13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2743

GLOBAL SOURCE PARAMETERS OF FINITE FAULT MODEL FOR STRONG GROUND MOTION SIMULATIONS OR PREDICTIONS

WANG Haiyun [1,2] TAO Xiaxin 1[1,3] LI Jie [2]

SUMMARY

Global source parameters of finite fault model are important in strong ground motion simulations or predictions near field. In this paper, theoretical relationships between moment magnitude and global source parameters of finite fault model including subsurface rupture length, downdip rupture width, rupture area, and average slip on the fault plane are deduced based on seismological theory. These theoretical relationships are further simplified by applying similarity conditions, and an unique form is established. Then, combining the simplified theoretical relationships between moment magnitude and global source parameters with seismic source data selected in this study, some practical semi-empirical relationships are established. The seismic source data selected is also used to derive empirical relationships between moment magnitude and global source parameters by the ordinary least square regression method. Comparisons between semi-empirical relationships and empirical relationships show that the former depicts distribution trends of data better than the latter. It is also observed that downdip rupture widths of strike slip faults are saturated when moment magnitude is more than 7.0, but downdip rupture widths of dip slip faults are not saturated in the moment magnitude ranges of this study.

INTRODUCTION

The global source parameters of finite fault model, e.g., rupture length, downdip rupture width, rupture area, and average slip on the fault plane are important in strong ground motion simulations or predictions near field. Several recent well-known earthquakes, for example, the 1994 Northridge earthquake (M_w 6.7), 1995 Kobe earthquake (M_w 6.9), 1999 Chichi earthquake (M_w 7.6), 1999 Kocaeli earthquake (M_w 7.4) and so on, show that strong ground motions near faults are affected intensively by source mechanism, fault orientation (strike, dip directivity, and dip angle), fault rupture dimension and slip distribution on the fault plane. Therefore, they are indispensable to the prediction of strong ground motion near faults for future earthquake on active faults.

To develop empirical relationships between earthquake magnitude and global source parameters, statistical analysis methods have been used by many researchers, for example, Tocher [1], Iida [2], Albee and Smith [3], Chinnery [4], Bonilla and Buchanon [5], Ohnaka [6], Slemmons [7,8], Acharya [9], Bonilla

[1] Institute of Engineering Mechanics, China Seismological Bureau, Harbin 150080, China
[2] Daqing Petroleum Institute, Daqing 163318, China
[3] Harbin Institute of Technology, Harbin 150001, China

et al. [10], Slemmons *et al.* [11], Wells and Coppersmith [12], Mai and Beroza [13], Stirling *et al.* [14]. However, the coefficients in the empirical relationships used in these studies are different, though the same methods, for example, least-square fit, have been used. The primary reason for generating different semi-empirical relationships may be related to the number and quantity of data used in these studies. Until now, the relationships proposed by Wells and Coppersmith [12] have been recognized as being more reliable. Empirical relationships between moment magnitude and fault rupture dimension were derived from more reliable data using the ordinary least square regression method. In the past, coefficients in the empirical relationships were likely thought to depend on the tectonic setting. However, separating the data according to extensional and compressional tectonic environments neither provides statistically different results nor improves the statistical significance of the regressions (Wells and Coppersmith [12]).

Some seismologists probed the relationship between seismic moment and/or magnitude and global source parameters based on seismological theory, and developed some well-known relationships used often in seismology (Gutenberg and Richter [15]; Kanamori and Anderson [16]; Hanks and Kanamori [17]). It is these theoretical studies that provide the basis for developing relationships between seismic moment and/or magnitude and global source parameters.

The objective of this study is to formulate theoretical relationships between moment magnitude and global source parameters based on seismological theory, and to simplify them for developing semi-empirical relationships for engineering and scientific practice.

A total of 149 worldwide historical earthquakes from Wells and Coppersmith's [12] database and nine historical earthquakes that occurred after 1993 were selected as the basic data for this study. The basic data is first used to derive the empirical relationships between moment magnitude and global source parameters on the fault. Besides, based on the basic data and the simplified theoretical relationships formulated, semi-empirical relationships between moment magnitude and global source parameters are also developed for different moment magnitude ranges and fault types by using the least square regression method.

Finally, comparisons between semi-empirical and empirical relationships and comparisons between corresponding relationships presented in the paper and those suggested by other researchers are made and discussed.

THEORETICAL ANALYSIS

Establishment of theoretical relationships

Based on seismological theory, Kanamori and Anderson [16] proposed the following theoretical relationship between moment magnitude and rupture area:

$$\log M_0 = 1.5 \log S + \log \Delta\sigma + \log C \qquad (1)$$

where

$$C = \begin{cases} \dfrac{16}{7\pi^{3/2}} & \text{(circular faults)} \\ \dfrac{\pi}{2}\left(\dfrac{W}{L}\right)^{1/2} & \text{(strike slip faults)} \\ \dfrac{\pi(\lambda+2\mu)}{4(\lambda+\mu)}\left(\dfrac{W}{L}\right)^{1/2} & \text{(dip slip faults)} \end{cases}$$

where $\Delta\sigma$ is stress drop, L is rupture length of fault, W is downdip rupture width of fault, S is fault rupture area, and λ and μ are Lame's constants.

From the similarity conditions (Kanamori and Anderson [16]):

$$\frac{W}{L} = c_1 \qquad \text{(aspect ratio)} \qquad (2\text{-}1)$$

and $$\frac{\overline{D}}{W} = c_2 \qquad \text{(strain drop)} \qquad (2\text{-}2)$$

where $\overline{D}$ is average slip on fault plane , $c1$ and $c2$ are constants, both the $\Delta\sigma$ and C in Eq. (1) are constants. Thus, the last two terms in Eq. (1) are constants, though stress drops for interplate and intraplate earthquakes are different (according to Kanamori and Anderson [16], stress drop is 3×10^6 Pa for interplate earthquakes and 10^7 Pa for intraplate earthquakes).

Hanks and Kanamori [17] presented the following well-known relationship between seismic moment and moment magnitude:

$$\log M_0 = 1.5M_w + 16.1 \qquad (3)$$

Therefore, a thoretical relationship between moment magnitude and rupture area can be deduced from Eqs. (1) and (3):

$$\log S = M_w + 10.7 - \frac{2}{3}(\log\Delta\sigma + \log C) \qquad (4)$$

According to the definition, the seismic moment can be expressed as:

$$M_0 = \mu\cdot S\cdot\overline{D} \qquad (5)$$

where the shear modulus, μ generally can be taken as 3.0×10^{10}Pa.

The stress drop is given by

$$\Delta\sigma = C'\mu\frac{\overline{D}}{\tilde{L}} \qquad (6)$$

where C' is a non-dimensional shape factor, and $\tilde{L}$ is radius of a circular fault or minimum dimension of a rectangle fault. $\overline{D}/\tilde{L} \equiv \Delta\tilde{e}$ is the strain drop.

For circular faults, $\tilde{L} = a$ and C'=7/π. For strike slip and dip slip faults, $\tilde{L} = W$, i.e., $\tilde{L}$ is downdip rupture width, but C' is different. For strike slip faults, C'=2/π, and for dip slip faults $C' = 4(\lambda+\mu)/\pi(\lambda+2\mu)$ (Kanamori and Anderson [16]).

From Eqs.(5) and (6) one obtains

$$\log M_0 = \log\tilde{L} + \log S + \log\Delta\sigma - \log C' \qquad (7)$$

Combining Eqs.(3), (4) and (7), the following theoretical relationship between moment magnitude and rupture radius (circular faults) or downdip rupture width (both strike slip and dip slip fault) is obtained:

$$\log\tilde{L} = 0.5M_w + 5.4 + \frac{2}{3}\log C + \log C' - \frac{1}{3}\log\Delta\sigma \qquad (8)$$

Similar theoretical relationships can be derived from Eqs.(3) and (7) for rectangle faults, considering their area being $S = L\times W$

$$\log L = 0.5M_w + 5.3 - \frac{4}{3}\log C - \log C' - \frac{1}{3}\log\Delta\sigma \qquad (9)$$

Furthermore, combining Eqs.(3), (4) and (5) or Eqs.(6) and (7) a theoretical relationship between moment magnitude and average slip can be obtained

$$\log\overline{D} = 0.5M_w + 5.4 + \frac{2}{3}(\log C + \log\Delta\sigma) - \log\mu \qquad (10)$$

Simplification of theoretical relationships

From the similarity conditions, i.e., Eq. (2), both $\Delta\sigma$ and $\log C$ in each theoretical relationship above are constants and $\log C'$ and/or $\log\mu$ are constants. Assembling all constant terms, all the theoretical relationships above can be simplified and become, respectively,

$$\log S = M_w - C_S \qquad (11\text{-}1)$$

$$\log L = 0.5M_w - C_L \qquad (11\text{-}2)$$

$$\log W = 0.5M_{\mathrm{w}} - C_W \tag{11-3}$$

and

$$\log \overline{D} = 0.5M_{w} - C_{\overline{D}} \tag{11-4}$$

in which C_S, C_L, C_W, and $C_{\overline{D}}$ denote constants related to rupture area, rupture length, rupture width and average slip, respectively. Equation (11) can be expressed as an unique equation as

$$\log Y = \alpha \cdot M_{\mathrm{w}} - C_{\mathrm{Y}} \tag{12}$$

where, Y in the left side and the subscript of C_Y in the right side represents fault rupture area, rupture length, or downdip rupture width, or average slip on fault plane, e.g., Y is S, L, W or $\overline{D}$. $\alpha = 0.5$ is for all cases except for rupture area, in which $\alpha = 1.0$. C_Y stands for constants, which vary according to fault types, and may vary for different moment magnitude ranges even though the fault types are the same.

FORMULATION OF SEMI-EMPIRICAL RELATIONSHIPS

Database

So far, Wells and Coppersmith's [12] database is more comprehensive and reliable for use in studying the relationships between magnitude and global source parameters. The database includes source parameters of 244 worldwide historical earthquakes from 1857 to 1993, and they are all shallow-focus (hypocentral depth less than 40 km), continental interplate or intraplate earthquakes of magnitudes greater than 4.5. Earthquakes associated with subduction zones, both plate interface earthquakes and those occurring within oceanic slabs, were excluded. For each earthquake in the database, seismological source parameters and fault characteristics were compiled, including seismic moment, magnitude, slip type, surface and subsurface rupture length, maximum and average surface displacement, downdip rupture width, and rupture area.

From Wells and Coppersmith's [12] database, 149 earthquakes, (in which there are 69 dip slip faults (normal 23, and reverse 46) and 80 strike slip faults) are selected for this study based on the following criteria (1) data must be reliable, source parameters that Wells and Coppersmith [12] considered to be unreliable are not included; (2) source parameters of each earthquake must be complete, earthquake data lacking individual source parameters are not included; and (3) parts of source parameters in Wells and Coppersmith's [12] database, for example, magnitude, moment magnitude, seismic moment, slip type, subsurface rupture length, downdip rupture width and rupture area are reserved.

However, all seismic moments in Wells and Coppersmith's database are greater than that calculated by Hanks and Kanamori's [17] equation, the former is generally 10 times of the latter. This study uses results calculated by Eq. (3).

The average slip of each earthquake is calculated by definition of the seismic moment, e.g. from Eq. (5).

Besides the 149 earthquakes selected from Wells and Coppersmith's [12] database, nine earthquakes, in which there are four dip slip faults and five strike slip faults, from published literature after 1993, are supplemented in the present analysis. Among these nine earthquakes, several are famous, for example, 1994 Northridge earthquake (M_w 6.7), 1995 Kobe earthquake (M_w 6.9), 1999 Chichi earthquake (M_w 7.6), and 1999 Kocaeli earthquake (M_w 7.4). Therefore, a total of 158 worldwide historical earthquakes are included in the database of source parameters used in this study, in which there are 73 dip slip faults and 85 strike slip faults. To avoid more length of this paper, the database of source parameters used in this study is not include in the paper. The database is available free on demand by haiyunwang_iem@yahoo.com.cn.

Empirical relationships

Empirical relationships between moment magnitude and global source parameters in different slip types (including all, dip slip, normal, reverse, strike slip) are derived by using the ordinary least-square regression method (Wells and Coppersmith [12]) for all analyses of fault parameters, and are summarized in Table 1, where corresponding coefficients from Wells and Coppersmith [12] are also listed for comparison. It can be found that all results obtained are consistent with those by Wells and Coppersmith [12], except for average slip. This is due to the fact that the average slip is referred to as the average slip on fault plane in the present study, while in Wells and Coppersmith's [12] relationships, the moment magnitude is related to the surface maximum or average displacement.

Correlation coefficients between moment magnitude and global source parameters for different slip types are different. Table 1 indicates that for the rupture area, all correlation coefficients are more than 0.91, among which the maximum value, 0.96 is referred to one of strike fault. For rupture length, except for one of normal fault equaling 0.88, the correlation coefficients of all other slip types are more than 0.91 with the maximum value, 0.95 referred to one of the strike fault. For downdip rupture width and average slip on fault plane, the correlation coefficients range from 0.85 to 0.90 and 0.84 to 0.92, respectively.

Semi-empirical relationships

Now if the constants, α , are assumed to be known, i.e. α = 0.5 for all cases except the rupture area, in which α = 1.0 as indicated above, and the constants C_Y are to be determined by using the ordinary least square regression method, semi-empirical relationships between moment magnitude and global source parameters in different moment magnitude ranges for different slip types can be derived as described in the following subsection.

Rupture area

Relationships between moment magnitude and rupture area for different magnitude ranges and fault types are derived as following,

$$\log S = \begin{cases} M_W - 4.0 & (4.5 < M_W \le 6.5) \\ M_W - 4.05 & (6.5 < M_W \le 7.0) \\ M_W - 4.2 & (7.0 < M_W) \end{cases} \quad \text{(All faults)} \qquad (13\text{-}1)$$

$$\log S = \begin{cases} M_W - 4.0 & (4.5 < M_W \le 6.5) \\ M_W - 4.05 & (6.5 < M_W \le 7.0) \\ M_W - 4.25 & (7.0 < M_W) \end{cases} \quad \text{(Dip slip faults)} \qquad (13\text{-}2)$$

$$\log S = \begin{cases} M_W - 4.0 & (4.5 < M_W \le 6.5) \\ M_W - 4.05 & (6.5 < M_W \le 7.0) \\ M_W - 4.2 & (7.0 < M_W) \end{cases} \quad \text{(Strike slip faults)} \qquad (13\text{-}3)$$

Comparisons between semi-empirical and empirical relationships are shown in Fig.1. It is found that for dip slip faults, when moment magnitude is more than 6.5, matching between semi-empirical and empirical relationships is worse, however, when the moment magnitude is less than 6.5, matching between semi-empirical and empirical relationships is better; for both all faults and strike slip faults, matching between semi-empirical and empirical relationships is also better.

Abe [18] suggested a remarkable linearity between $\log M_0$ and $\log S$ for great shallow earthquakes:

$$\log M_0 = 1.5 \log S + 15.1 \qquad (14)$$

where, the unit for the seismic moment is N-m and the unit for the rupture area is km^2. Transforming the unit of seismic moment into dyne-cm, we have

Table 1 Empirical relationships among subsurface rupture length, downdip width, rupture area, average slip on fault surface and moment magnitude.

Equation	Slip type	Event number	Coefficients and Standard Errors a	S_a	b	S_b	Standard deviation	Correlation coefficient	Magnitude ranges
$\log L = aM_w + b$	All	149 (167)	0.57 (0.59	0.02 (0.02)	-2.29 (-2.44)	0.11 (0.11)	0.12 (0.16)	0.93 (0.94)	4.57～7.77 (4.80～8.10)
	DS	69	0.53	0.03	-2.11	0.19	0.19	0.91	4.70～7.59
	N	23 (24)	0.54 (0.50)	0.06 (0.06)	-2.15 (-1.88)	0.38 (0.37)	0.21 (0.17)	0.88 (0.88)	4.80～7.29 (5.20～7.30)
	R	46 (50)	0.53 (0.58)	0.04 (0.03)	-2.10 (-2.42)	0.22 (0.21)	0.18 (0.16)	0.92 (0.93)	4.70～7.59 (4.80～7.60)
	SS	80 (90)	0.60 (0.62)	0.02 (0.02)	-2.46 (-2.57)	0.13 (0.12)	0.16 (0.15)	0.95 (0.96)	4.57～7.77 (4.80～8.10)
$\log W = aM_w + b$	All	149 (153)	0.31 (0.32)	0.02 (0.02)	-0.96 (-1.01)	0.10 (0.10)	0.16 (0.15)	0.85 (0.84)	4.57～7.77 (4.80～8.10)
	DS	69	0.37	0.03	-1.28	0.16	0.16	0.86	4.70～7.59
	N	23 (23)	0.39 (0.35)	0.04 (0.05)	-1.42 (-1.14)	0.25 (0.28)	0.14 (0.12)	0.90 (0.86)	4.80～7.29 (5.20～7.30)
	R	46 (43)	0.36 (0.41)	0.03 (0.03)	-1.23 (-1.61)	0.22 (0.20)	0.18 (0.15)	0.85 (0.90)	4.70～7.59 (4.80～7.60)
	SS	80 (87)	0.26 (0.27)	0.02 (0.02)	-0.71 (-0.76)	0.12 (0.12)	0.14 (0.14)	0.85 (0.84)	4.57～7.77 (4.80～8.10)
$\log S = aM_w + b$	All	149 (148)	0.87 (0.91)	0.03 (0.03)	-3.25 (-3.49)	0.16 (0.16)	0.26 (0.24)	0.94 (0.95)	4.57～7.77 (4.80～7.90)
	DS	69	0.89	0.05	-3.38	0.30	0.30	0.92	4.70～7.59
	N	23 (22)	0.93 (0.82)	0.08 (0.08)	-3.57 (-2.87)	0.47 (0.50)	0.27 (0.22)	0.93 (0.92)	4.80～7.29 (5.20～7.30)
	R	46 (43)	0.88 (0.98)	0.06 (0.06)	-3.33 (-3.99)	0.38 (0.36)	0.32 (0.26)	0.91 (0.94)	4.70～7.59 (4.80～7.60)
	SS	80 (83)	0.86 (0.90)	0.03 (0.03)	-3.17 (-3.42)	0.18 (0.18)	0.22 (0.22)	0.96 (0.96)	4.57～7.77 (4.80～7.90)
$\log \overline{D} = aM_w + b$	All	149	0.63	0.03	-2.18	0.16	0.26	0.89	4.57～7.77
	DS	69	0.61	0.05	-2.04	0.30	0.30	0.84	4.70～7.59
	N	23	0.58	0.08	-1.86	0.49	0.27	0.84	4.80～7.29
	R	46	0.62	0.06	-2.10	0.38	0.32	0.84	4.70～7.59
	SS	80	0.64	0.03	-2.26	0.18	0.22	0.92	4.57～7.77

Note: 1. All_all type faults; DS_dip slip faults; N_Normal faults; R_Reverse faults; SS_strike slip faults.
2. Data in the parentheses are corresponding coefficients from Wells and Coppersmith (1994).

$$\log M_0 = 1.5 \log S + 22.1 \tag{15}$$

Combining Eq. (3) and (15), we obtain

$$M_w = \log S + 4.0 \tag{16}$$

This is the same as the relationship obtained above for moment magnitudes less than 6.5.

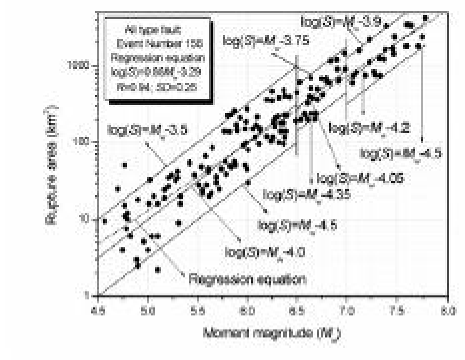
Sato [19] suggested the following relationship for great shallow earthquakes ($M \geq 5.0$):

$$\log S = M - 4.07 \tag{17}$$

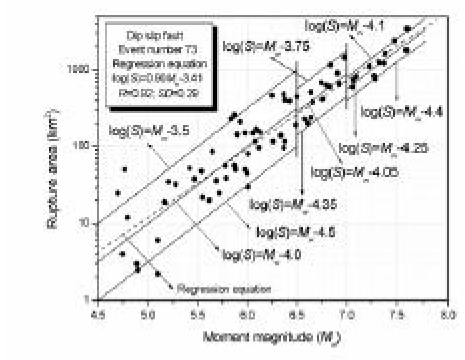
where M is earthquake magnitude. Equation (17) is closest to the desired result when moment magnitude is in the range of 6.5 and 7.0 (Eq. 13).

Somerville *et al*. [20] proposed the following relationship between moment magnitude and rupture area,

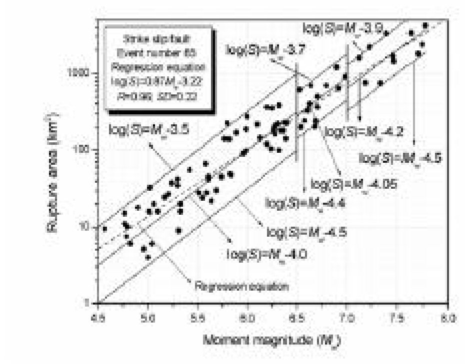
$$M_w = \log S + 3.95 \tag{18}$$



(a) All faults

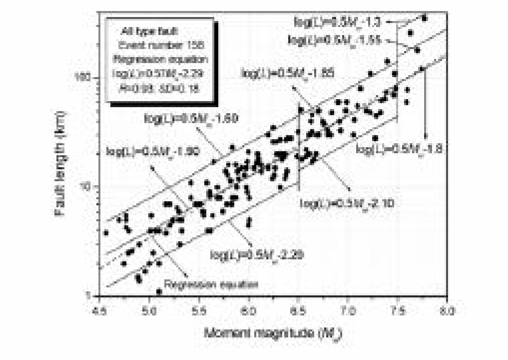


(b) Dip slip faults

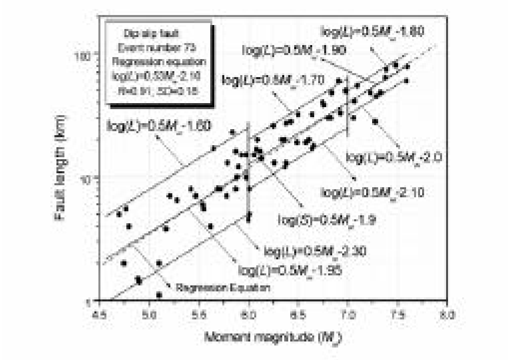


(c) Strike slip faults

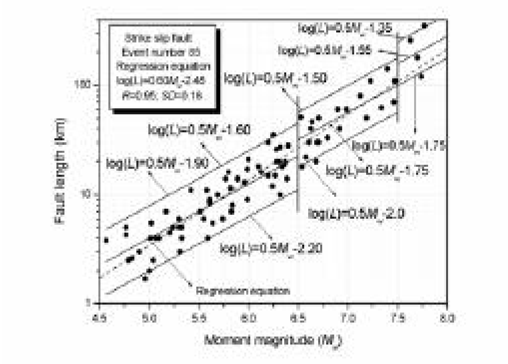
Fig.1 Comparison between semi-empirical and empirical relationships for rupture area



(a) All faults



(b) Dip slip faults



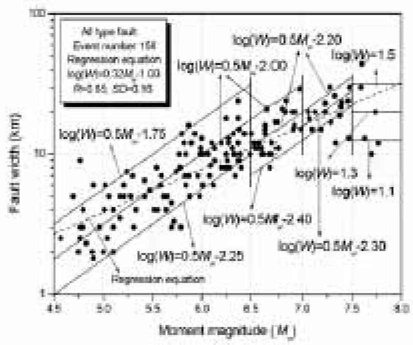
(c) Strike slip faults

Fig.2 Comparison between semi-empirical and empirical relationships for rupture length

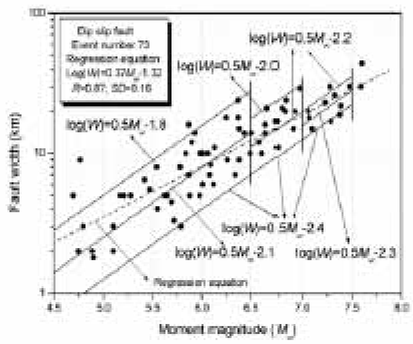
where the constant, 3.95 is less than the C_S values given in Eq. (13). This implies that Eq. (18) will provide less moment magnitude and/or more rupture area than from the method described in this paper when moment magnitude is given. Somerville *et al*. [20] suggested that the relationship reflects the zone of fault radiated seismic energy, and is directly relevant to the prediction of strong ground motions.

Examining Wells and Coppersmith's [12] empirical relationship of strike slip faults by seven well-documented California strike slip large earthquakes, Working Group [21] derived a relationship for large magnitude earthquakes

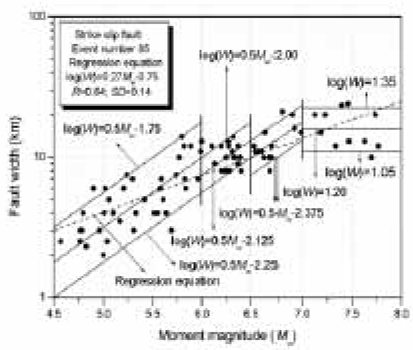
$$M_{\mathrm{w}} = \log S + k \tag{19}$$



(a) All faults

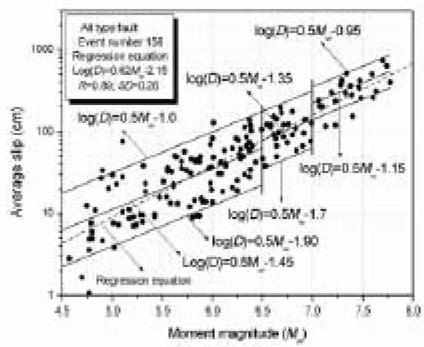


(b) Dip slip faults

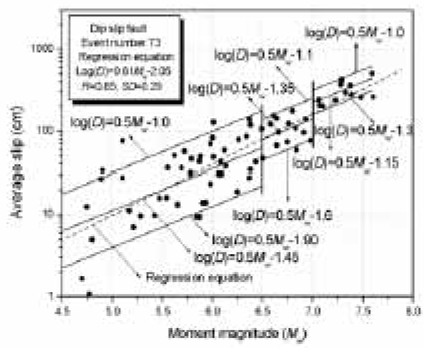


(c) Strike slip faults

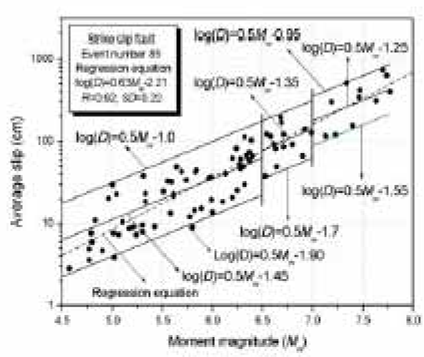
Fig.3 Comparison between semi-empirical and empirical relationships for downdip width



(a) All faults



(b) Dip slip faults



(c) Strike slip faults

Fig.4 Comparison between semi-empirical and empirical relationships for average slip

where k = 4.2 - 4.3 The results are the same as in the present paper when moment magnitude is more than 7.0 ((Eq. 13)).

Relationships by other researchers described only distribution trends of data in some or other magnitude ranges, and semi-empirical relationships of this study comprehensively describe relationships between rupture area and moment magnitude.

Rupture length

Relationships between moment magnitude and rupture length for different magnitude ranges and fault types are derived as following,

$$\log L = \begin{cases} 0.5M_W - 1.9 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 1.85 & (6.5 < M_W \le 7.5) \\ 0.5M_W - 1.55 & (7.5 < M_W) \end{cases} \quad \text{(All faults)} \qquad (20\text{-}1)$$

$$\log L = \begin{cases} 0.5M_W - 1.95 & (4.5 < M_W \le 6.0) \\ 0.5M_W - 1.90 & (6.0 < M_W) \end{cases} \quad \text{(Dip slip faults)} \qquad (20\text{-}2)$$

$$\log L = \begin{cases} 0.5M_W - 1.90 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 1.75 & (6.5 < M_W \le 7.5) \\ 0.5M_W - 1.55 & (7.5 < M_W) \end{cases} \quad \text{(Strike slip faults)} \qquad (20\text{-}3)$$

Comparisons of semi-empirical and empirical relationships are shown in Fig.2. It is found that the semi-empirical relationship agrees well with the empirical relationship either for dip slip faults or for both all faults and strike slip faults, when the moment magnitude is less than 7.5. However, when the moment magnitude is more than 7.5, the agreement becomes worse. However, semi-empirical relationships depict better distribution trends of data than empirical relationships.

Rupture width

The maximum downdip width of faults is controlled by depth (or thickness) of the seismogenic zone, which is limited to some extent by the Earth's free surface and the brittle-ductile transition at depth (Ito [22, 23]; Scholz [24]). Once large earthquakes reach a certain size, their continued growth is constrained in size in one dimension. Because strike-slip earthquakes occur primarily on vertical faults and the extent of the seismogenic zone is limited in depth, this effect should be evident at lower values of seismic moment than for dip-slip events. Only very large reverse faulting earthquakes are likely to be affected by this constraint, because reverse faults often traverse the seismogenic zone at shallow angles (Mai and Berozal [13]).

Therefore, when a large earthquake reaches a certain size, especially for strike slip events, downdip width of faults will be a constant. Critical earthquake magnitude of strike slip faults are determined as $M_w = 7.0$ while downdip width is a constant. Downdip width of dip slip faults are not saturated in moment magnitude ranges given in the database. When moment magnitude is more than 7.0, downdip width of strike slip faults can be expressed as follows:

$$\log W = C \qquad (21)$$

where C is a constant.

Relationship between moment magnitude and rupture width for different magnitude ranges and fault types are derived as following,

$$\log W = \begin{cases} 0.5M_W - 2.00 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 2.20 & (6.5 < M_W \le 7.0) \\ 0.5M_W - 2.30 & (7.0 < M_W \le 7.5) \\ 1.3 & (7.5 < M_W) \end{cases} \quad \text{(All faults)} \qquad (22\text{-}1)$$

$$\log W = \begin{cases} 0.5M_W - 2.10 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 2.20 & (6.5 < M_W \le 7.0) \\ 0.5M_W - 2.30 & (7.0 < M_W) \end{cases} \quad \text{(Dip slip faults)} \qquad (22\text{-}2)$$

$$\log W = \begin{cases} 0.5M_W - 2.00 & (4.5 < M_W \le 6.0) \\ 0.5M_W - 2.125 & (6.0 < M_W \le 6.5) \\ 0.5M_W - 2.25 & (6.5 < M_W \le 7.0) \\ 1.2 & (7.0 < M_W) \end{cases} \quad \text{(Strike slip faults)} \qquad (22\text{-}3)$$

Comparisons of semi-empirical and empirical relationships are shown in Fig.3. It can be observed that the semi-empirical and empirical relationships are a good match only for dip slip faults, when $6.0 \le M_w \le 7.0$. However, once again, semi-empirical relationships depict better distribution trends of data than the empirical relationships.

Average slip

Relationships between moment magnitude and average slip for different magnitude ranges and fault types are derived as following,

$$\log \overline{D} = \begin{cases} 0.5M_W - 1.45 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 1.35 & (6.5 < M_W \le 7.0) \\ 0.5M_W - 1.15 & (7.0 < M_W) \end{cases} \quad \text{(All faults)} \qquad (23\text{-}1)$$

$$\log \overline{D} = \begin{cases} 0.5M_W - 1.45 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 1.35 & (6.5 < M_W \le 7.0) \\ 0.5M_W - 1.15 & (7.0 < M_W) \end{cases} \quad \text{(Dip slip faults)} \qquad (23\text{-}2)$$

$$\log \overline{D} = \begin{cases} 0.5M_W - 1.45 & (4.5 < M_W \le 6.5) \\ 0.5M_W - 1.35 & (6.5 < M_W \le 7.0) \\ 0.5M_W - 1.25 & (7.0 < M_W) \end{cases} \quad \text{(Strike slip faults)} \qquad (23\text{-}3)$$

Comparisons of semi-empirical and empirical relationships are shown in Fig.4. It is found that: the semi-empirical relationships agree well with empirical relationships for strike slip faults, and for both all faults and dip slip faults, when moment magnitude is not more than 7.0. However, for both all faults and dip slip faults when moment magnitude is more than 7.0, the agreement between the semi-empirical relationships with the empirical relationships degrades. However, once again, semi-empirical relationships depict better distribution trends of data than empirical relationships.

Sato [19] suggested the following relationship for great shallow and large earthquakes ($M \ge 5.0$):

$$\log \overline{D} = 0.5M - 1.40 \qquad (24)$$

where M is earthquake magnitude. The relationship is closest to the desired result when the moment magnitude varies in the range of 6.5 to 7.0.

Somerville *et al*. [20] proposed the following relationship between moment magnitude and average slip .

$$\overline{D} = 1.56 \times 10^{-7} \times M_0^{1/3} \qquad (25)$$

combining the relationship and Eq. (3), we have

$$\log \overline{D} = 0.5M_{\mathrm{w}} - 1.44 \qquad (26)$$

It is nearly the same as the semi-empirical relationship given in this study in the moment magnitude range ($4.5 \le M_w \le 6.5$).

CONCLUSION

Theoretical relationships between moment magnitude and global source parameters are developed based on seismological theory and are then simplified by using similarity conditions: aspect ratio of a fault, and strain drop (or stress drop) of an earthquake are constants. The simplified theoretical relationships obtained have a very simple and unique form.

$$\log Y = \alpha \cdot M_{\mathrm{w}} - C_{\mathrm{Y}}$$

where, Y both on the left side and in the subscript of C_Y on the right side represents fault rupture area, rupture length, or downdip rupture width, or average slip on fault plane, e.g. Y is S, L, W or $\overline{D}$; $\alpha = 0.5$ for all cases except for rupture area, in which $\alpha = 1.0$. C_Y stands for constants, which vary according to fault types, and they may vary for different moment magnitude ranges even though the fault types are the same.

A total of 149 worldwide historical earthquakes in Wells and Coppersmith's [12] database and nine historical earthquakes after 1993 are selected as the basic data for this study. The database is reliable, and all selected earthquakes are of shallow-focus, continental interplate or intraplate with moment magnitudes in the range of 4.5 and 7.77. Based on the database described above, empirical relationships between moment magnitude and global source parameters are derived by using the ordinary least square regression method. Results from the present study are generally consistent with Wells and Coppersmith [12], except for average slip. This is due to the fact that in this study, the average slip is referred to the average slip on fault plane, while in Wells and Coppersmith's [12] relationships, the moment magnitude is related to the surface maximum or average displacement.

The database selected is also used to determine constants C_Y in the unique form of the relationships between moment magnitude and global source parameters, and a series of semi-empirical relationships are established for different moment magnitude ranges and different slip types.

Comparisons between semi-empirical and empirical relationships show that semi-empirical relationships depict distribution trends of data between moment magnitude and global source parameters better than empirical relationships, particularly for strike slip faults.

Comparisons with corresponding relationships suggested by some other researchers have also been made. It shows that the semi-empirical relationships in this study comprehensively describe relationships between moment magnitude and global source parameters; however, relationships presented by other researchers describe only distribution trends of data in some or other magnitude ranges.

In the ranges of moment magnitude in this study, saturation phenomena of downdip rupture width of strike slip faults occur when moment magnitude is greater than 7.0; however, saturation phenomena of downdip rupture width of dip slip faults does not appear.

Relationships in this study can be directly used to determine global source parameters in finite fault modeling of strong ground motion predictions near faults for future earthquakes on active faults, and can be also applied to seismic hazard analyses of active faults,

For further study, more reliable source parameters need to be collected for historical earthquakes throughout the world, especially when moment magnitudes are less than 4.5 and greater than 7.5. Practical and reliable semi-empirical relationships in those moment magnitude ranges in engineering and scientific research will also need to be developed.

ACKNOWLEDGEMENT

The financial supports for this project by the China National Social Commonweal Research Foundation under Grant No. 2002DIB30076 and the China Earthquake Science Foundation under Contract No.201009 are thankfully acknowledged.

REFERENCES

1. Tocher D, "Earthquake energy and ground breakage," *Bull. Seism. Soc. Am.* 1958, **48:** 147-153.

2. Iida K, "Earthquake energy and earthquake faults, Nagoya University," *J, Earth Sci.* 1959, **7:** 98-107.

3. Albee AL and Smith JL, "Earthquake characteristics and fault activity in southern California," in *Engineering Geology in southern California*, R. Lung and D. W. Proctor (Editors), Association of Engineering Geologists, Los Angeles Section, 9-34, 1966.

4. Chinnery MA, "Earthquake magnitude and source parameters," *Bull. Seism. Soc. Am.* 1969, **59:** 1969-1982.

5. Bonilla MG and Buchanon JM, "Interim report on worldwide historical surface faulting," U. S. Geol. Surv. *Open-File-report*, 70-34, 1970.

6. Ohnaka M, "Earthquake-source parameters related to magnitude," *Geophys. J. R. Astr. Soc.,* 1978, **55**: 45-66.

7. Slemmons DB, "Faults and earthquake magnitude," U. S. Army Corps of Engineers, Waterways Experimental Station, Miscellaneous paper S-73-1, Report 6, 1-129, 1977.

8. Slemmons DB, "Determination of design earthquake magnitude for microzonation," *Proc. of the third international earthquake microzonation conf.* 1982, *Vol.*1, U. S. National Science Foundation, Washington, D. C., 119-130.

9. Acharya HK, "Regional variations in the rupture-length and magnitude relationships and their dynamical significance," *Bull. Seism. Soc. Am.,* 1979, **69:** 2063-2084.

10. Bonilla MG, Mark RK and Lienkaemper JJ, "Statistical relations among earthquake magnitude," surface rupture length, and surface fault displacement, *Bull. Seism. Soc. Am.* 1984, **74:** 2379-2411.

11. Slemmons DB, Bodin P and Zang X, "Determination of earthquake size from surface faulting events," *proc. of the International Seminar on seismic Zonation,* Guangzhou, China, State Seismological Bureau, Beijing, 13 , 1989.

12. Wells and Coppersmith， "New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement," *Bull. Seism. Soc. Am*., 1994, **84**(4): 974-1002.

13. Mai MP. and Beroza GC, "Source scaling properties from finite-fault-rupture models," *Bull. Seism. Soc. Am*. 2000, **90** (3): 604-615.

14. Stirling M, Rhoades D and Berryman K, "Comparison of earthquake scaling relations derived from data of the instrumental and preinstrumental Era," *Bull. Seism. Soc. Am*. 2002, **92:** 812-830.

15. Gutenberg B and Richter CF, "Magnitude and energy of earthquakes," *Ann. Geofis.*, 1956, **9**: 1-15.

16. Kanamori H and Anderson DL, "Theoretical basis of some empirical relations in seismology," *Bull. Seism. Soc. Am*. 1975, **65**: 1073-1096.

17. Hanks TC and Kanamori H, "A moment-magnitude scale," *J. Geophys. Res*. 1979, **84:** 2348-2350.

18. Abe K, "Reliable estimation of the seismic moment of large earthquakes," *J. Phys. Earth*, 1975, **23**: 381-390.

19. Sato R, "Theoretical basis on relationships between focal parameters and earthquake magnitude," *J. Phys. Earth*, 1979, **27**: 353-372.

20. Somerville, Irikula *et al*, "Characterizing Crustal Earthquake Slip Models for the Prediction of Strong Ground Motion," *Seismological Research Letters*, 1999, **70**(1): 59-80.

21. Working Group, "Earthquake Probabilities in the San Francisco Bay Region: 2000 to 2030—A Summary of Findings, USGS," *Open-File Report* 99-517, 1999.

22. Ito K, "Regional variations of the cutoff depth of seismicity in the crust and their relation to heat flow and large inland-earthquakes," *J. Phys. Earth*, 1990, **38**: 223-250.

23. Ito K, "Seismogenic layer, reflective lower crust, surface heat flow and large inland earthquakes." *Tectonophysics,* 1999, **306**: 423-433.

24. Scholz CH, "Scaling laws for large earthquakes: consequences for physical models," *Bull. Seism. Soc. Am*., 1982, **72**: 1-14.