number of events versus magnitude difference for the two data sets are shown in Figure 3, in which the upper diagram is made for the first data set and the lower one for the second data set. From the upper diagram, it can be seen that the number of events is quite uniform for \( \Delta M_H < 1.2 \), and from the lower diagram, the number of events distributes in a wider range of \( \Delta M \) value. In order to compare the two variations quantitatively, the mean values, standard deviations and their ratio are computed. For the first data set, the mean value \( (m_1) \) is 0.46 and the standard deviation \( (\sigma_1) \) is about 0.29. Their ratio, i.e. \( C_v_1 = \delta_1/m_1 \), is 0.63. For the second data set, the mean value \( (m_2) \), standard deviation \( (\sigma_2) \) and the \( C_v_2 \) value are 0.99, 0.51, and 0.52, respectively. The mean value of the first data set is smaller than that of the second data set. The two \( C_v \) values (0.63 and 0.52) are smaller than 1, and thus the distributions of number vs. magnitude difference are not considered to be the Poisson distribution. In order to test the hypothesis \( H_0: m_1 = m_2 \) vs. \( H_1: m_1 < m_2 \), we must employ the test statistic

\[ t = (m_1 - m_2)/S \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \]  

(5)

where \( n_1 \) and \( n_2 \) are the numbers of events of the two data sets and \( S \) is the pooled sample variance and calculated by the following formula:

\[ S = \frac{\Sigma(X_1 - m_1)^2 + \Sigma(Y_1 - m_2)^2}{(n_1 + n_2 - 2)}. \]  

(6)

Fig. 3. The number of earthquakes with a \( \Delta M \) value: (a) for the first data set and (b) for the second data set.
In Eq. (6), $X_i$ and $Y_i$ are the $i$-th values of the first and the second data sets, respectively. The $t$-value with risky coefficient $\alpha=0.05$ is 3.36, which is greater than the theoretical $t$ value (1.699) for the degree of freedom $= 29$. Hence, the $H_1$ hypothesis is held, i.e. the fact that the mean value (0.46) of the first data set is smaller than that (0.99) of the second data set is statistically reasonable and not due to the uncertainty of given data. The reason for this distinction is unclear.

Figure 4 shows the data points of $\log T$, where $T$ indicates the difference in occurrence times of mainshock and its largest aftershock in hours, versus the magnitude ($M$) of mainshock. In this figure, the data points of the first data set (denoted by open circles) depart from those of the second data set (denoted by solid circles). For a certain $M$, the $T$ values of the first data set are in general larger than those of the second one. In about 23\% of the earthquake sequences, the values of difference in time are less than one day. For earthquake sequence No. 6 with mainshock magnitude of 7.1, the difference in time is less than one hour. Generally speaking, the distribution of the data points is quite dispersive. Nevertheless, the $\log T$ value decreases somewhat with magnitude. It means that on the average, the largest aftershock occurs earlier after a bigger mainshock than after a smaller one.

![Figure 4](image)

**Fig. 4.** Figure shows the data points of $\log T$ vs. $M$: the open circles for first data set and the solid circles for the second data set.

To understand the correlation of the long-period magnitude $M_s$ to the short-period magnitude $m_b$ for an earthquake sequence, the data points of $M_s$ vs. $m_b$ for four earthquake sequences Nos. 16, 27, 29 and 30, whose numbers of data are greater than 8, are shown in Figure 5. The data points for aftershocks are denoted by small open circles and those for mainshocks by large open circles. The solid lines for the four cases are the regression lines obtained from the data points of aftershocks through the least-squared method. The data points of earthquake sequences Nos. 27, 29 and 30 show linear distribution, while those of earthquake sequence No. 16 somewhat form a cluster. Hence, the regression lines of the former three sequences are more reliable than those of the latter one. The slope values of the three regression lines of the three earthquake sequences are very similar. This seems to demonstrate a very similar $M_s$-$m_b$ scaling law for aftershocks of the three sequences. The relation of $M_s$-$m_b$ scaling for 16 moderate Taiwan earthquakes deduced by Wang (1985) is also shown in Figure 5 with a dashed line. Except for the solid line of the No. 16 sequence, the other three solid lines are very consistent with the dashed line obtained by Wang (1985). Essentially, the source scaling based on the $M_s$-$m_b$ relation for aftershocks of the three mainshocks is the same as that of moderate Taiwan earthquakes. For earthquake
sequence No. 27, the data point of mainshock departs from the regression line to some extent. This implies that the scaling of source property of the mainshock might be different from that of aftershocks. Since the data points of the mainshocks is beyond the regression line, the long-period waves generated by the mainshock must be stronger than those from aftershocks and the short-period waves produced by the mainshock are comparable with those from aftershocks. Through synthetic seismogram analysis, Wu et al. (1989) reported that the source process of the mainshock of this earthquake sequence consisted mainly of three subevents. Hence, the deviation of the data point of mainshock from the regression line is physically reasonable.

![Diagram](image)

Fig. 5. Figure shows the data points of $M_s$ vs. $m_b$ for four earthquake sequences: (a) for No. 16, (b) for No. 27, (c) for No. 29 and (d) for No. 30. (Large open circles for mainshocks and small ones for aftershocks). The solid lines represent the regression lines from the four data points of aftershocks. The dotted line of (a) is explained in the text. The dashed line represents the $M_s$-$m_b$ relation obtained by Wang (1985).
For earthquake sequence No. 16, the data point of mainshock deviates very much from the solid line, since the data points are not distributed along the regression line very well. As discarding two data points as shown by open circles with a small bar, whose Ms and mb values were estimated from few earthquake data, a new regression line is quite different from the old one and displayed with a dotted line. It is obvious that the data points of mainshock are close to the new regression line. The new line coincides with the dashed line obtained by Wang (1985) and, of course, is consistent with the solid lines of the other three sequences. Hence, according to the similarity of the Ms-mb scaling of aftershocks as mentioned in the above, the new line seems to be acceptable. However, from the limited data, it is actually quite difficult to determine which line is correct. Based on the source rupture process from the teleseismic long-period P waves, Chou and Wang (1992) concluded that the mainshock of July 23, 1978 Lanhsu, earthquake sequence, i.e. the present one, consisted of at least two large subevents with a time difference of about 23 sec. This difference in time could appear in the teleseismic P waves, which accounts for mb value, but not in the teleseismic Rayleigh waves, which are used for the determination of Ms value. The first-arriving P waves must be generated by the first subevent, and thus the mb value of mainshock concerned the first subevent. The Ms value was estimated from the teleseismic Rayleigh waves, which were formed by the superposition of P waves and S waves generated from the two subevents and some others, and thus the Ms value was associated with the total behavior of the subevents. Hence, the deviation of the data points of mainshock from the regression line must be reasonable. The old line rather than the new line can show the deviation. This means that the present data can not lead to a substantial conclusion.

On the other hand, for earthquake sequence No. 29 and No. 30, the data point of mainshock is very close to the individual regression line estimated from aftershocks. This means that the source scaling is the same for mainshock and aftershocks. Unlike earthquake sequences No. 16 and No. 27, both Ms and mb values of the mainshocks of the two present earthquake sequences are small. The source rupture properties of the two mainshocks might be not so complicated as those of the former. It is proposed that the mainshocks and their aftershocks of the present two earthquake sequences must have similar source scaling.

The data points of logN vs. Ms for four earthquake sequences Nos. 16, 27, 29 and 30 are shown in Figure 6. Although the data set is very small, an interesting result can still be obtained. The regression line is shown in Figure 6 with a solid line but the related regression equation is not given. Generally speaking, the data point of mainshock is somewhat away from the trend of the data points for aftershocks. The values of difference in magnitude of mainshock and the maximum magnitude estimated from the regression line are 0.9, 1.6, 0.6, and 0.9 for earthquake sequences No. 16-No. 30. In other words, the mainshock magnitude cannot be predicted from the logN-M relation of aftershocks. The difference in magnitude between the mainshock and the maximum event estimated from the regression equation increases somewhat with the magnitude of the mainshock. Results of this study are similar to those obtained by Wesnousky et al. (1983) and Davison and Scholz (1985). Hence, the maximum magnitude model proposed by Wesnousky et al. (1983) seems to be more appropriate to describe the behavior of Taiwan earthquake sequences than the b-value model.
Fig. 6. The four diagrams show the data points of logN vs. $M_s$ for four earthquake sequences: (a) for No. 16, (b) for No. 27, (c) for No. 29 and (d) for No. 30 (Large open circles for mainshocks and the small open circles for aftershocks). The solid lines represent the regression lines of the data points of aftershocks.

4. CONCLUSION

From the given data, several points can be concluded as follows:

1. The difference ($\Delta M$) in the magnitude of mainshock and the largest aftershock increases with the mainshock magnitude ($M$). The variations of $\Delta M$ vs. $M$ are different for Hsu's data set and the EDR data set. The difference might be due to the difference in the use of the peak amplitudes of magnitude scales in the two catalogues: a 1-second signal for the former and a 20-second one for the latter.

2. The data points of the difference value (T) in the original times of mainshocks and the largest aftershocks versus the magnitude of the mainshocks ($M$) are quite scattered. Nevertheless, the T value somewhat decreases with the increases of the M value.
(3.) From the data of four earthquakes, the departure of \( M_a - m_b \) scaling of the mainshock from that of aftershocks seems to be bigger for larger mainshocks than for smaller ones. 

(4.) The mainshock magnitude is larger than the maximum magnitude estimated from the log\( N - M \) obtained from aftershock data. The value of difference is bigger for larger mainshocks than for smaller mainshocks.

Acknowledgements The authors would like to express their thanks to our colleague Mr. S. N. Cheng for providing some seismic data for earthquakes after 1978. This study was financially supported by Academia Sinica, R.O.C..

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