Relationships Among Magnitudes and Seismic Moment of Earthquakes in the Taiwan Region

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ABSTRACT

The seismic moments (M_o), body-wave magnitudes (m_b), and surface-wave magnitudes (M_s) of 201 Taiwan earthquakes with $4.8 \leq m_b \leq 6.6$ published in the Global CMT catalog from 1976 to 2006 are used to study the correlations among the three source parameters. The resultant relationships are: $\log(M_o) = (1.07 \pm 0.04) M_s + (18.72 \pm 0.20)$; $\log(M_o) = (1.73 \pm 0.09) m_b + (15.09 \pm 0.52)$; and $M_s = (1.46 \pm 0.08) m_b - (2.52 \pm 0.43)$. The three relationships have high agreement with those of earthquakes in the circum-Pacific seismic belt. This might imply that the tectonic conditions and source properties of the Taiwan region behave like the average ones of the circum-Pacific seismic belt. The relationships between the three source parameters and local magnitude are: $\log(M_o) = (1.27 \pm 0.06) M_L + (17.23 \pm 0.35)$; $m_b = (0.66 \pm 0.03) M_L + (1.69 \pm 0.17)$; and $M_s = (1.03 \pm 0.06) M_L - (0.53 \pm 0.36)$.

(Key words: Seismic moment, Magnitude scales, Relationship)

1. INTRODUCTION

Magnitude is regarded as the most directly measurable and simple parameter to specify quantitatively the size of an earthquake. Since Richter (1935) first defined the local magnitude, M_L, several magnitude scales have been proposed. The surface-wave magnitude (M_s) and body-wave magnitude (m_b) are two commonly-used scales. From the study of source mechanism by an elastic dislocation theory, Aki (1966, 1967) stated that the amplitude of a very long period wave is proportional to the seismic moment, M_o, of an earthquake. Aki (1966) first measured the value of M_o of the 1964 Niigata, Japan, earthquake. Ben-Menahem et al. (1969) also suggested

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that the far-field static-strain field is proportional to M_o. From then on, seismic moment was considered a new parameter to specify the size of an earthquake. Based on M_o, moment magnitude has been defined by Hanks and Kanamori (1979) since 1979.

M_L, M_s, m_b, and M_o are estimated from seismic waves of different types and periods (cf. Miyamura 1978): M_L from the maximum trace amplitude in millimeters recorded on a Wood-Anderson standard torsion seismograph, M_s from teleseismic surface waves in the period range of 17 - 23 sec, m_b from teleseismic P-waves in the period range of 0.1 - 3 sec., and M_o from mantle waves, a very long period range. Various magnitude scales will sample different information of the radiated spectrum generated from the fracture process of an earthquake. Miyamura (1982) stated that combined use of different magnitude scales will give better description of the nature of an earthquake and seismicity. Nortman and Duda (1983) argued that the large variety of magnitude scales indicates that the strength of an earthquake needs to be determined from various parts of the radiated spectrum.

There are some relationships among source parameters (Chung and Bernreuter 1981; Wang 1992). This concept can be illustrated by the scaling law proposed by Aki (1967). Aki (1967) first studied the correlation between M_s and m_b, which is the original body-wave magnitude defined by Gutenberg (1945), constructed by Gutenberg and Richter (1956). His results showed that the ω^{-2} model proposed by Aki (1967) is better than the ω^{-3} model suggested by Haskell (1964). The two source spectral models are briefly described below: at low frequencies, the spectral amplitude is almost proportional to the seismic moment; while at high frequencies, especially for higher than the corner frequency, the spectral amplitude is proportional to ω^{-2} for the former and ω^{-3} for the latter. Aki (1972) constructed the theoretical correlation for $\log(M_o)$ versus M_s. His results show that $\log(M_o)$ exponentially increase with M_s. Of course, his correlation can be simplified to be: $\log(M_o) \sim 3\,M_s$ as $M_s > 7$ and $\log(M_o) \sim M_s$ as $M_s < 7$. Kanamori and Anderson (1975) studied the correlation between these based on the ω^{-2} model, with a more reliable relation between fault length and duration time than that suggested by Aki (1972). Their results show $\log(M_o) \sim 1.5\,M_s$ for common earthquakes and $\log(M_o) \sim 3\,M_s$ for some events with long duration times. Geller (1976) studied the correlations of M_o versus M_s and M_s versus m_b based on the ω^{-3} model. His results show the dependence of the correlations upon magnitude range. Ekstrom and Dziewonski (1988) obtained the empirical relationship of $\log(M_o)$ versus global earthquakes: (1) $\log(M_o) = 19.24 + M_s$ for $M_s \leq 5.3$; (2) $\log(M_o) = 30.20 - (92.45 - 11.40\,M_s)^{1/2}$ for $5.3 \leq M_s \leq 6.8$; and (3) $\log(M_o) = 16.14 + 1.5\,M_s$ for $M_s \geq 6.8$. Koyama (1994) obtained theoretical correlations among the three parameters: (1) $\log(M_o) \sim M_s$ for $M_s < 7.5$ and $\log(M_o) \sim 2\,M_s$ for $M_s > 7.5$; (2) $\log(M_o) \sim 2.5\,m_b$.

However, the relationships should be of regional dependence (cf. Chung and Bernreuter 1981). The interrelations among various source parameters may display regional characteristics. A particularly significant problem is to discriminate different tectonic provinces by the use of the above-mentioned concept. In a series of papers, Nuttli (1983a, b, c) found distinction between the average source parameter relations for mid-plate earthquakes and those for plate-margin earthquakes.

Because Taiwan is situated at the collision boundary between the Eurasian plate and the Philippine Sea plate (Tsai et al. 1977; Wu 1978; Lin 2002), the earthquakes occurring in this region should have plate-margin characteristics. Wang (1985) estimated the relationships of

M_o versus M_s, M_o versus m_b, and M_s versus m_b for 16 earthquakes in the Taiwan region, and stated that the relationships for regional events are similar to those for global earthquakes inferred by Nuttli (1985). Yeh et al. (1982) determined the local magnitude from the maximum amplitude of the Wood-Anderson-type seismograms simulated from accelerograms. Yeh and Hsu (1985) determined the local magnitude from the maximum amplitude of the seismogram recorded by a simulated Wood-Anderson seismograph operated by the Institute of Earth Sciences (IES), Academia Sinica (Liu 1981). They related this local magnitude to duration magnitude. Cheng and Yeh (1989) related this local magnitude to m_b for 143 events that occurred from 1873 to 1985. Wang et al. (1989) determined the local magnitude from the maximum amplitude of the seismogram recorded by the same simulated Wood-Anderson seismograph and also related the local magnitude to M_o and m_b determined from teleseismic data. Li and Chiu (1989) correlated seismic moment to local magnitude for earthquakes in Taiwan. Wang (1998) reviewed numerous relationships among seismic moment and earthquake magnitudes. Shin (1993) determined the local magnitude from the maximum amplitudes of the Wood- Anderson-type seismograms simulated from short-period seismograms of the Central Weather Bureau Seismic Network (CWBSN). Since 1991, this local magnitude has been used by CWBSN to quantify earthquakes in Taiwan. Although this local magnitude is not defined based on a standard Wood-Anderson seismograph, it is still denoted by M_L below.

However, the relationships inferred by Wang (1985) were just based on a small data set. Since 1985 more earthquakes have occurred in the Taiwan region. To understand the general characteristics of the source spectra of earthquakes, it is necessary to investigate the relationships again. Therefore, in this study these relationships will be inferred by using more data published in the Earthquake Data Report (EDR) of the United States Geological Survey (USGS). Since September 1991 the local magnitude of earthquakes has been routinely determined by the CWBSN (Shin 1993). Hence, it is significant to investigate the relationships of M_o versus M_L, m_b versus M_L, and M_s versus M_L.

2. DATA

Since 1968, the body-wave magnitudes and surface-wave magnitudes have been routinely determined by the USGS for large earthquakes around the world. Since October 1982 the seismic moment has been also provided in the EDR of the USGS for larger-sized earthquakes. Since the summer of 2006, the main activities of the Harvard CMT Project have been under "The Global CMT Project." The CMT solutions and the best double couples are published at the web site http://www.globalcmt.org/. Since September 1991, the CWBSN has routinely estimated the local magnitude of earthquakes from simulated Wood-Anderson seismograms, which are produced from digital three-component short-period seismograms (Shin 1993). A total of 209 earthquakes in the Taiwan region, ranging from 119 to 123.5°E and 21 to 26°N, during the period of January 1977 to October 2006 are selected from the Global CMT catalog. The selected data are compared with those events located by the CWBSN. Eight distant events are excluded because they are not located by the CWBSN. The related source parameters of 201 earthquakes are $4.2 \leq M_s \leq 7.8$; $4.8 \leq m_b \leq 6.6$; $4.6 \leq M_L \leq 7.3$; and 1.4×10^{23} dyne-cm $\leq M_o \leq 3.38 \times 10^{27}$ dyne-cm. The focal depths range from 0.5 to 61 km. Earthquake locations as

well as focal depths taken from the CWBSN catalog and source parameters are listed in Table 1. The columns denoted by 'M$_o$', 'm$_b$', 'M$_s$', and 'M$_L$' present the seismic moment, body-wave magnitude, surface-wave magnitude, and local magnitude, respectively. Figure 1 shows their epicenters. Most events are located in eastern and offshore Taiwan.

Table 1. Seismic source parameters of 201 moderate Taiwan earthquakes during January 1977 to October 2006. The data are selected from the Global CMT catalog of the United States Geological Survey. The unit of M$_o$ is 10^{25} dyne-cm.

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m$_b$	M$_s$	M$_L$	M$_o$
1	1977/01/07/19:36	21.81	120.25	5.00	5.7	5.1	—	0.388
2	1977/07/15/02:12	23.96	122.38	0.60	5.5	5.7	—	0.681
3	1978/02/08/00:15	23.92	122.70	5.00	5.5	5.7	—	1.4
4	1978/03/14/20:32	23.90	122.78	6.62	5.5	5.4	—	0.671
5	1978/04/29/19:25	24.65	122.77	14.00	5.4	5.8	—	0.845
6	1978/07/23/14:42	22.35	121.33	6.10	6.5	7.4	—	86.4
7	1978/08/09/18:35	23.50	121.50	13.04	5.2	5.5	—	0.171
8	1978/09/10/16:34	24.04	121.76	3.06	5.4	5.1	—	0.248
9	1978/12/23/11:23	23.30	122.00	4.12	6.6	7.0	—	35.6
10	1979/12/02/05:25	22.96	121.41	19.05	5.5	5.7	—	0.804
11	1980/10/18/00:08	24.26	121.89	10.00	5.0	5.5	—	0.225
12	1980/11/07/12:36	23.96	122.30	24.28	5.4	5.4	—	0.581
13	1981/01/29/04:51	24.42	121.91	12.81	5.6	5.5	—	0.968
14	1981/02/20/20:09	22.91	121.43	21.26	5.4	5.7	—	0.071
15	1981/03/02/12:13	22.95	121.43	14.30	5.5	5.9	—	1.48
16	1982/01/23/14:10	23.91	121.63	3.25	5.6	6.0	—	1.307
17	1982/10/20/20:01	23.77	121.96	3.13	5.4	5.9	—	0.837
18	1983/05/10/00:15	24.46	121.51	1.23	5.7	5.4	—	0.427
19	1983/06/21/14:48	23.90	122.57	14.77	5.8	6.3	—	2.58
20	1983/06/25/19:40	23.82	122.64	16.28	5.5	5.0	—	0.174
21	1983/09/07/23:11	23.90	122.49	21.68	5.5	5.7	—	0.265

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
22	1983/09/09/17:01	23.92	122.60	15.88	5.3	5.1	—	0.3
23	1983/09/21/19:20	23.94	122.32	18.00	6.0	6.4	—	5.06
24	1983/09/23/12:29	23.89	122.35	12.32	5.7	5.9	—	1.102
25	1983/10/07/20:05	23.84	122.66	17.69	5.1	4.7	—	0.048
26	1984/01/19/11:12	24.04	122.49	21.62	5.1	5.2	—	0.065
27	1984/03/28/09:11	23.88	122.78	10.30	5.5	5.9	—	0.88
28	1984/04/19/17:29	24.82	122.24	6.10	5.2	5.0	—	0.081
29	1984/12/29/01:06	24.80	122.02	60.74	5.4	5.0	—	0.284
30	1985/01/13/21:51	24.01	122.22	44.15	5.8	5.3	—	0.173
31	1985/02/18/19:41	23.44	123.00	10.33	5.7	5.6	—	0.315
32	1985/06/12/17:22	24.57	122.19	3.31	5.2	5.8	—	0.772
33	1985/09/20/15:01	24.53	122.20	6.11	5.3	5.0	—	0.18
34	1986/01/16/13:04	24.76	121.96	10.22	5.5	5.9	—	1.071
35	1986/02/27/06:23	23.91	122.47	7.20	5.8	5.4	—	0.568
36	1986/03/22/04:45	23.36	121.74	28.45	5.6	5.1	—	0.847
37	1986/03/22/10:31	24.75	122.92	33.00	5.2	5.7	—	0.285
38	1986/03/22/12:06	24.76	122.20	7.08	5.3	5.7	—	0.535
39	1986/03/22/14:27	24.56	122.61	1.25	4.9	5.5	—	0.126
40	1986/03/25/12:13	24.76	122.66	5.90	5.1	5.0	—	0.063
41	1986/05/20/05:25	24.08	121.59	15.82	6.2	6.3	—	2.37
42	1986/06/04/16:21	23.94	121.68	1.41	5.2	5.3	—	0.097
43	1986/07/30/11:31	24.63	121.79	1.55	5.6	5.6	—	0.22
44	1986/07/31/11:36	24.83	122.66	6.50	5.1	5.2	—	0.093
45	1986/11/14/21:20	23.99	121.83	15.00	6.2	7.8	—	130
46	1986/11/15/07:24	23.90	121.69	14.20	5.5	5.8	—	0.529
47	1987/01/06/05:07	23.91	121.84	28.61	5.8	5.6	—	0.399
48	1987/04/11/18:13	23.86	122.21	7.54	5.6	4.7	—	0.091
49	1987/06/27/07:38	24.32	121.63	0.48	5.2	4.9	—	0.063

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
50	1987/12/18/05:53	23.38	120.78	1.92	5.0	5.3	—	0.083
51	1988/02/12/19:15	23.81	122.40	7.13	5.6	5.3	—	0.342
52	1988/04/07/03:05	23.98	121.63	1.35	5.2	4.5	—	0.332
53	1988/04/24/20:03	23.45	122.01	18.40	5.6	5.5	—	0.166
54	1988/07/20/23:15	23.91	121.73	32.29	5.8	5.6	—	0.814
55	1988/08/09/16:51	24.12	122.49	29.89	5.3	5.0	—	0.061
56	1988/08/11/03:40	22.15	121.27	19.60	5.4	4.8	—	0.15
57	1988/10/16/12:09	22.02	121.83	0.75	5.3	5.0	—	1.332
58	1989/08/03/11:31	23.08	122.01	5.61	5.9	6.3	—	4.83
59	1989/08/21/23:12	23.96	122.44	8.12	5.6	6.2	—	2.82
60	1989/09/23/17:51	22.54	122.00	13.68	5.5	5.0	—	0.196
61	1990/07/16/19:14	24.18	121.80	1.39	5.6	5.8	—	0.417
62	1990/08/21/16:01	22.60	121.97	20.70	5.3	5.3	—	0.162
63	1990/09/11/14:09	22.81	120.80	24.16	5.8	5.6	—	0.542
64	1990/11/11/23:59	24.10	121.74	34.33	5.4	5.3	—	0.204
65	1990/12/13/03:01	23.88	121.55	2.82	5.9	6.2	—	3.18
66	1990/12/13/19:50	23.77	121.63	1.26	5.9	6.3	—	3.63
67	1990/12/14/02:37	23.60	121.68	11.07	5.2	4.6	—	0.104
68	1990/12/18/04:39	23.84	121.60	1.84	4.9	4.8	—	0.121
69	1990/12/19/00:20	23.67	121.59	5.20	5.3	5.3	—	0.276
70	1990/12/19/23:38	23.73	121.55	7.72	5.4	5.2	—	0.183
71	1990/12/25/14:21	23.77	121.57	2.04	5.6	5.7	—	0.76
72	1991/01/18/01:36	23.68	121.27	0.79	5.9	5.5	—	0.364
73	1991/03/12/06:04	23.25	120.07	12.26	5.6	5.3	—	0.155
74	1991/03/26/03:58	21.67	121.66	12.14	5.8	6.3	—	3.03
75	1991/03/26/06:19	21.70	121.67	16.60	5.2	5.2	—	0.201
76	1991/03/26/10:24	21.42	121.91	39.60	5.3	5.4	—	0.145
77	1991/09/30/09:44	22.60	121.43	18.81	5.6	5.2	5.89	0.139

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
78	1992/02/10/12:38	21.57	121.78	32.64	5.0	5.2	4.87	0.103
79	1992/04/19/18:32	23.84	121.57	8.07	5.9	6.1	5.55	1.56
80	1992/05/28/23:19	23.13	121.35	13.68	5.4	5.1	5.42	0.238
81	1992/08/06/21:29	24.66	122.46	0.88	5.3	5.7	5.32	0.25
82	1992/08/14/17:26	24.03	121.63	26.07	5.0	4.9	5.18	0.061
83	1992/09/28/14:06	23.88	122.67	17.58	5.9	6.1	5.72	1.67
84	1993/01/23/08:59	24.08	121.74	28.50	5.4	5.3	5.40	0.424
85	1993/12/06/23:00	21.84	120.99	20.79	5.2	4.8	5.29	0.132
86	1993/12/15/21:49	23.21	120.52	12.50	5.6	5.2	5.70	0.153
87	1994/03/17/11:28	23.96	122.42	0.59	5.3	5.4	5.65	0.244
88	1994/05/23/05:36	23.92	122.69	7.21	5.7	6.0	5.77	1.89
89	1994/05/23/15:16	23.86	122.64	5.54	5.9	5.7	6.00	0.813
90	1994/05/24/04:00	23.83	122.60	4.45	6.0	6.6	6.60	6.6
91	1994/06/05/01:09	24.46	121.84	5.30	6.0	6.5	6.50	3.8
92	1994/10/28/23:51	24.64	122.27	2.00	5.4	5.4	5.66	0.328
93	1994/12/13/00:50	23.93	122.65	15.85	5.0	4.6	5.47	0.103
94	1995/01/10/07:55	23.68	121.43	3.81	5.1	4.8	5.12	0.062
95	1995/02/23/05:19	24.20	121.69	21.69	5.8	6.2	5.77	2.45
96	1995/04/03/11:54	23.94	122.43	14.55	5.7	5.5	5.88	0.365
97	1995/04/03/22:33	23.95	122.32	3.94	5.3	5.0	5.35	0.12
98	1995/04/09/04:44	21.83	121.03	15.70	5.2	4.7	5.33	0.08
99	1995/05/27/18:11	23.01	121.46	19.73	5.2	5.6	5.26	0.402
100	1995/06/25/06:59	24.61	121.67	39.88	5.8	5.7	6.50	1.022
101	1996/03/05/14:52	23.93	122.36	6.00	6.1	6.4	6.40	3.59
102	1996/03/05/17:32	23.90	122.30	10.81	5.6	5.6	5.96	0.733
103	1996/03/29/03:28	23.97	122.33	5.79	5.4	5.5	5.64	0.52
104	1996/08/10/06:23	23.89	122.65	5.65	5.3	5.3	5.76	0.342
105	1996/09/05/23:42	22.00	121.37	14.76	6.4	6.6	7.07	19.1

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
106	1996/09/06/11:34	21.69	121.32	19.90	5.5	4.9	5.59	0.138
107	1996/11/26/08:22	24.16	121.70	26.18	5.1	4.8	5.35	0.077
108	1997/01/05/10:34	24.62	122.53	1.13	5.3	4.9	5.78	0.074
109	1997/05/03/02:46	22.54	121.40	3.64	5.1	5.0	5.27	0.035
110	1997/06/22/09:36	22.17	121.38	1.83	5.2	4.9	5.40	0.076
111	1997/07/04/18:37	23.06	120.79	5.16	4.9	4.7	5.18	0.05
112	1997/08/24/12:17	21.64	120.20	41.53	5.3	4.6	5.25	0.146
113	1997/08/24/18:58	21.63	120.27	45.62	5.3	5.0	5.35	0.105
114	1998/01/18/19:56	22.73	121.09	3.28	4.8	4.7	5.07	0.073
115	1998/07/17/04:51	23.50	120.66	2.80	5.5	5.4	6.20	0.431
116	1998/07/24/18:44	21.63	121.84	6.67	5.6	5.9	5.93	1.73
117	1998/09/13/05:34	24.24	123.01	28.11	5.2	4.6	5.82	0.122
118	1998/11/17/22:27	22.83	120.79	16.49	5.2	5.1	5.51	0.113
119	1999/02/22/13:49	23.98	122.65	4.21	5.4	5.6	5.90	0.805
120	1999/09/10/14:18	22.44	121.82	5.19	5.4	4.8	5.41	0.144
121	1999/09/20/17:47	23.85	120.82	8.00	6.5	7.7	7.30	338
122	1999/09/20/21:46	23.58	120.86	8.57	5.8	6.5	6.59	4.83
123	1999/09/22/00:14	23.83	121.05	15.59	6.2	6.4	6.80	5.03
124	1999/09/22/00:49	23.76	121.03	17.38	5.9	5.9	6.20	0.631
125	1999/09/22/12:17	23.74	120.98	24.02	5.1	4.9	6.00	0.093
126	1999/09/23/12:44	23.93	121.09	18.35	5.3	4.8	5.63	0.088
127	1999/09/25/08:43	23.69	120.95	7.12	5.2	4.8	5.09	0.051
128	1999/09/25/23:52	23.85	121.00	12.06	6.2	6.4	6.80	6.01
129	1999/10/02/17:14	23.96	122.50	6.59	5.0	4.8	5.30	0.061
130	1999/10/22/02:18	23.52	120.42	16.59	5.7	5.6	6.40	0.695
131	1999/10/22/03:10	23.53	120.43	16.74	5.2	5.3	6.00	0.251
132	1999/10/30/08:27	24.02	121.32	14.36	5.1	4.6	5.15	0.133
133	1999/11/01/17:53	23.36	121.73	31.33	6.1	6.1	6.90	3.29

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
134	2000/02/15/21:33	23.32	120.74	14.71	5.3	4.9	5.59	0.085
135	2000/05/17/03:25	24.19	121.10	9.74	5.4	5.3	5.59	0.161
136	2000/06/10/18:23	23.90	121.11	16.21	6.2	6.2	6.70	5.35
137	2000/06/19/21:56	23.92	121.09	27.02	5.0	4.6	5.18	0.092
138	2000/07/14/00:07	24.05	121.73	7.19	5.2	5.0	5.70	0.135
139	2000/07/28/20:28	23.41	120.93	7.35	5.6	5.6	6.10	0.345
140	2000/08/23/00:49	23.64	121.63	27.48	5.2	4.9	5.57	0.113
141	2000/09/10/08:54	24.09	121.58	17.74	5.6	5.6	6.20	0.583
142	2000/09/16/23:04	23.92	122.50	15.10	5.2	4.8	5.30	0.089
143	2000/12/12/20:32	23.97	122.68	19.43	5.1	5.3	5.29	0.157
144	2001/03/01/16:37	23.84	121.00	10.93	5.3	4.9	5.80	0.089
145	2001/06/14/02:35	24.42	121.93	17.29	5.7	5.6	6.30	0.78
146	2001/06/19/05:16	23.18	121.08	6.58	5.0	4.8	5.41	0.119
147	2001/06/19/05:43	23.20	121.10	11.70	5.1	4.7	5.22	0.058
148	2001/11/10/00:37	24.88	122.71	5.00	5.0	4.8	4.81	0.049
149	2001/12/18/04:02	23.87	122.65	12.00	6.3	7.3	6.70	20.8
150	2001/12/22/21:40	24.12	122.91	8.73	5.0	4.8	5.39	0.061
151	2001/12/28/00:41	23.99	122.90	9.46	5.2	4.9	5.49	0.057
152	2002/02/12/03:27	23.74	121.72	29.98	5.8	5.4	6.20	0.379
153	2002/03/31/06:52	24.14	122.19	13.81	6.4	7.4	6.80	54.5
154	2002/04/03/18:06	24.32	121.87	12.87	5.0	4.9	5.27	0.1
155	2002/04/28/13:23	24.13	122.87	9.18	5.3	4.6	5.54	0.07
156	2002/05/15/03:46	24.65	121.87	8.52	5.5	6.2	6.20	1.91
157	2002/05/28/16:45	23.91	122.40	15.23	5.8	5.9	6.20	1.49
158	2002/06/13/20:40	24.78	122.13	8.14	4.9	4.7	5.03	0.066
159	2002/07/11/07:36	23.94	122.41	14.22	5.6	5.6	5.79	0.652
160	2002/07/13/12:07	23.80	122.68	6.26	5.0	4.4	5.14	0.029
161	2002/08/28/17:05	22.26	121.37	12.03	5.7	5.1	6.03	0.255

Table 1. (Continued)

No.	Time	Latitude (^{o}N)	Longitude (^{o}E)	Depth (km)	m_b	M_s	M_L	M_o
162	2002/09/01/05:56	23.92	122.43	8.81	5.5	5.7	5.46	0.183
163	2002/09/01/07:07	23.97	122.37	15.56	5.3	5.4	5.48	0.112
164	2002/09/15/01:06	23.92	122.53	11.03	5.0	4.7	5.17	0.058
165	2002/12/21/06:09	21.53	121.37	12.29	5.1	5.0	5.01	0.056
166	2003/05/15/01:17	25.06	122.52	17.58	4.8	4.9	5.21	0.054
167	2003/06/09/01:52	24.37	122.02	23.22	5.3	5.5	5.72	0.642
168	2003/06/10/08:40	23.50	121.70	32.31	5.8	5.7	6.48	1.041
169	2003/07/30/18:36	23.92	122.46	12.34	4.9	4.6	5.15	0.078
170	2003/12/10/04:38	23.07	121.40	17.73	6.0	6.7	6.42	20.03
171	2003/12/11/00:01	22.79	121.39	33.58	5.1	5.1	5.39	0.179
172	2003/12/17/16:27	22.61	121.31	32.20	5.2	5.1	5.43	0.121
173	2004/01/01/03:15	23.34	121.71	24.88	5.1	4.8	5.35	0.069
174	2004/02/04/03:24	23.38	122.15	17.36	5.4	5.0	5.64	0.138
175	2004/05/01/07:56	24.08	121.53	21.55	5.2	5.1	5.25	0.073
176	2004/05/08/08:02	21.93	121.64	6.61	5.7	5.4	5.59	0.25
177	2004/05/16/06:04	23.05	121.98	12.85	5.3	5.0	5.72	0.262
178	2004/05/19/07:04	22.71	121.37	27.08	5.8	6.1	6.03	2.57
179	2004/07/06/07:32	24.90	122.27	5.96	4.8	4.7	5.22	0.081
180	2004/11/08/15:55	23.79	122.76	10.00	5.9	6.1	6.58	3.202
181	2004/11/08/19:38	23.93	122.51	15.74	5.3	5.2	5.50	0.069
182	2004/11/10/14:48	23.97	122.42	14.87	5.2	4.8	5.15	0.044
183	2004/11/11/02:16	24.31	122.16	27.26	5.7	5.5	6.09	0.359
184	2004/12/16/00:10	23.95	122.41	8.56	5.0	5.1	5.13	0.049
185	2005/02/18/20:18	23.34	121.67	15.28	5.6	5.2	5.60	0.154
186	2005/03/05/19:06	24.65	121.80	6.95	5.7	5.6	5.96	0.528
187	2005/04/30/14:48	24.04	121.62	8.45	5.2	4.9	5.62	0.103
188	2005/06/07/16:45	23.99	121.74	2.09	5.1	4.6	5.16	0.036
189	2005/07/20/13:06	24.75	122.25	7.60	5.1	4.9	5.22	0.093

Table 1. (Continued)

No.	Time	Latitude (°N)	Longitude (°E)	Depth (km)	m_b	M_s	M_L	M_o
190	2005/09/06/01:16	23.96	122.28	16.76	5.8	6.1	6.00	0.552
191	2005/11/16/13:39	23.93	122.50	20.87	4.9	4.2	5.08	0.014
192	2006/01/22/07:07	23.96	122.32	5.83	5.1	4.8	4.94	0.028
193	2006/01/23/04:18	24.01	122.29	17.62	5.0	4.5	4.86	0.021
194	2006/04/01/10:02	22.88	121.08	7.20	6.0	6.2	6.23	1.992
195	2006/04/15/22:40	22.86	121.30	17.90	5.5	5.9	6.04	0.874
196	2006/04/28/09:05	23.99	121.61	9.78	5.1	5.6	5.21	0.084
197	2006/05/07/01:53	21.59	120.73	42.46	5.4	5.4	5.23	0.116
198	2006/06/05/00:39	21.38	122.05	19.98	4.9	4.5	5.02	0.04
199	2006/07/28/07:40	23.97	122.66	27.97	5.7	5.9	6.02	0.76
200	2006/08/11/23:51	22.54	121.40	25.40	5.4	5.1	5.39	0.074
201	2006/10/12/14:46	23.96	122.65	25.30	5.7	5.7	5.80	0.532
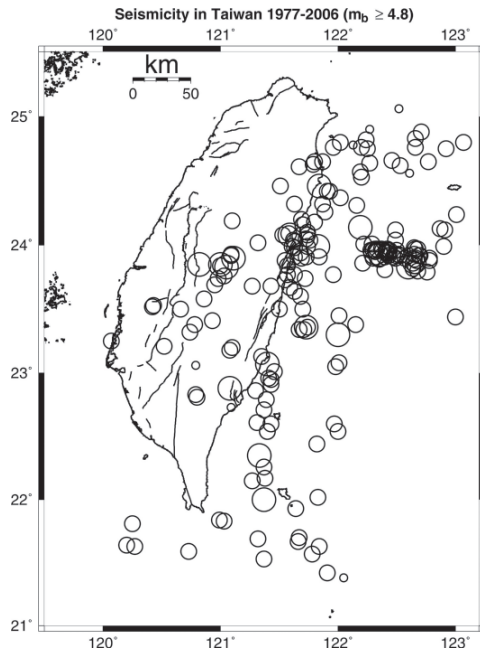
Fig. 1. The epicentral distribution of earthquakes shown in Table 1.

3. RESULTS

According to the source parameters of these 201 events, the plots of $\log(M_o)$ versus M_s, $\log(M_o)$ versus m_b, and M_s versus m_b are shown in Figs. 2 - 4, respectively. Obviously, a linear relationship exists between any two parameters. Hence, the $\log(M_o)$ - Ms, $\log(M_o)$ - m_b, and M_s - m_b relationships are evaluated through the least-square method. The resulting formulas are:

$$\log(M_o) = (1.07 \pm 0.04) \, M_s + (18.72 \pm 0.20) \quad , \tag{1}$$

$$\log(M_o) = (1.73 \pm 0.09) \, m_b + (15.09 \pm 0.52) \quad , \tag{2}$$

$$M_s = (1.46 \pm 0.08) \, m_b - (2.52 \pm 0.43) \quad . \tag{3}$$

The related regression lines are depicted with a solid line, respectively, in Figs. 2 - 4. The number next to each circle presents the event number listed in Table 1. In Fig. 2, the M_o - M_s relation fits the given data comparatively well. In comparison of Fig. 2 with Fig. 3, it can be found that for the given data, there is more scattering in the plot of M_o versus M_s than that of M_o versus m_b, especially for $M_s \leq 5.6$. This might be due to the fact that the number of readings used to estimate the magnitude is usually smaller for M_s than for m_b; therefore, a higher uncertainty for M_s than m_b is unavoidable.
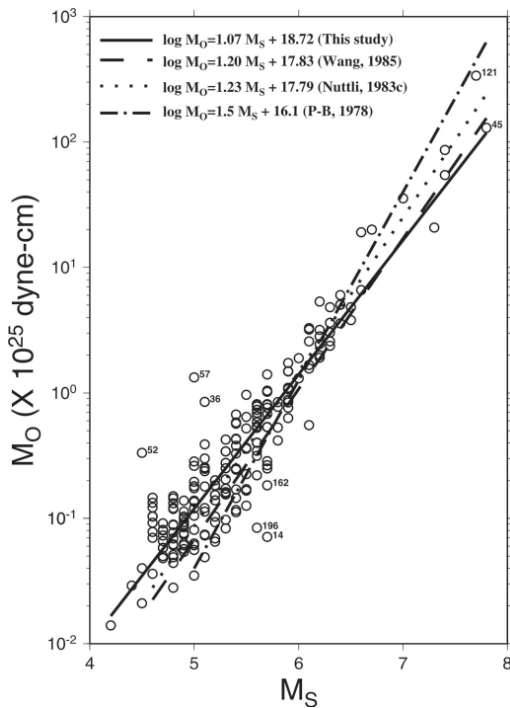
Fig. 2. The plot of $\log(M_o)$ versus M_s and related regression lines. The number next to the dot denotes the event number shown in Table 1. The solid line is deduced by this study. The dashed line is given by Wang (1985). The dotted line is given by Nuttli (1985). The dotted-dashed line is taken from Purcaru and Berckhemer (denoted by P-B 1978).
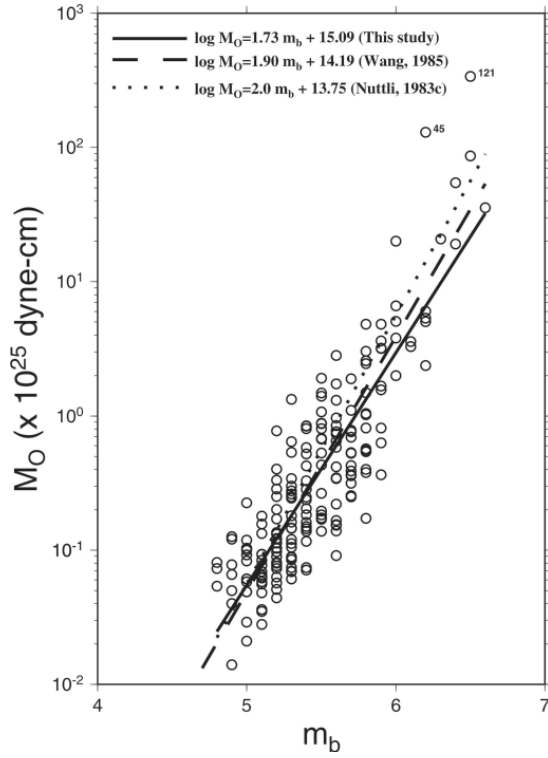
Fig. 3. The plot of log(M_o) versus m_b and related regression lines. The associated symbols are the same as in Fig. 2.
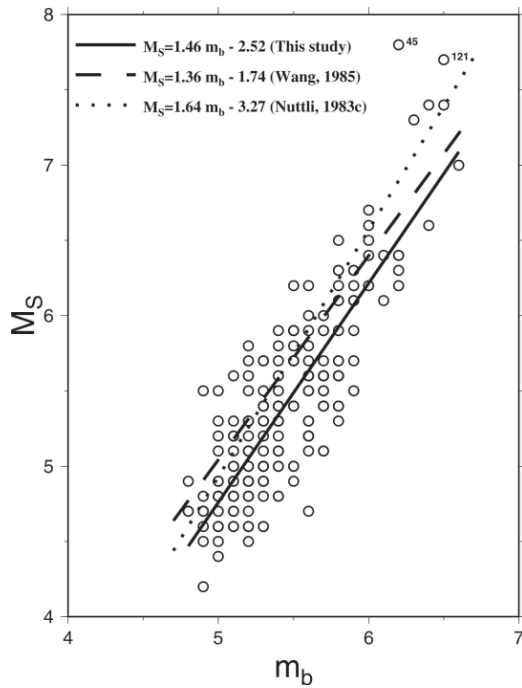
Fig. 4. The plot of M_s versus m_b and the related regression lines. The associated symbols are the same as in Fig. 2.

For 125 events with local magnitude, the plots of $\log(M_o)$ versus M_L, m_b versus M_L, and M_s versus M_L are shown in Figs. 5 - 7, respectively. Obviously, a linear relationship exists between any two parameters. Hence, the $\log(M_o)$ - M_L, m_b - M_L, and M_s - M_L relationships evaluated through the least-square method are:

$$\log(M_o) = (1.27 \pm 0.06)\, M_L + (17.23 \pm 0.35) \quad , \tag{4}$$

$$m_b = (0.66 \pm 0.03)\, M_L + (1.69 \pm 0.17) \quad , \tag{5}$$

$$M_s = (1.03 \pm 0.06)\, M_L - (0.53 \pm 0.36) \quad . \tag{6}$$

The related regression lines are depicted with a solid line, respectively, in Figs. 5 - 7.
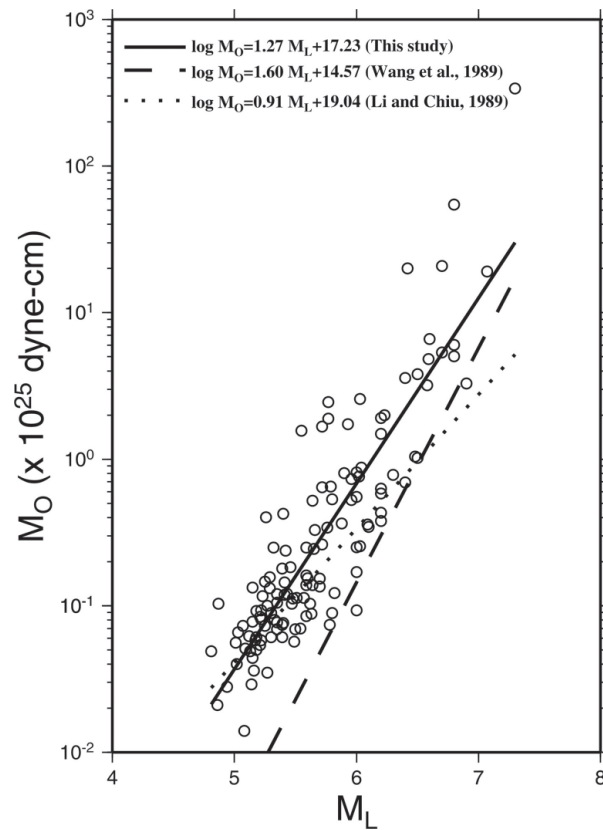
Fig. 5. The plot of $\log(M_o)$ versus M_L and related regression lines. The solid line is deduced by this study. The dashed line is given by Wang et al. (1989). The dotted line is given by Li and Chiu (1989).
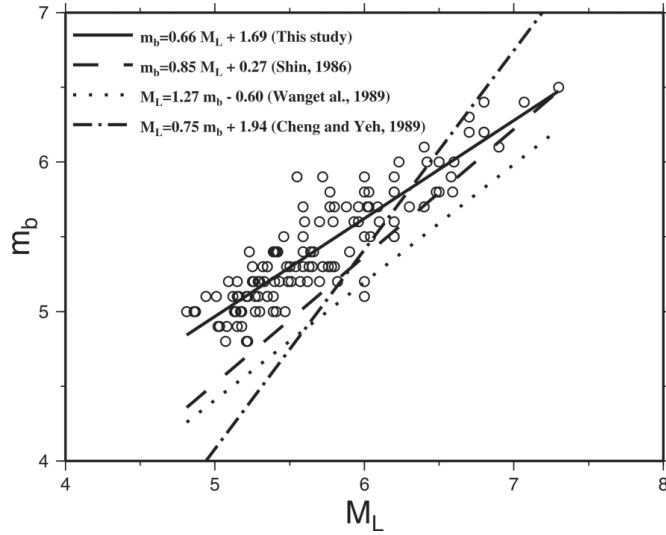
Fig. 6. The plot of m_b versus M_L and the related regression lines. The solid line is deduced by this study. The dashed line is given by Shin (1986). The dotted line is given by Wang et al. (1989). The dotted-dashed line is taken from Cheng and Yeh (1989).
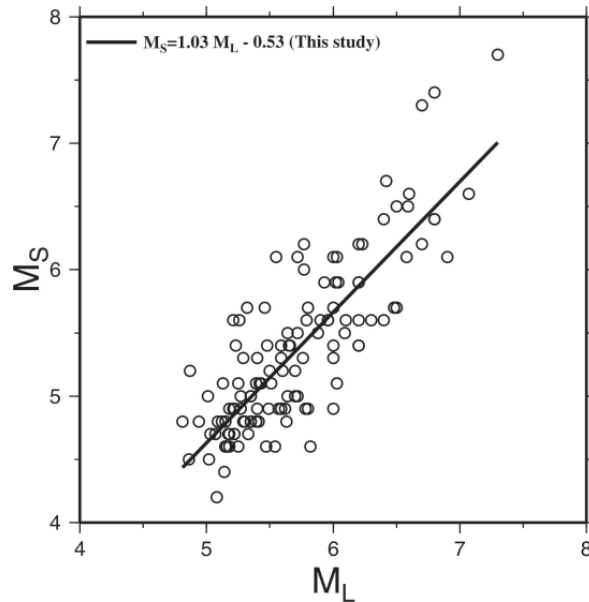
Fig. 7. The plot of M_s versus M_L and the related regression line. The solid line is deduced by this study.

4. DISCUSSION

Figure 2 shows that the data points related to three events (event No. 36, 52, and 57) with $M_s \leq 5$ are above the cluster of data points and deviate greatly from Eq. (1). This deviation might be due to over-estimates of M_o or under-estimates of M_s for the three events. Meanwhile, the data points related to three events (event No. 14, 162, and 196) with $M_s < 6$ are below the cluster of data points and deviate also from Eq. (1). This might be due to under-estimates of M_o or over-estimates of M_s for those events.

Figures 2 - 4 show that the data point (event No. 45), with $M_s = 7.8$, $m_b = 6.2$, and $M_o = 1.30 \times 10^{27}$ dyne-cm, related to the 1986 Offshore Hualien earthquake (Chen and Wang 1988) and that the data point (event No. 121), with $M_s = 7.7$, $m_b = 6.5$, and $M_o = 3.38 \times 10^{27}$ dyne-cm, associated with the 1999 Chi-Chi earthquake (Ma et al. 1999) depart from Eq. (2). Two possible reasons can cause the observations. The first one is saturation of amplitudes around 1 second, which are used for determining the m_b scale, usually contributes to under-estimation of m_b for large earthquakes. The second one is the existence of stronger low-frequency spectral amplitudes than high-frequency ones for the two events. For the 1999 earthquake, there are numerous observations (Hwang et al. 2001; Huang and Wang 2002; Wang et al. 2002; Wang 2006a, b) to confirm this possibility, while for the 1986 event information is insufficient. In addition, M_o is higher for the 1999 Chi-Chi earthquake than for the 1986 Offshore Hualien earthquake, yet the opposite is true for M_s. This indicates that low-frequency spectral amplitudes are higher for the former than for the latter.

As mentioned above, Wang (1985) first estimated the relationships of M_o versus M_s, M_o versus m_b, and M_s versus m_b for 16 earthquakes in the Taiwan region. The results are:

$$\log(M_o) = 1.20\ M_s + 17.83 \quad , \tag{7}$$

$$\log(M_o) = 1.90\ m_b + 14.19 \quad , \tag{8}$$

$$M_s = 1.36\ m_b - 1.74 \quad . \tag{9}$$

Equations (7) - (9) are depicted with dashed lines, respectively, in Figs. 2 - 4. Obviously, the dashed lines are close to the solid lines and, thus, Eqs. (7) - (9) can describe the data points well. This indicates that Eqs. (7) - (9) are reliable even though they were inferred from a small number of data.

For global earthquakes, the M_o - M_s and M_o - m_b, and M_s - m_b relationships inferred by Nuttli (1985) are, respectively:

$$\log(M_o) = 1.23\ M_s + 17.79 \quad (6.2 \leq M_s \leq 7.8) \quad , \tag{10}$$

$$\log(M_o) = 2.00\ m_b + 13.75 \quad (4.4 \leq M_s \leq 6.9) \quad , \tag{11}$$

$$M_s = 1.64\ m_b - 3.27 \quad . \tag{12}$$

Equations (10)- (12) are depicted with dotted lines, respectively, in Figs. 2 - 4. The dotted lines

do not depart from the solid lines too much. This leads to the same conclusion stated by Wang (1985) that M_o - M_s, M_o - m_b, and M_s - m_b relationships for earthquakes in the Taiwan region have good agreement with the average relations for plate-margin earthquakes obtained by Nuttli (1985).

The empirical M_o - M_s relationship inferred by Purcaru and Berckhember (1978) for $5 \leq M_s \leq 7.5$ is:

$$\log(M_o) = 1.5 \, M_s + 16.1 \quad , \tag{13}$$

which is depicted with a dotted-dashed line in Fig. 2. Obviously, Eq. (13) departs from Eq. (1) and cannot describe the data points well.

A conjecture based on the above-mentioned results and Nuttli's proposition (1985) that spectral scaling and source parameter studies can be carried out for individual earthquake source zones might be figured out. The conjecture is that the tectonics of the Taiwan region behave like the average property of the circum-Pacific oceanic plate margin. This conjecture can explain the agreement of relationships in this region with Nuttli's results (1985). Moreover, the earthquake magnitude has a close relation with seismic energy. Thus, the seismic moment-magnitude relation will reflect the accumulation of energy due to regional tectonic activities. Consequently, the above-mentioned agreement displays that the preparatory process of earthquake energy and source properties of the Taiwan region are the average ones of the circum-Pacific oceanic seismic belt.

Equation (1) and Fig. 2 show $\log(M_o) \sim M_s$ as proposed by Aki (1972) and Koyama (1994) for $M_s < 7$ and by Ekstrom and Dziewonski (1988) for $M_s < 5.8$ rather than $\log(M_o) \sim 1.5 \, M_s$ as suggested by Kanamori and Anderson (1975) for large earthquakes. Nuttli (1985) almost obtained a similar correlation from Eq. (10), yet not from Eq. (13) by Purcaru and Berckhember (1978). The definition of seismic moment is $M_o = \mu DLW$, where μ, D, L, and W are, respectively, the rigidity of materials in the source region, the average displacement on a fault plane, the fault length, and the fault depth. D is usually proportional to L rather than W (cf. Wang and Ou 1988). Kanamori and Anderson (1975) assumed $W \sim L$, thus leading to $M_o \sim L^3$ or $\log(M_o) \sim 3 \log(L)$. Let τ and v be the rise time and rupture velocity of an earthquake, respectively. For most large earthquakes, they proposed $M_s \sim 2 \log(L)$ when $\tau < T_o / \pi$ and $(L / v) > T_o / \pi$, where $T_o = 20$ sec of wave motions. Hence, the two correlations result in $\log(M_o) \sim 1.5 \, M_s$. This contrasts with our observation. On the other hand, for moderate earthquakes Kanamori and Anderson (1975) also suggested $M_s \sim 3 \log(L)$ when $\tau < T_o / \pi$ and $(L / v) < T_o / \pi$. This leads to $\log(M_o) \sim M_s$. Based on Haskell's model (Haskell 1964), Geller (1976) obtained $\log(M_o) \sim M_s$ when $M_s < 6.76$. His theoretical result can interpret our observation.

Equations (2) and (11) both suggest $\log(M_o) \sim 2 \, m_b$. This observed correction is inconsistent with the theoretical correlation: $\log(M_o) \sim 2.5 \, m_b$ proposed by Koyama (1994) for three kinds of distributions of peak and trough amplitudes. Hence, his proposition is questionable and needs further study for exploring the theoretical relationship between M_o and m_b.

Equation (3) and Fig. 4 show $M_s \sim 1.5 \, m_b$. Nuttli (1985) almost obtained a similar correlation from Eq. (12). According to Haskell's source model, Geller (1976) obtained: (1) $M_s \sim 1.5 \, m_b$ when $2.86 < M_s < 4.90$; (2) $M_s \sim 3 \, m_b$ when $4.90 < M_s < 6.27$; and (3) $m_b = 6.0$ when $6.27 < M_s$.

As mentioned above, the surface-wave magnitude is in the study range 4.2 to 7.8. Obviously, Geller's results can only describe our observation when $4.20 < M_s < 4.90$ for small earthquakes, yet not for moderate and large events with $4.9 \leq M_s \leq 7.8$. Figure 5 in Geller (1976) is the basis for him to claim that his theoretical relations can fit the data. However, that figure shows high dispersion of data points, especially for those with $6.0 \leq M_s \leq 8.5$. From Haskell's model, Geller (1976) developed the scaling relations between source parameters on the basis of three similarity relations among five source parameters, i.e., the fault length (L), fault width (W), average dislocation (D), rupture velocity (β), and rise time (τ). The three similarity relations are: (1) W / L = constant (aspect ratio); (2) D / L = constant (strain drop); and (3) $\beta\tau / L$ = constant (dynamic similarity). Kanamori and Anderson (1975) stressed that the first relation seems reasonable for most earthquakes; the second one is valid for large events; and the third does not hold for large events. However, the results by Wang and Ou (1998) implicated that the first similarity relation is valid for small events, yet not for large ones. These reasons might make the scaling relations developed by Geller (1976) questionable.

Figure 5 displays the plot of $\log(M_o)$ versus M_L. The data points are somewhat dispersive, even though they follow a linear trend. Regardless of the small number of data, the data points associated with $M_L > 6.5$ depart from the solid line. This implies that the size of large earthquakes could be under-estimated when local magnitude is used. For the Taiwan earthquakes, the relation between M_o and M_L has been determined by others:

$$\log(M_o) = (1.598 \pm 0.236) M_L + (14.571 \pm 1.683) \quad , \tag{14}$$

by Wang et al. (1989); and

$$\log(M_o) = (0.914 \pm 0.035) M_L + (19.043 \pm 0.533) \quad , \tag{15}$$

by Li and Chiu (1989). Equations (14) and (15) are depicted with dashed and dotted lines, respectively, in Fig. 5. Obviously, these two lines depart from Equation (4) and cannot describe the data points well. These two lines lie somewhat below the solid line. This means that the local magnitude determined by Wang et al. (1989) and Li and Chiu (1989) is larger than that by Shin (1993). The difference in seismic moment between dotted and solid lines increases with M_L, while that between dashed and solid lines decreases with increasing M_L.

The M_L scale is not restricted to a particular wave type or period. It is not easy to develop relations between M_L and other source parameters. Nevertheless, Hanks and Boore (1984) constructed the correlation between M_o and M_L in three frequency ranges based on three particular frequencies, i.e., f_s (the natural frequency of the Wood- Anderson seismograph, f_o (the corner frequency), and f_{max} [the cut-off frequency defined by Hanks (1982)]. The correlations are: (1) $\log(M_o) \sim 3.0 M_L$ as $f_o \ll f_s$ (for large events); (2) $\log(M_o) \sim 1.5 M_L$ as $f_s \ll f_o < f_{max}$ (for moderate events); (3) $\log(M_o) \sim 1.0 M_L$ as $f_o > f_{max}$ (for small events). Since most of events in use can be classified into large or moderate earthquakes, Eq. (4) cannot be interpreted by the theoretical relationships of Hanks and Boore (1984). They developed correlations on the basis of the instrumental response curve of the standard Wood-Anderson seismograph. While Shin

(1993) used short-period digital seismograms recorded by S-13 and L-4C sensors to simulate the Wood-Anderson waveforms. The instrumental response curves of the two kinds of sensors are different from that of the standard Wood-Anderson seismograph, although the simulations are made based on the response curve of the Wood-Anderson seismograph, the resultant waveforms cannot be completely the same as the standard Wood-Anderson seismograms. Hence, the existence of a distinction between observed and theoretical relationships is inevitable.

It is interesting and necessary to compare m_b and M_L. Both of them are determined from the peak amplitudes of seismograms at short periods: m_b is estimated from the telemetered P waves around 1 second, while M_L is based on the local or regional S waves or Lg waves. Figure 6 shows a linear trend of data points, even though they are somewhat dispersive. Three relations between m_b and M_L determined by others are:

$$m_b = 0.85 \, M_L + (0.27 \pm 0.60) \quad , \tag{16}$$

by Shin (1986);

$$M_L = (1.268 \pm 0.094) \, m_b - (0.604 \pm 0.485) \quad , \tag{17}$$

by Wang et al. (1989); and

$$M_L = 0.75 \, m_b + 1.94 \quad , \tag{18}$$

by Cheng and Yeh (1989). Equations (16) - (18) are depicted with dashed, dotted and dotted-dashed lines, respectively, in Fig. 6. Essentially, the three lines depart from Eq. (5) and lie below the data points. Obviously, the three relationships cannot interpret the data points well, implying that the ML used in the previous study is larger than that in this study. The dashed and dotted lines are somewhat in parallel and do not depart too much. The deviation between the two lines decreases with increasing M_L. The dotted-dashed line remarkable deviates from others.

The difference in M_L may be caused by, at least, three reasons: the use of different attenuation functions, the different numbers of seismograms used in the determination of local magnitude and site amplification. Shin (1993) derived a new attenuation function for the calculation of local magnitude in the Taiwan area. He also obtained a relationship between new [denoted by $M_L(new)$] and old [denoted $M_L(old)$] local magnitudes estimated, respectively, from new and old attenuation functions in the form:

$$M_L(new) = 0.97 \, M_L(old) + 0.09 \quad . \tag{19}$$

If the M_L used in this study is divided by 0.97, however, most of the data points still lie above the lines of Equations (16) and (17). This indicates that the difference in M_L is not simply caused by the use of different attenuation functions. The M_L used in this study is the averaged value of local magnitudes measured from the simulated Wood-Anderson seismograms of all CWBSN stations (Shin 1993), while those in other studies are either estimated directly from

seismograms recorded at a single simulated Wood-Anderson station (Shin 1986; Wang et al. 1989) or converted from the duration magnitude or other magnitudes (Cheng and Yeh 1989). This would result in deviations. In addition, the simulated Wood-Anderson seismograph of IES was installed in the Taipei basin where site amplification caused by unconsolidated sediments is high (Wen and Peng 1998; Chen 2003). Therefore, M_L could be overestimated in the previous studies.

If we consider the calculation of m_b to be consistently the same, Eq. (5) where M_L is denoted by $M_L(CWB)$ and Eq. (16) where M_L is denoted by $M_L(WA)$, then this leads to:

$$M_L(CWB) = 1.29\ M_L(WA) - 2.15 \qquad [\,4.0 \leq M_L(WA) \leq 6.6\,] \quad . \qquad (20)$$

Equation (20) can be used to unify the local magnitude for pre-1991 earthquakes determined from only a single Wood-Anderson seismogram [$M_L(WA)$] in Taiwan and for post-1991 events routinely determined by the CWBSN [$M_L(CWB)$].

Figure 7 shows the plot of M_s versus M_L. The data points follow a linear trend, but they are somewhat dispersive. Like Figure 5, some data points associated with $M_L > 6.5$ depart from the solid line. This implies that the size of large earthquakes could be under-estimated when the local magnitude is used.

5. CONCLUSIONS

According to the seismic moments and magnitudes for earthquakes occurring in the Taiwan region published in the Global CMT catalog, the M_o - M_s, M_o - m_b, and M_s - m_b relationships are estimated. The inferred relationships have good agreement with Wang's results (1985). Meanwhile, the inferred relationships do not depart from Nuttli's results (1985) too much. This might imply that the tectonic conditions, accumulation of earthquake energy, and source properties of the Taiwan region behave like the average of the circum-Pacific seismic belt. For large earthquakes used in this study, the value of local magnitude could be underestimated. The local magnitude, used in previous studies, was determined from only a single simulated Wood-Anderson seismograph of IES at the Taipei Basin. Its value was overestimated due to site amplification caused by unconsolidated sediments.

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