

Relationships of Seismic Source Scaling in the Taiwan Region

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ABSTRACT

Source scaling relationships are analyzed for the Taiwan region through the estimates of source parameters. Such estimated parameters include corner frequency, source dimension, stress drop, average slip and seismic moment. The ultimate goal of this study is to provide regional scaling laws on the above source parameters for the Taiwan region. The corner frequency and seismic moment are first estimated independently from strong-motion recordings after having been corrected for geometrical spreading, high-frequency decay and anelastic attenuation. The results reveal that earthquakes in the Ilan-Hualien source area are mainly associated with the northward subduction of the Philippine Sea plate beneath the Eurasian plate. The stress drop values of earthquakes in this area are statistically smaller than those occurring on Taiwan Island. This implies that earthquakes occurring on the island with shallow focal depth are most likely intra-plate events. In general, the stress drop of earthquake events in the Taiwan region shows an increasing trend with regard to the earthquake magnitudes. Based on the results of $M 6$, the stress drop of earthquakes in the subduction zone is usually under 220 bars, while that of earthquakes on Taiwan Island is not greater than 290 bars. The empirical scaling laws for the source parameters of the northeast seismic zone are more reliably established, and thus are better results than those of the three other source areas in the Taiwan region. The use of Brune's source model tends to overestimate the corner frequency, and therefore underestimate the radius of the source dimension. Accordingly, the stress drop and average slip are overestimated. As a result, the corner frequency, stress drop and average slip obtained in this study should be treated as upper-bound values, and the diameters of the source rupture area estimated should be considered lower-bound values of the rupture length for earthquake events in the Taiwan region.

(Key words: Scaling law, Corner frequency, Stress drop, Average slip, Seismic moment)

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1. INTRODUCTION

In need of earthquake resistant design, specialists in the fields of engineering seismology and earthquake engineering regard the estimate of ground motion induced by potential target earthquake as one of their major concerns. Ordinarily, peak ground acceleration is estimated by empirical attenuation equations which are obtained by regression analysis of observed strong-motion data (e.g., Joyner and Boore, 1981; Campbell, 1981; Campbell, 1985; Joyner and Boore, 1988). Alternatively, response spectrum analyses of strong ground accelerations are performed so as to produce design response spectra that represent the design criteria at sites in consideration (e.g., Seed *et al.*, 1976; Newmark *et al.*, 1973; Mohraz, 1976; Joyner and Boore, 1988). These conventional approaches, however, mostly ignore the important factors of source parameters that are related to the characteristics of regional seismic zones, such as source mechanism, stress drop and source scaling laws.

It is well-understood that seismic sources of various characteristics may have different effects on the observed strong ground motions. Nevertheless, the influence of source parameters on ground motions has not been explicitly taken into account in the above mentioned approaches. The effects of source, path and site have usually been implicitly included among the uncertainties of the strong-motion estimates. When the ground motion parameter of concern is solely that of peak ground acceleration, empirical attenuation equations, with specified values of uncertainty, are considered adequate to do the job of ground motion estimation. However, if the whole time record is needed for the dynamic analysis of engineered structures, the characteristics of the potential sources, the frequency contents, the strong-motion duration and the envelope function of ground motion are essentials in fully describing the synthesized acceleration time history for the site of interest. Thus, the need to investigate source parameters, especially the regional scaling law of potential seismic sources, becomes more apparent for the simulations of strong ground motions.

The analysis of source characteristics in the Taiwan region has only been implemented in some local areas (e.g., Wen and Yeh, 1991; Ou and You, 1992; You, 1992; Ou and Tsai, 1993). In this study, systematic analyses of the source characteristics are applied to the whole Taiwan region. Empirical equations of source scaling laws concerning corner frequency, stress drop, average slip and source dimension in relation to seismic moment for the Taiwan region are analyzed and discussed.

2. DATA USED

Data used in this study can be classified into two categories. The first one consists of earthquake data that are used in the first stage for the purpose of evaluating the methods of estimating source parameters of earthquakes. Seven earthquakes in the Taiwan region, which have been investigated for their source parameters, are collected for the first category of data. Table 1 lists the details for these events.

The second category consists of strong-motion data recorded in Taiwan. It includes the recordings from stations that are deployed and maintained by the Institute of Earth Sciences (IES), Academia Sinica, National Chung-Cheng University (NCCU) and the Seismology Center, Central Weather Bureau (CWB), Republic of China. Of these strong-motion data, forty-eight

Table 1. The source parameters of seven earthquakes which have triggered strong-motion recordings in the Taiwan region.

Event No.	Location	y/m/d	M_0 (dyne-cm)	$\Delta\sigma$ (bars)	M_s	M_L	Mechanism	References
1	22.352°N 121.329°E	1978/7/23	4.6×10^{26}		7.4	6.8	strike-slip	Pezzopane and Wesnousky (1989)
			8.64×10^{26}					Giardini <i>et al.</i> (1985)
2	23.914°N 121.626°E	1982/1/23	1.31×10^{25}		5.9			Wang (1985)
3	24.595°N 122.547°E	1982/12/17	6.34×10^{25}					Wang (1985)
4	24.647°N 122.589°E	1983/4/26	6.31×10^{24}					Wang (1985)
5	24.419°N 121.560°E	1983/5/10	4.28×10^{24}		5.4			Wang (1985)
			4.30×10^{24}	12.8	5.4	6.4	normal	Chen and Wang (1984)
6	24.082°N 121.592°E	1986/5/20	2.60×10^{25}			6.5	thrust	Hwang and Kanamori (1989)
			2.70×10^{25}		6.4			Wu <i>et al.</i> (1989)
7	23.992°N 121.833°E	1986/11/14	1.72×10^{27}		7.3	6.8	thrust	Hwang and Kanamori (1989)
			0.64×10^{27}		7.8			Wu <i>et al.</i> (1989)

island-wide IES stations (including station E02 in the SMART1 array) and three NCCU stations (stations TUT, USH and TCH) are on rock sites. Six CWB stations (stations WTP, STY, SCL, TAI, ALS and KAU) in the Jia-Nan area of Taiwan, which were triggered by the 1993 Tapu earthquake, are on soil sites.

More information about the data is described in the following appropriate sections.

3. EVALUATION OF THE METHODS

Anderson and Humphrey (1991) used the least-squares method on the strong-motion recordings to estimate three source parameters: corner frequency, f_0 (Brune, 1970; 1971), seismic moment, M_0 , and the spectral decay parameter, κ (kappa, Anderson and Hough, 1984). In the frequency domain, they approximated the observed spectrum of acceleration $A(f)$ using a smooth spectrum model of $Y(f)$:

$$Y(f) = A_0 \frac{(2\pi f)^2}{1 + \left(\frac{f}{f_0}\right)^2} e^{-\pi\kappa f} \quad (1)$$

$$A_0 = \frac{0.85M_0}{4\pi\rho\beta^3 R} \quad (2)$$

where f is the frequency, ρ the density, β the shear wave velocity and R the source to site distance. Applying the least-squares regression of $Y(f)$ on $A(f)$, f_0 , A_0 and κ can be obtained simultaneously. From Equation (2), M_0 can be estimated through the value of A_0 . To find the best fit to the observed spectrum, the error is defined as:

$$\chi(f_0', A_0', \kappa') = \frac{1}{NF} \sum_{i=1}^{NF} [\ln A(f_i) - \ln Y(f_i)]^2 \quad (3)$$

where NF is the number of calculated frequencies; f_0' is the designated value for the corner frequency f_0 ; and A_0' and κ' are values of A_0 and κ , respectively, as calculated on the basis of f_0' . Given an adequate range of f_0' , the least total error can be obtained by minimizing $\chi(f_0', A_0', \kappa')$. The optimal values of M_0 and κ are those corresponding to f_0' that produces the minimum value for $\chi(f_0', A_0', \kappa')$. Then the source dimension (radius of an assumed circular crack) r and the stress drop $\Delta\sigma$ can be calculated as follows (Brune, 1970, 1971):

$$r = \frac{2.34\beta}{2\pi f_0} \quad (4)$$

$$\Delta\sigma = \frac{7}{16} \frac{M_0}{r^3} \quad (5)$$

Rovelli *et al.* (1991) proposed an alternative approach which first calculates the corner frequency f_0 using the theoretical form (Andrews, 1986):

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{\int_0^{\infty} V^2(f) df}{\int_0^{\infty} D^2(f) df}} \quad (6)$$

where $V(f)$ and $D(f)$ are the velocity spectrum and displacement spectrum, respectively. Using a different spectrum model from that of Anderson and Humphrey (1991), they adopted

$$Y(f) = A_0 \frac{(2\pi f)^2}{1 + \left(\frac{f}{f_0}\right)^2} e^{-\pi\kappa f} e^{-\pi R f / \beta Q_0} \quad (7)$$

to implement the regression analysis for M_0 , where Q_0 is the quality factor that is independent of frequency. Both approaches need to be checked for their applicability to strong-motion data in Taiwan.

As described previously, seven earthquakes in the Taiwan region have been investigated for their source parameters. Table 1 lists the source parameters for these events from various investigators. Unfortunately, some records from three of these events are found to have no P waves and no clear S waves because the epicenters are too far away from the recording sites. Hence, they are not suitable for use in checking the applicability of the above two methods. (Direct S waves from the seismic sources are used for the estimates of the source parameters; surface waves are not considered here.) These three events are the earthquakes of 1982/12/17

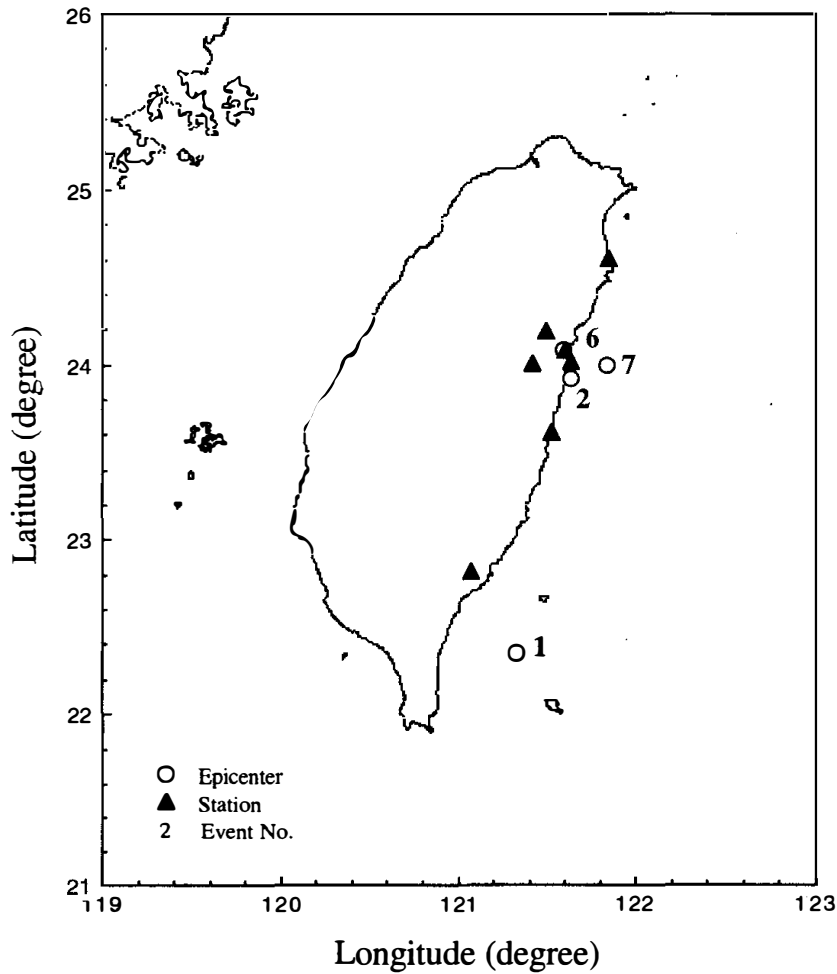


Fig. 1. Epicenter distributions of four earthquake events (circles) listed in Table 1: 1978/7/23 (y/m/d), 1982/1/23, 1986/5/20 and 1986/11/14 as well as locations of recording sites (triangles) that recorded strong-motions from the four events. Digits in the vicinity of epicenters are the event numbers as shown in Table 1.

(y/m/d), 1983/4/26 and 1983/5/10.

Figure 1 shows the locations of the recording sites triggered by the other four earthquake events, and the epicenters of these events. All four belong to intermediate and larger magnitude events. The fitted spectrum curves obtained by the above two approaches are shown together with the observed ones in Figure 2 for some representative stations on rock sites. The fitted curves vary in shape, depending on the site condition. If the site effects are insignificant (though they are all on rock sites) and if the observed spectrum can be described by the Brune (1970) f^{-2} source model, the theoretical curves can be better fitted to the observed ones [Figure 2 (d)]. However, both methods have the same tendency of overestimating f_0 while underestimating M_0 . Two sets of estimates of f_0 , κ and A_0 (in $\text{cm}\cdot\text{sec}$), respectively, are shown in parenthesis at the bottom of each plot. Those on the left are calculated from Ander-

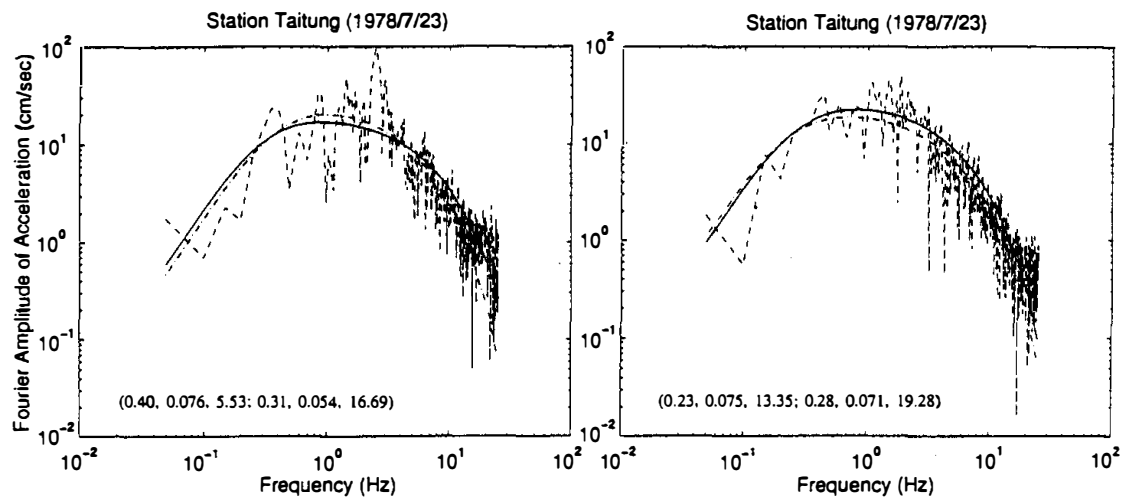
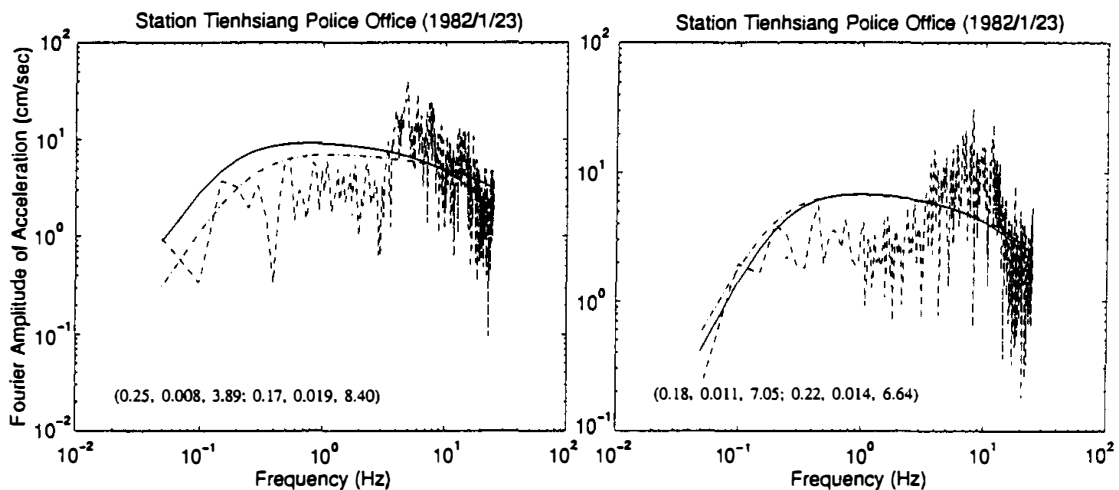
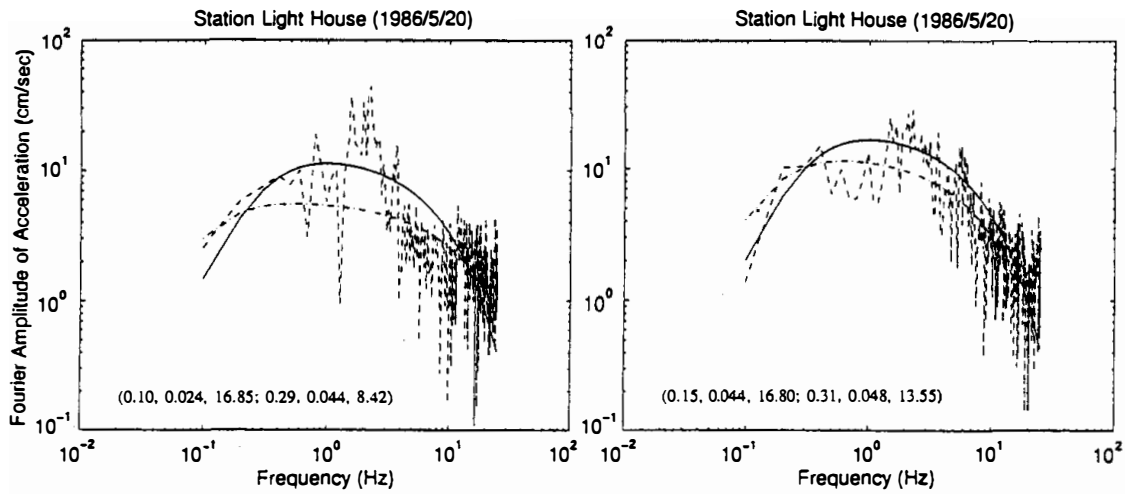
(a) Event 1 with M 6.8.(b) Event 2 with M 5.9.

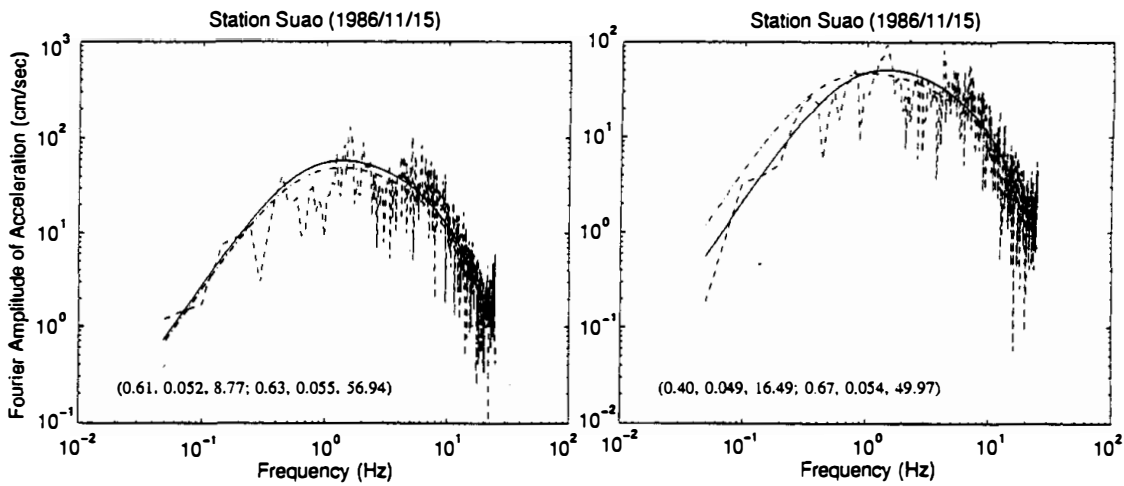
Fig. 2. Comparisons of theoretical smoothed Fourier spectra to observed ones for some representative stations on rock sites (two horizontal components of the records are both shown). Solid lines represent the results using the procedure of Rovelli *et al.* (1991) and dashdotted lines the results using that of Anderson and Humphrey (1991). The two sets of values shown in parenthesis at the bottom of each plot are the estimates of f_0 (in Hz), κ and A_0 (in cm · sec) which are calculated from Anderson and Humphrey (left) and Rovelli *et al.* (right).

son and Humphrey (1991), and those on the right from Rovelli *et al.* (1991). Figure 3 shows the scattergram of M_0 for the results obtained by the two methods against those found in the literature.

It is found that although the two methods mentioned above can objectively estimate the



(c) Event 6 with M 6.5.



(d) Event 7 with M 6.8.

Fig. 2. (Continued)

source parameters, difficulties are encountered when they are used for the inversion of source parameters. There are large differences in the source parameters f_0 , M_0 , r , $\Delta\sigma$ and the average slip obtained from various recording sites for the same earthquake event. Furthermore, the source parameters may vary even more due to topographic and geologic effects on the recording sites. Due to the scattered estimates of source parameters obtained for the Taiwan region, a procedure different from the above two approaches is suggested in the next section.

4. ANALYSIS OF SOURCE PARAMETERS FOR THE TAIWAN REGION

It is proposed in this study that f_0 and M_0 be independently estimated following the procedure below.

Only direct S waves radiating from the seismic source are considered for the estimates of

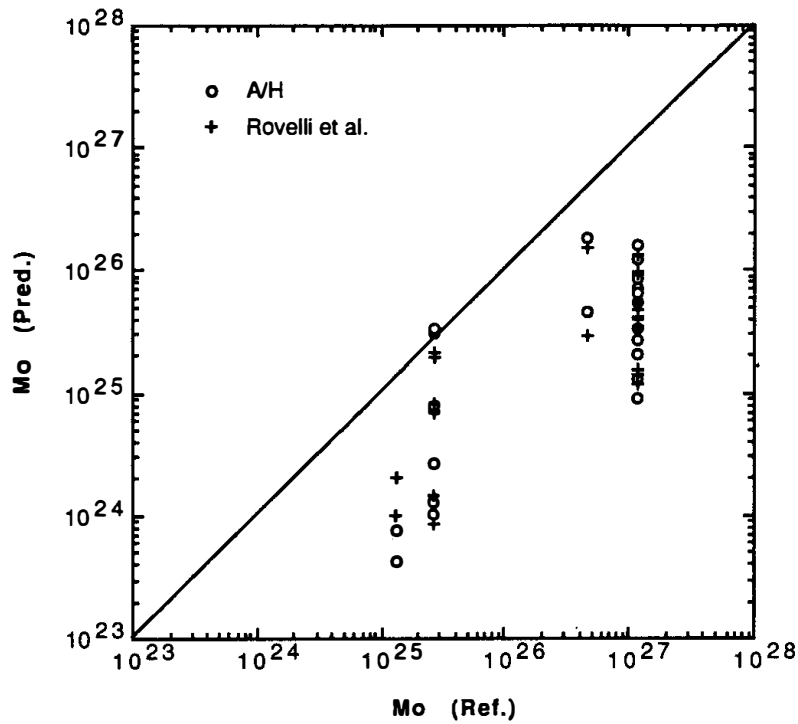


Fig. 3. Scattergram of M_0 for the results obtained by Anderson and Humphrey (1991) (denoted by "o") and Rovelli *et al.* (1991) (denoted by "+") against those found in the literature. The solid line represents the equal condition of M_0 .

the source parameters. The acceleration spectra are first corrected for geometrical spreading (R^{-1}), high-frequency decay ($e^{-\pi\kappa f}$) and anelastic attenuation ($e^{-\pi\eta R/\beta Q(f)}$), and are then used in estimating the source spectrum. The quality factor $Q(f)$ adopted depends on frequency. The source spectrum is then related to the Brune (1970) f^{-2} model as below:

$$A(f)R e^{\pi\kappa f} e^{\pi\eta R/\beta Q(f)} = \frac{0.85M_0}{4\pi\rho\beta^3} \frac{(2\pi f)^2}{1 + \left(\frac{f}{f_0}\right)^2} \quad (8)$$

For $f \gg f_0$,

$$1 + \left(\frac{f}{f_0}\right)^2 \cong \left(\frac{f}{f_0}\right)^2$$

Equation (8) can be approximated by:

$$A(f)R e^{\pi\kappa f} e^{\pi\eta R/\beta Q(f)} = \frac{0.85M_0}{4\pi\rho\beta^3} (2\pi f_0)^2 \quad (9)$$

That is, the source spectrum reaches a constant value and approaches its maximum at high frequencies ($f \gg f_0$). When $f = f_0$, Equation (8) yields:

$$A(f_0)R e^{\pi r f_0} e^{\pi f_0 R / \beta Q(f_0)} = \frac{0.85 M_0 (2 \pi f_0)^2}{4 \pi \rho \beta^3} \frac{1}{2} \quad (10)$$

Equation (10) indicates that the source spectrum has half of its maximum value at $f = f_0$. Based on this, the corner frequency f_0 can be estimated. The maximum value of the source spectrum can be calculated by regression analysis of the corrected acceleration spectrum for frequencies $f \gg f_0$. With the maximum value and f_0 both substituted into Equation (9), the seismic moment M_0 can be calculated. Furthermore, from the relationship $M_0 = \mu S \bar{u}$, the average slip \bar{u} can be estimated, where μ is the shear modulus of the crust and S the rupture area of the fault. The quality factor $Q(f) = 117 f^{0.77}$ is assumed for the Taiwan region following Chen *et al.* (1989). The density and shear wave velocity are assumed to be 2.8 gm/cm³ and 3.8 km/sec, respectively, following Hwang and Kanamori (1989).

Seismogenic zones in the Taiwan region are divided into four sub-units: (1) the Northeast Seismic Zone covering 23.5°-26° N and 121°-124° E; (2) the Southeast Seismic Zone covering 21° - 23.5° N and 121°-124° E; (3) the Southwest Seismic Zone covering 21° - 23.5° N and 119°-121° E; and (4) the Northwest Seismic Zone covering 23.5°-26° N and 119°-121° E. These sub-zones represent the Ilan-Hualien offshore source area, the Taitung offshore source area, the Jia-Nan source area and the Hsinchu-Taichung source area, respectively.

The strong-motion data analyzed include (1) the recordings of the IES island-wide strong-motion network (SMA-1) during the period 1976-1993; (2) the recordings from rock station E02 in the SMART1 array in Lotung during 1983-1987; (3) the recordings of NCCU's strong-motion network in the Jia-Nan area during 1990-1991; and (4) those collected by the CWB strong-motion network for the 1993 Tapu earthquake in the Jia-Nan area. Except for six stations maintained by CWB in the Jia-Nan area that are on soil sites, all of the stations used are on rock sites. Figure 4 shows the epicenter distribution for the earthquake events used in this study.

Theoretically, the source parameters estimated from various strong-motion recordings triggered by an earthquake event should report the same values. However, due to experimental errors, simplifications in the source model, the topographical effects and geologic conditions at recording sites, as well as propagation (path) effects, the estimates of the source parameters of an earthquake event may vary from one record to another. To pursue accurate source parameters for an earthquake event is, therefore, impractical. More practical is to find the overall characteristics of a seismic zone in terms of optimal source parameters. To do this, f_0 and M_0 are independently estimated according to the above procedure. Then the relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 are determined by regression analyses, assuming that the statistical estimates of the five parameters all inherit certain errors. Figures 5 through 8 depict the relationships of the source parameters for the four seismic sub-zones. The empirical equations describing the source parameters for each seismic sub-zone are as follows:

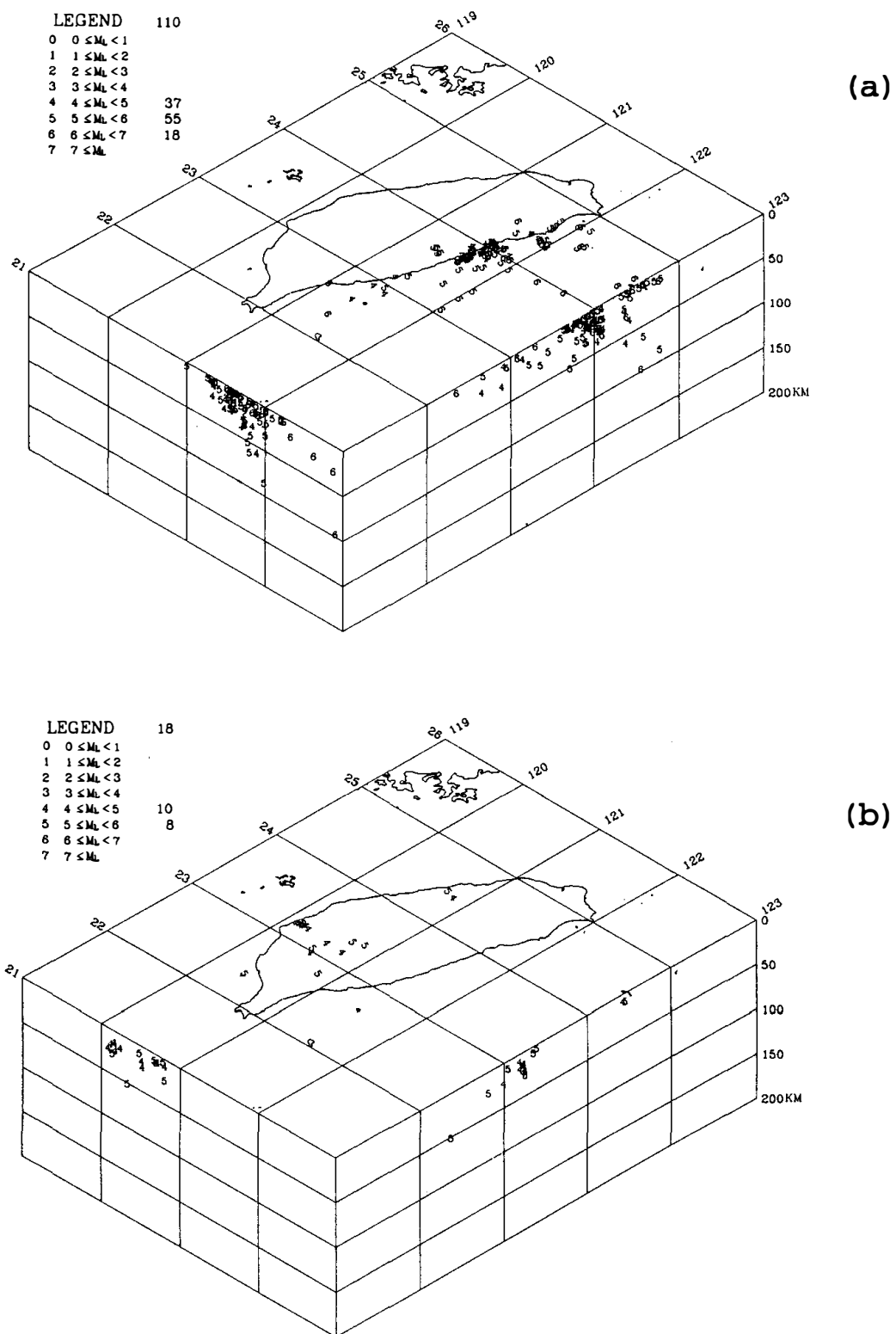


Fig. 4. (a) Epicentral and Hypocentral distributions of earthquake events in the Northeast and Southeast Seismic Zones for source parameter estimations used in this study. (b) Epicentral and hypocentral distributions of earthquake events in the Northwest and Southwest Seismic Zones for source parameter estimations used in this study.

The Northeast Seismic Zone

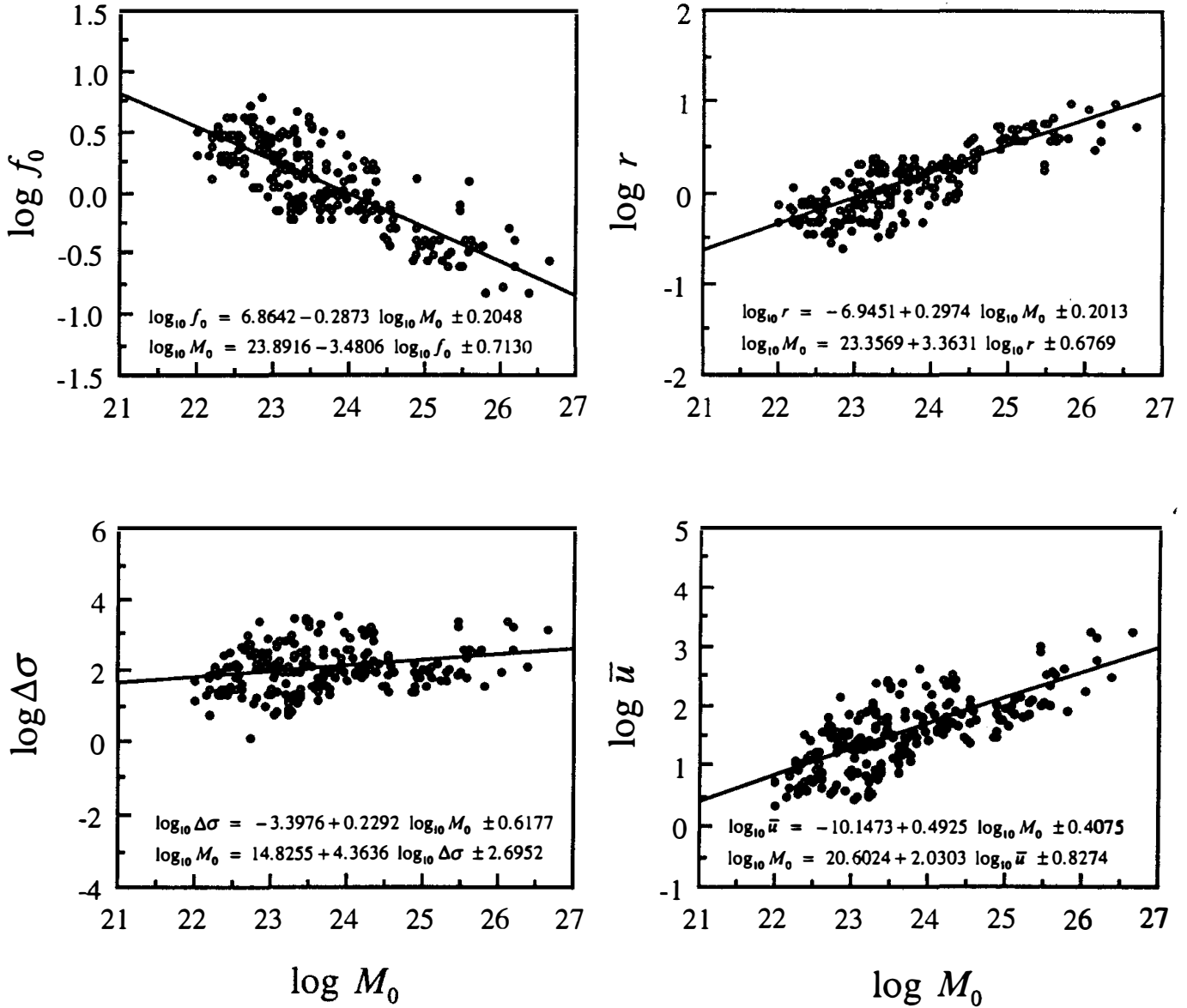


Fig. 5. Scaling relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 for the Northeast Seismic Zone.

(1) the Northeast Seismic Zone (the Ilan-Hualien offshore source area)

$$\begin{aligned}
 \log_{10} f_0 &= 6.8642 - 0.2873 \log_{10} M_0 \pm 0.2048 \\
 \log_{10} r &= -6.9451 + 0.2974 \log_{10} M_0 \pm 0.2013 \\
 \log_{10} \Delta\sigma &= -3.3976 + 0.2292 \log_{10} M_0 \pm 0.6177 \\
 \log_{10} \bar{u} &= -10.1473 + 0.4925 \log_{10} M_0 \pm 0.4075
 \end{aligned}
 \tag{11}$$

The Southeast Seismic Zone

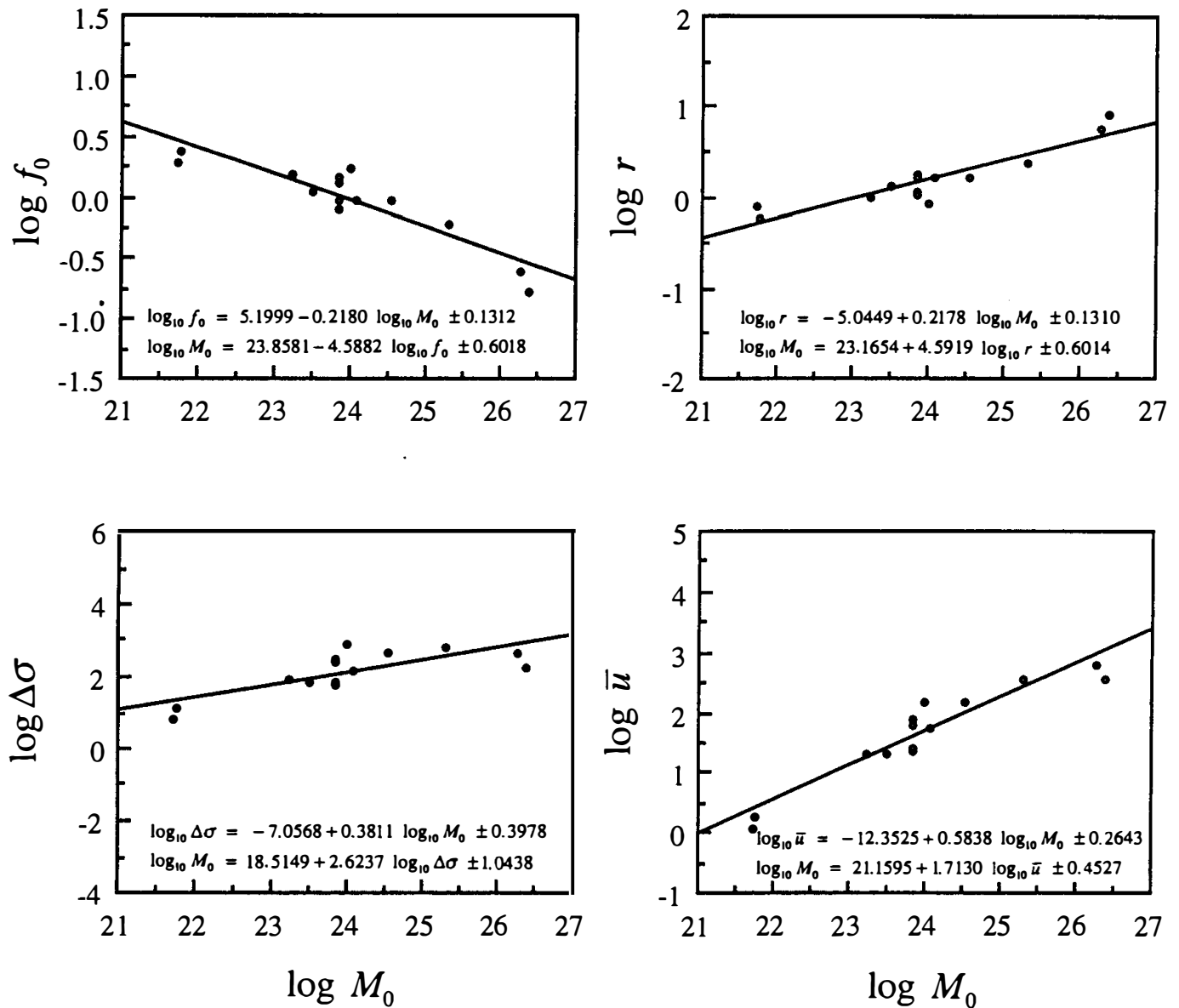


Fig. 6. Scaling relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 for the Southeast Seismic Zone.

(2) the Southeast Seismic Zone (the Taitung offshore source area)

$$\begin{aligned}
 \log_{10} f_0 &= 5.1999 - 0.2180 \log_{10} M_0 \pm 0.1312 \\
 \log_{10} r &= -5.0449 + 0.2178 \log_{10} M_0 \pm 0.1310 \\
 \log_{10} \Delta\sigma &= -7.0568 + 0.3811 \log_{10} M_0 \pm 0.3978 \\
 \log_{10} \bar{u} &= -12.3525 + 0.5838 \log_{10} M_0 \pm 0.2643
 \end{aligned} \tag{12}$$

The Southwest Seismic Zone

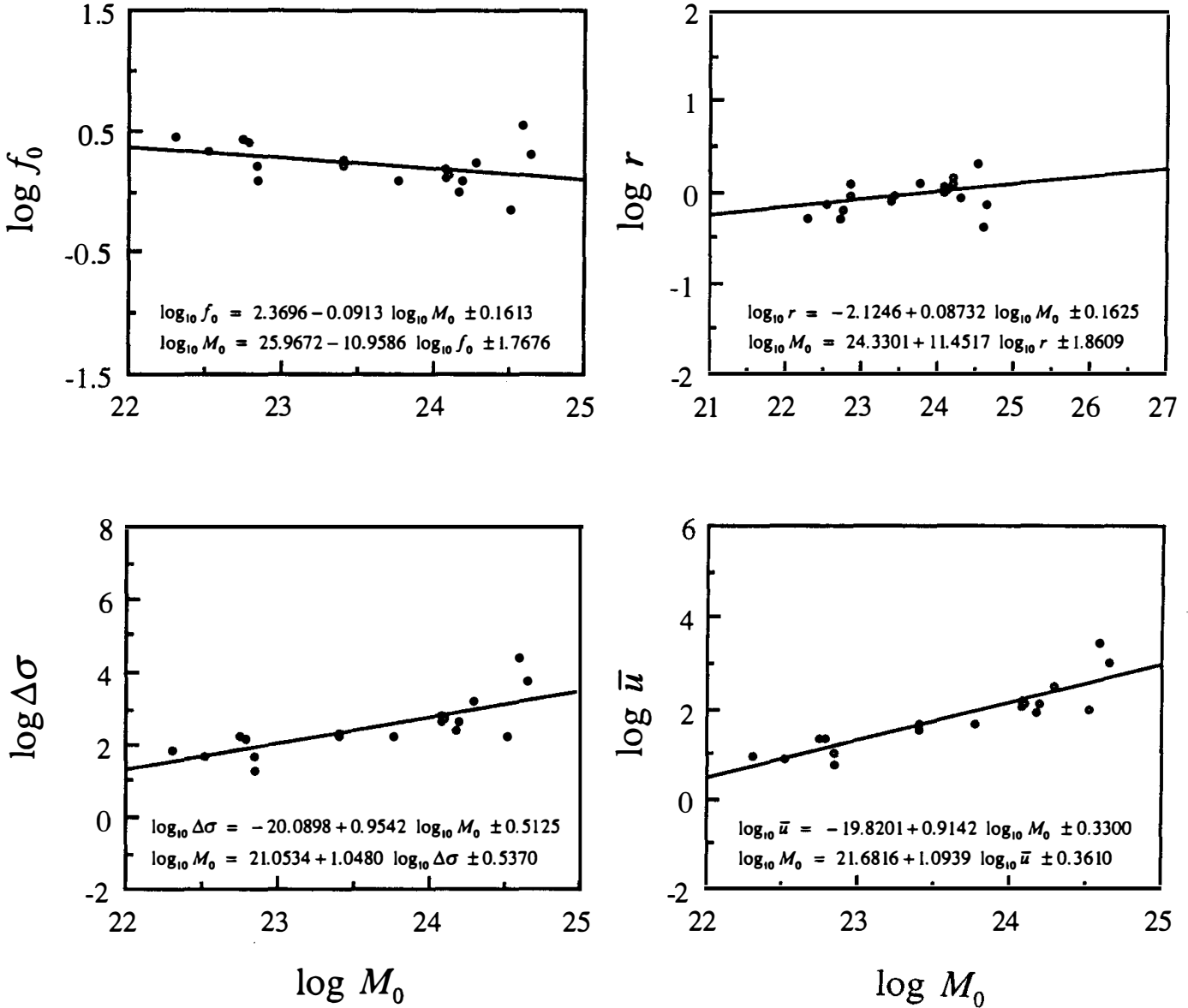


Fig. 7. Scaling relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 for the Southwest Seismic Zone.

(3) the Southwest Seismic Zone (the Jia-Nan source area)

$$\begin{aligned}
 \log_{10} f_0 &= 2.3696 - 0.0913 \log_{10} M_0 \pm 0.1613 \\
 \log_{10} r &= -2.1246 + 0.08732 \log_{10} M_0 \pm 0.1625 \\
 \log_{10} \Delta\sigma &= -20.0898 + 0.9542 \log_{10} M_0 \pm 0.5125 \\
 \log_{10} \bar{u} &= -19.8201 + 0.9142 \log_{10} M_0 \pm 0.3300
 \end{aligned}
 \tag{13}$$

The Northwest Seismic Zone

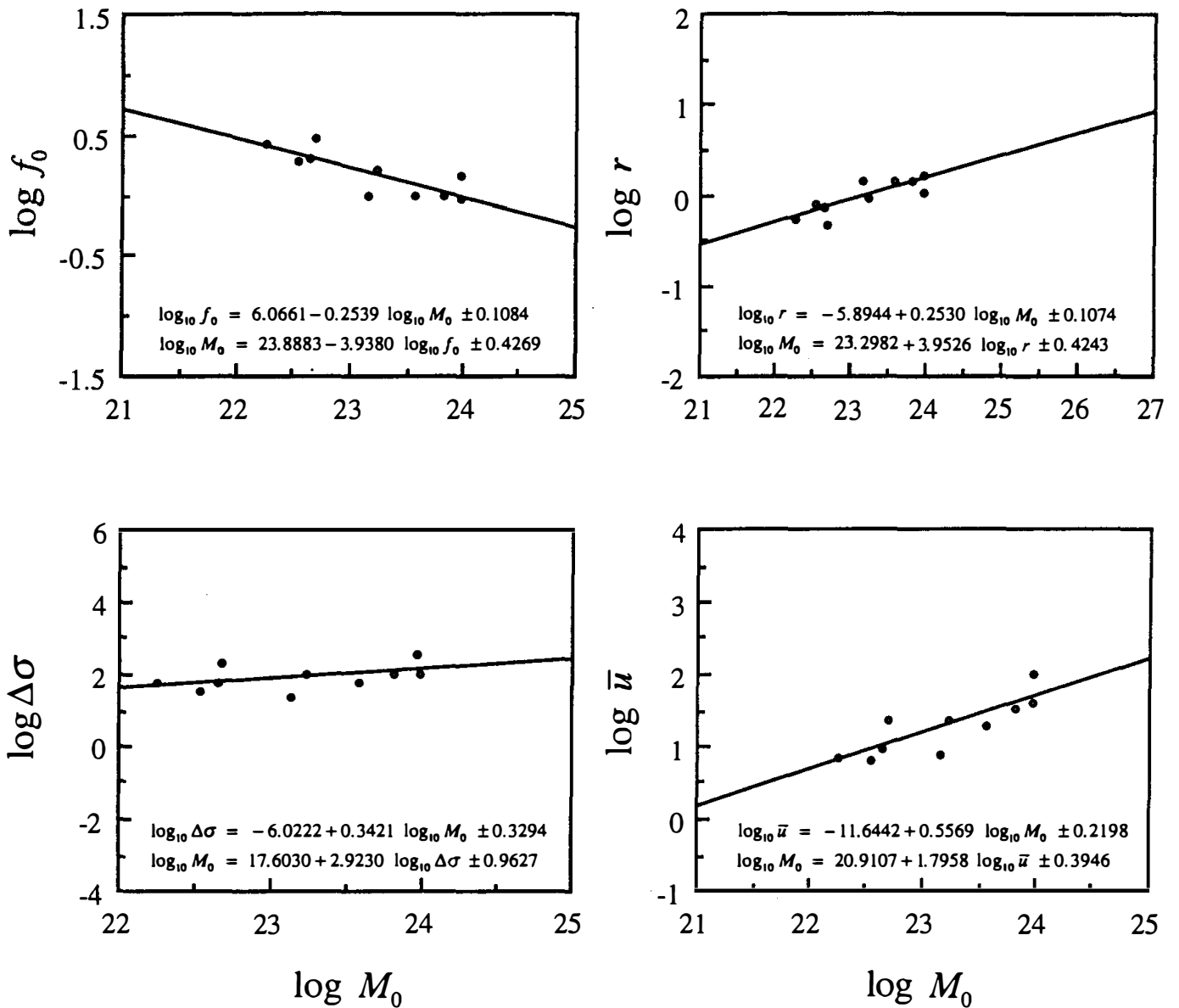


Fig. 8. Scaling relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 for the Northwest Seismic Zone.

(4) the Northwest Seismic Zone (the Hsinchu-Taichung source area)

$$\begin{aligned}
 \log_{10} f_0 &= 6.0661 - 0.2539 \log_{10} M_0 \pm 0.1084 \\
 \log_{10} r &= -5.8944 + 0.2530 \log_{10} M_0 \pm 0.1074 \\
 \log_{10} \Delta\sigma &= -6.0222 + 0.3421 \log_{10} M_0 \pm 0.3294 \\
 \log_{10} \bar{u} &= -11.6442 + 0.5569 \log_{10} M_0 \pm 0.2198
 \end{aligned} \tag{14}$$

If all of the source areas in the Taiwan region are treated as one seismic source, the rela-

The Whole Taiwan Region

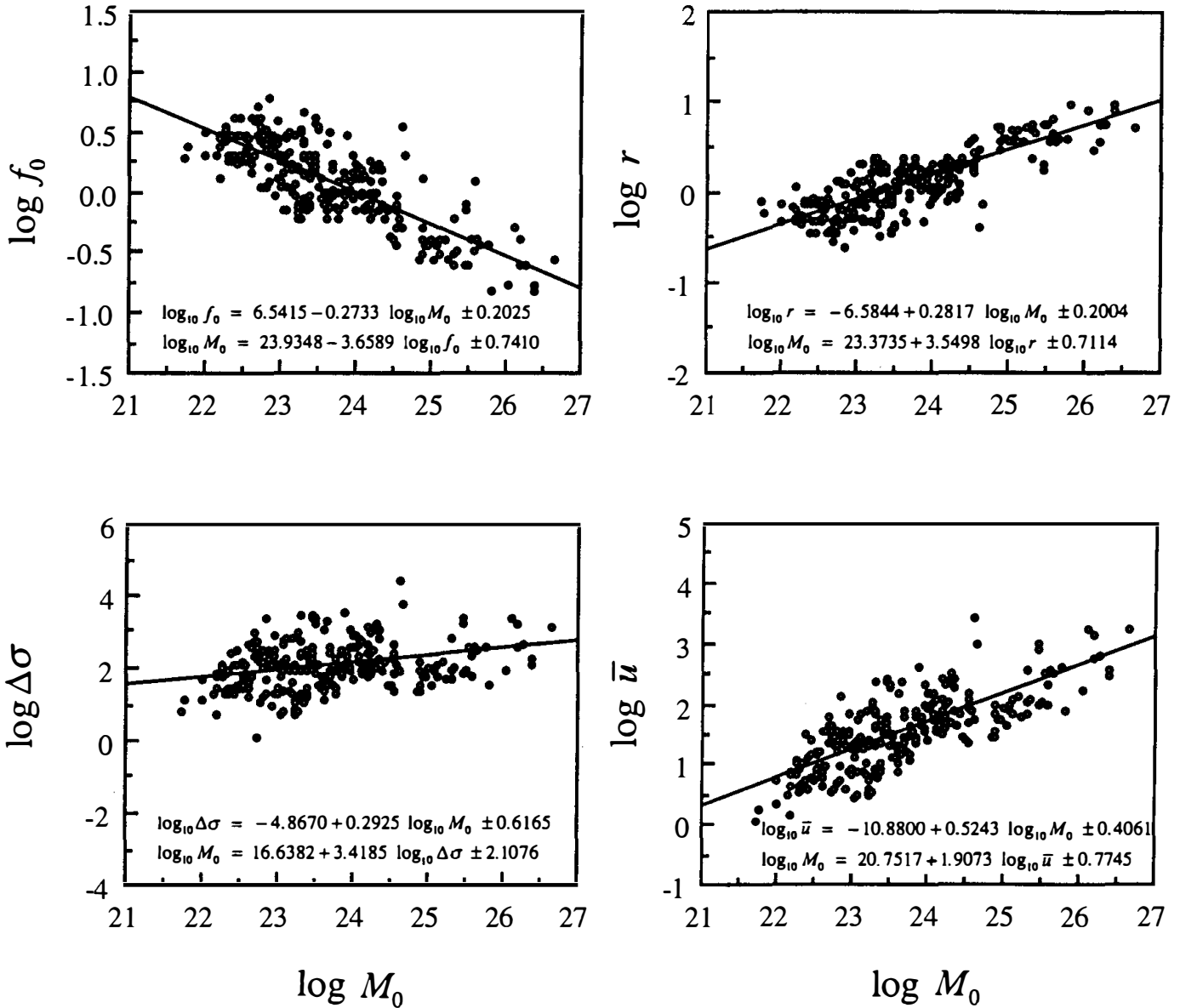


Fig. 9. Scaling relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 for the whole Taiwan region.

tionships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 are somewhat similar to those of the Northeast Seismic Zone; Figure 9 illustrates the results. The empirical equations yield:

$$\begin{aligned}
 \log_{10} f_0 &= 6.5415 - 0.2733 \log_{10} M_0 \pm 0.2025 \\
 \log_{10} r &= -6.5844 + 0.2817 \log_{10} M_0 \pm 0.2004 \\
 \log_{10} \Delta\sigma &= -4.8670 + 0.2925 \log_{10} M_0 \pm 0.6165 \\
 \log_{10} \bar{u} &= -10.8800 + 0.5243 \log_{10} M_0 \pm 0.4061
 \end{aligned}
 \tag{15}$$

Equations (11) through (15) indicate the relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 . Conversely, the relationship of M_0 with respect to f_0 , r , $\Delta\sigma$ and \bar{u} can also be found in Figures 5 - 9.

5. DISCUSSION

The procedures proposed by Anderson and Humphrey (1991), and Rovelli *et al.* (1991) are not only suitable but also very advantageous for the batch processing of a large number of strong-motion data. Nevertheless, though the procedures are efficient and objective, they tend to overestimate f_0 and underestimate M_0 . To overcome these defects, in analyzing the source parameters of the Taiwan region, f_0 and M_0 are estimated independently in this study. At the same time, to avoid the effect of soft soil layers, the strong-motion data adopted here are all from rock sites except for a few taken from soil sites in the Jia-Nan area. As such, the relationships of f_0 , r , $\Delta\sigma$ and \bar{u} with respect to M_0 are basically free of the geologic effects of soft soil except for those few exceptions (obtained from soil sites recording the earthquake events located in the Southwest Seismic Zone in Taiwan). The adequacy of Equations (11) through (14) should now be discussed in terms of the value of n in the relationship $M_0 f_0^n = \text{const.}$ and in terms of the inferred stress drop.

The relationships of $f_0 - M_0$, $r - M_0$, $\Delta\sigma - M_0$ and $\bar{u} - M_0$ shown in Figures 5-9 reveal linear behavior on log-log plots. In the relationship $M_0 f_0^n = \text{const.}$, the value n , according to Brune (1970), should be close to 3. In this study, the Northeast, the Southeast, the Southwest and the Northwest Seismic Zones have values of n equal to 3.48, 4.59, 10.96 and 3.94, respectively. This means that only the Northeast Seismic Zone has the value of n close to 3, which reveals the most reasonable relationship of f_0 with M_0 compared to that of the others. The other three zones in the Taiwan region show unreasonable results for n , which raises the issue as to whether or not those values of n are in fact reliable and representative. One explanation may be that a lack of data for those three source areas biases the results of n . Additionally, to explain the n value of 10.96 (much larger than 3) in the Southwest Seismic Zone is the fact that the geologic condition at the recording sites in this area is soft soil. This may in turn bias the estimates for f_0 and M_0 in that zone.

Because only the Northeast Seismic Zone has a reasonable value of n , the empirical relationships obtained for $r - M_0$, $\Delta\sigma - M_0$ and $\bar{u} - M_0$ for other source areas are not reliable. Nevertheless, the estimated n for the whole Taiwan source area [as shown in Equation (15)] is equal to 3.66. Though it is not ideally close to 3, the relationships of $f_0 - M_0$, $r - M_0$, $\Delta\sigma - M_0$ and $\bar{u} - M_0$ for the whole Taiwan region can be considered acceptable or good first approximations. Thus, until more strong-motion data are available, Equation (15) may be used for source areas other than the Northeast Seismic Zone.

In general, the stress drop exhibits a value of about 30 bars for inter-plate earthquake events and about 100 bars for intra-plate ones (Kanamori and Anderson, 1975). Applying the median values of Equations (11) and (15) to the relationship (Hanks and Kanamori, 1979):

$$\log_{10} M_0 = 1.5M + 16.1 \quad (16)$$

Table 2. The values of stress drop inferred from Equations (11) and (15) for earthquakes occurring in the Northeast Seismic Zone and in the whole Taiwan region.

M	The Northeast Seismic Zone	The whole Taiwan region
	$\Delta\sigma$ (bar)	$\Delta\sigma$ (bar)
4.5	67	63
5.0	100	105
5.5	149	174
6.0	221	288
6.5	328	478
7.0	487	792
7.5	724	1313

the values of stress drop of earthquakes in the Taiwan region for magnitudes 4.5 up to 7.5 with 0.5 increments are listed in Table 2. Apparently, the stress drop increases in accordance with the magnitude for both the northeast and the whole Taiwan source areas. The relationship of stress drop and seismic moment shown in Equation (15), which is for the whole Taiwan region, also represents the source characteristics of the Northwest and the Southwest Seismic Zones. From the table, it is found that, except for small earthquake magnitudes (e.g., M 4.5), the values of stress drop obtained for larger magnitudes for the whole Taiwan region are all larger than those of the Northeast Seismic Zone. This implies that the stress drop of earthquakes occurring in the Northeast Seismic Zone is, on average, smaller than that of earthquakes occurring within Taiwan Island, especially on the west side of the plate boundary represented by the Longitudinal Valley that is associated with the oblique collision between the Eurasian plate and the Philippine Sea plate. Both the Northwest and the Southwest Seismic Zones in Taiwan belong to the seismotectonic region of the Eurasian plate. Most of the earthquakes occurring in these source areas are intra-plate events. On the other hand, the earthquakes occurring in the Northeast Seismic Zone which is within the collision zone of the plate boundary are inter-plate events. As such, Table 2 implies that the values of the stress drop of earthquakes occurring on the Eurasian plate within the Northwest and the Southwest Seismic Zones in Taiwan are larger than those of earthquakes occurring on the plate boundary of the collision zone. This is consistent with the results obtained by Kanamori and Anderson (1975) in which the stress drop of intra-plate events is, in general, larger than that of inter-plate events.

Even so, the values of the stress drop obtained in this study are, for the most part, somewhat larger than those obtained by Kanamori and Anderson (1975). One rational explanation could be that Brune's (1970) source model and Anderson and Hough's (1984) modification of high frequency decay, together with the anelastic attenuation term [as shown in Equation (8)], may not be adequate to delineate strong-motion recordings that have lower values of corner

frequency f_0 than those obtained from the least-squares fit. Also, for large earthquake events, the rupture area may not be adequately represented by the shape of a circular rupture conforming to the Brune source model because earthquake events of intermediate or larger magnitudes have more complicated rupture shapes. Applying the circular rupture to the delineation of the inferred seismic moment may underestimate the source dimension. As a result, the values of rupture length and rupture area of intermediate and larger earthquakes are underestimated. Thus, in turn, the corner frequency f_0 and the stress drop $\Delta\sigma$ may be, to some extent, overestimated in this study.

6. CONCLUSIONS

The earthquake source parameters in terms of corner frequency, seismic moment, source dimension, stress drop and average slip for the Taiwan region have been estimated in this study. The strong-motion data, mostly collected from rock sites on Taiwan, are analyzed assuming the Brune (1970) source model with those modifications suggested by Anderson and Hough (1984) for high-frequency decay, and by Tsai (1992) for a path attenuation filter. The adequacy of the analyzing methods has been tested using the strong-motion data whose source parameters (at least a few of them named above) are available in the literature. Some conclusions can be drawn for the characteristics of the source parameters for the Taiwan region as follows:

- (1) Earthquakes in the Ilan-Hualien offshore source area (the Northeast Seismic Zone) are mainly associated with the northward subduction of the Philippine Sea plate beneath the Eurasian plate. The values of stress drop of earthquake events in this area are statistically smaller than those in Taiwan Island. This result is consistent with that of Kanamori and Anderson (1975). That is, the stress drop of an inter-plate earthquake is smaller than that of an intra-plate event. This may imply that those earthquakes occurring in Taiwan Island which have a shallow focal depth are most likely derived from intra-plate events.
- (2) The values of n for the Northeast Seismic Zone and the whole Taiwan region can be deemed reasonable. The stress drop of earthquakes in the whole Taiwan region increases with increasing earthquake magnitude. The stress drop of earthquake M 6 in the Northeast Seismic Zone is less than 220 bars and that of M 6 occurring within Taiwan Island is on average less than 290 bars.
- (3) The source parameters obtained from Equations (11) and (15) are better estimated than those from Equations (12), (13) and (14), and are deemed adequate for magnitudes between 4 and 7.
- (4) The corner frequency f_0 obtained using Brune's (1970) source model is overestimated. Thus, the source dimension inferred from Equations (11) and (15) tends to be underestimated, and the stress drop and the average slip tend to be overestimated. As a result, f_0 , $\Delta\sigma$ and \bar{u} obtained herein should be considered values of upper-bounds and $2r$ be treated as values of lower-bounds for the whole Taiwan source area.

The above conclusions can provide source parameters to contribute a basis to new models for the estimation and synthesis of strong ground motions in Taiwan. The results drawn in this study can also be useful for earthquake resistant design in major engineering projects in Tai-

wan.

Some difficulties have been encountered in the procedures followed in this study. The major issue lies in the lack of large earthquake events and in the lack of strong-motion recordings for major events, say, $M > 7.5$. Except for the Northeast Seismic Zone (i.e. the Ilan-Hualien source area), earthquake events in other source areas are still, relatively speaking, insufficient. More strong-motion data are required. Future studies of this kind may try source models other than the Brune model in order to overcome the problem of overestimating the source corner frequency f_0 .

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