RELIABLE ESTIMATION OF THE SEISMIC MOMENT OF LARGE EARTHQUAKES

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Large earthquakes on the Pacific coast are characterized, on the average, by $\sigma \approx 30$ bars and $L \approx 2w$ independently of the size, where $\sigma$ is the stress drop, $L$ is the fault length, and $w$ is the fault width. It follows from these that the seismic moment is determined straightforwardly from the fault size alone. Such a convenient method of estimation of the seismic moment is also applicable to the major earthquakes in the Japanese islands which are characterized, on the average, by $\sigma \approx 60$ bars and $L \approx 2w$. These results can be used for reliable assignment of moment to future large earthquakes as well as historical large earthquakes for which detailed mechanism studies cannot be made. The uncertainty in the method presented here is much less than that in estimating moments from the earthquake magnitude.

1. Introduction

Estimation of the seismic moment as defined in the dislocation theory of faulting is indispensable to a quantitative discussion on physical magnitude of earthquakes. The convenient and timesaving method to estimate this moment has been based on empirical relationships between moment and earthquake magnitude scale. Though most convenient, the magnitude is critically dependent on the dimensions of earthquakes. In fact, the proposed relationships are found to be uncertain by more than a factor of ten at magnitude 7.5 or greater (e.g., Brune, 1968; IchiKawa, 1970; Aki, 1972b). Owing to such a large uncertainty, the magnitude-moment relation becomes useless for large earthquakes.

In recent years, reliable data on the fault parameters became available for a number of large earthquakes. On the basis of these data, the present paper attempts to find another method to assign the reliable moment to historical large earthquakes, and to predict the moment of future large earthquakes.

2. Dislocation Model

It is now widely accepted that most earthquakes are caused by a sudden
release of tectonic stress in the form of faulting. An appropriate model for this earthquake mechanism is an earthquake dislocation theory (for summary, see Aki, 1972a). Within the framework of this theory, several physical quantities can be defined in terms of stress drop $\sigma$ and fault area $S$:

1. Seismic moment $M_o$;

$$M_o = \xi \sigma S^{\nu/\alpha}$$

where $\xi$ is the parameter associated with the fault geometry. The parameter $\xi$ of present interest is given by

$$\xi = \frac{3\pi}{16} \sqrt{\frac{w}{L}}$$

for a buried dip-slip faulting on a rectangular fault with length $L$ and width $w$ (Starr, 1928; Aki, 1966), and

$$\xi = \frac{16}{7\pi^{\nu/\alpha}}$$


2. Dislocation $D$;

$$D = \frac{M_o}{\mu S} = \frac{\xi \sigma S^{\nu/\alpha}}{\mu}$$

where $D$ is the average slip dislocation over the fault surface (Aki, 1966) and $\mu$ is the rigidity.

3. Strain energy $W$;

$$W = \frac{\sigma M_o}{2\mu} = \frac{\xi \sigma^2 S^{\nu/\alpha}}{2\mu}$$

where the shear stress at the fault surface is assumed to vanish after the faulting (Starr, 1928; Keylis-Borok, 1959).

We shall attempt to scale $M_o$, $D$ and $W$ using $S$ alone in the following.

3. Fault Parameters of Large Earthquakes

The fault parameters are accurately determined from the analysis of long-period seismic waves. In recent years, such an analysis was made for a number of large earthquakes which occurred at shallow depths on the Pacific coast; as a result, we now have a wealth of reliable data on the fault parameters (Abe, 1970, 1972a, b, 1973; Kanamori, 1970a, b, 1971a, b, c, 1972a; Shima-zaki, 1974; Wu and Kanamori, 1973; Yoshioka and Abe, 1975). Most of these earthquakes represent, in the framework of plate tectonics, a slip at the interface between the oceanic and continental plates. A large assemblage of these earthquake data are used to estimate the best possible values of $\xi$ and $\sigma$. 
Seismic Moment of Large Earthquakes

We first evaluate $\xi$ of Eq. (2) in which fault lengths and widths are included. In Fig. 1, is shown the fault length and width of the large earthquakes. The data for the circum-Pacific earthquakes (open circles) clearly show that the fault length is approximately twice as large as the fault width independently of the size; the standard deviation is 0.5 for $L=2w$. Then, the parameter $\xi$ of Eq. (2) is calculated to be 0.417 for $L=2w$. Inasmuch as $\xi$ of Eq. (3) is 0.410, we can take $\xi=0.41$ for both the rectangular and circular faults.

The other remarkable feature common to the large earthquakes is found in the stress drop. Figure 2 shows the seismic moment, fault area and stress drop obtained for the large earthquakes. Equal stress-drop lines are calculated from Eq. (1) with the value of $\xi$ given above. The data (open circles) clearly show that the stress drop of the circum-Pacific earthquakes is almost constant independently of the seismic moment and fault area. The stress drop does not greatly differ from one region to another. We obtain $30\pm8$ bars as an average value of the stress drop. Such a constancy in the stress drop is not unexpected in view of the common feature of the faulting; most of these earthquakes are characterized by a slip at the interface between the oceanic and continental plates.

Fig. 1. Fault length $L$ and fault width $w$ of large earthquakes. The longer length of the fault is taken as $L$, which is equal to the horizontal length of the fault except for three earthquakes.
Fig. 2. Relationship among fault area, seismic moment and stress drop for large earthquakes. The right-hand scale is the surface-wave magnitude where scaling is made on the basis of the magnitude versus moment relationship of AKI (1972b). The circum-Pacific and Japanese islands earthquakes are found to be characterized, on the average, by a constant stress drop of 30 and 60 bars, respectively.

Since $\xi$ and $\sigma$ are found to be almost constant for the circum-Pacific earthquakes, the seismic moment can be determined from $S$ alone. Using $\xi=0.41$ and $\sigma=30$ bars, we can rewrite Eq. (1) in the form

$$M_s = 1.23 \times 10^{28} S^{8/3} \text{ dyne} \cdot \text{cm}$$

(6)

where $S$ should be given in units of km$^2$. The data deviate from Eq. (6) within a factor of 1.3 for $M_s \geq 10^6$ dyne cm. If an appropriate value for the rigidity is assumed, the dislocation and strain energy are also determined from $S$ alone. For example, we have

$$D = 2.46 S^{1/3} \text{ cm}$$

(7)

where $\mu=0.5 \times 10^6$ dyne/cm$^2$ is assumed and $S$ should be given in units of km$^2$.

The results of this study can be used for reliable assignment of moment
to large earthquakes for which detailed mechanism studies cannot be made, provided that the fault size is inferred from such evidence as discussed in the next section.

Though the major concern of this paper is large earthquakes on the Pacific coast, we shortly discuss the nature of inland earthquakes. To Figs. 1 and 2 are added the fault parameters for several major earthquakes (\(M_0=10^{25}-10^{27}\) dyne·cm) which occurred at shallow depths in the Japanese islands and North America (Abe, 1974a, b, 1975a, b; Kanamori, 1972b, 1973; Mikumo, 1973a, b; Tsai and Aki, 1969, 1970). Since the data on North America are very scanty, we limit the discussion to the Japanese islands earthquakes. The data (closed circles) show \(L \approx 2w\) on the average. The stress drop for the Japanese islands earthquakes is found to vary widely, probably reflecting regional variations of tectonic stresses (Abe, 1975a). We get \(\sigma = 60 \pm 30\) bars on the average. This average stress drop is twice as large as that of the circum-Pacific earthquakes. This makes the numerical coefficients of Eqs. (6) and (7) doubled. Considering the variations in the data and source mechanism, we estimate that assignment of moment to a particular inland-earthquake on the basis of \(S\) alone may be uncertain within a factor of two in the range of the data used here.

4. Application

To apply the results to a particular earthquake, the fault size must be estimated on the basis of some seismic and geodetic evidence. One familiar method is based on the aftershock area. For large earthquakes, the aftershock area just after the main shock gives an approximate size of the fault area (Mogi, 1968). Later aftershock activity, which usually spreads out the aftershock area, seems to represent readjustment of the stress unbalanced by the main shock beyond the fault area. The one-day aftershock area has frequently been used (e.g., Kanamori, 1970a; Abe, 1972a). The other method is based on tsunami data. The tsunami source area can be determined from the arrival times of tsunamis observed along the coast. The area has been found to approximately coincide with the fault size (Abe, 1973). Figure 3 shows an example how the tsunami source area is consistent with the fault area. In this example, the tsunami source area is slightly larger than the fault area. In general, in relationship to the tsunami source area there is a tendency to overestimate the fault area for dip-slip earthquakes because movement of the sea bottom is directly related to generation of tsunamis (Abe, 1973). This is shown in Fig. 4, where the fault area \(S\) and the tsunami source area \(S_t\) are plotted. The tsunami data are taken from the works of T. Hatori (Hatori, 1969, 1974). From Fig. 4, we obtain the relation between \(S\) and \(S_t\):

\[
S = 0.8S_t
\]
Vertical deformation of the sea bottom predicted by the seismic fault model (thin curves) is consistent in both sense and magnitude with the wave front (thick curves) at the tsunami source area (hatched area) of the 1968 Tokachi-Oki earthquakes. Here $D_0$ is the average vertical displacement predicted by the seismic fault and $H_0$ is the average sea level disturbance at the tsunami source area. Figure 8 of Abe (1973) was slightly modified.

where the standard deviation is 0.2. This relation is introduced empirically, but it will be useful for the case that no aftershock data are available. For future large earthquakes, the area of prominent seismic gap in activity, the gap in tsunami generation areas, and the area of precursory crustal deformation will provide the key to estimating fault size. The following is an example of the application.

In the vicinity of Hokkaido, Japan, the region between the aftershock areas of the 1969 Kurile Islands and 1952 Tokachi-Oki earthquake constitutes a typical seismic gap in activity for large earthquakes (Fig. 5). The last large event within the seismic gap was the Nemuro-Oki earthquake of 1894 ($M=7.9$). This seismic gap has been considered a candidate site for a future earthquake of $M \approx 8$ (e.g., Utsu, 1972). Applying the previous result to this particular region, we estimate reliable fault parameters for the 1952 Tokachi-Oki earthquake of which mechanism has not been determined, and for a future earthquake which is expected in the seismic gap.
Fig. 4. Relation between $S$ (fault area) and $S_t$ (tsunami source area). The straight line is for $S=0.8 S_t$.

Fig. 5. Large earthquakes on the northeastern coast of Japan. The hatched areas show the aftershock area and the arrows show the slip direction. The area delineated by the broken line is the seismic gap, which has been considered as a candidate site for a future earthquake of $M=8$. 
The one-day aftershock area of the 1952 Tokachi-Oki earthquake is estimated as $1.2 \times 10^4$ km$^2$ (e.g., MOGI, 1968). This size does not greatly differ from the size of the tsunami source area (HATORI, 1974). With $S=1.2 \times 10^4$ km$^2$, we get $M_s=1.6 \times 10^{28}$ dyne·cm and $D=2.7$ m from Eqs. (6) and (7). Fault geometry such as dip angle and slip direction can be inferred from precise determinations of the earthquake mechanism of several large earthquakes which occurred in the neighboring regions. These values are summarized in Table 1. The magnitude of the 1952 event is 8.1. For a 8.1 magnitude earthquake, the magnitude versus moment relationship of AKI (1972b) gives $M_0=2 \times 10^{29}$ dyne·cm and $D=33$ m (see Fig. 2). We find the dislocation much too large in view of the observed crustal deformation and tsunami generation.

Table 1. Fault parameters of large earthquakes in the northeastern Japan.

<table>
<thead>
<tr>
<th></th>
<th>Kurile Is.$^{a1}$ Aug. 11, 1969</th>
<th>Tokachi-Oki$^{a2}$ May 16, 1968</th>
<th>Tokachi-Oki$^{a3}$ Mar. 4, 1952</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M^*$</td>
<td>7.8</td>
<td>7.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Slip direction</td>
<td>N50°W</td>
<td>N60°W</td>
<td>N60°W</td>
</tr>
<tr>
<td>Dip angle</td>
<td>16°</td>
<td>20°</td>
<td>20°</td>
</tr>
<tr>
<td>$M_e$ (10$^8$ dyne·cm)</td>
<td>2.2</td>
<td>2.8</td>
<td>1.6</td>
</tr>
<tr>
<td>$S$ (10$^4$km$^2$)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>$D$ (m)</td>
<td>2.9</td>
<td>4.1</td>
<td>2.7</td>
</tr>
<tr>
<td>$\sigma$ (bar)</td>
<td>29</td>
<td>32</td>
<td>30</td>
</tr>
</tbody>
</table>

$^{a1}$ ABE (1973), $^{a2}$ KANAMORI (1971a), $^{a3}$ Calculated in the text,
$^{a4}$ Magnitude determined by the Japan Meteorological Agency.

For future earthquakes in the seismic gap, it may be reasonable to assume the fault area similar to the size of the seismic gap. Implicit in this estimation is the assumption that a seismic gap will eventually be filled by a single event. From Fig. 5, we get $L=160$ km and $w=80$ km, i.e., $S=1.28 \times 10^4$ km$^2$. This size is consistent with the tsunami source area of the 1894 event which was the last event in the seismic gap (HATORI, 1974). Using this size, we predict $M_s=1.8 \times 10^{28}$ dyne·cm and $D=2.8$ m. These values are very similar to those for neighboring large earthquakes (Table 1). In 1973, a moderately large 7.4 magnitude earthquake occurred within the seismic gap. The fault size is estimated as $0.6 \times 10^4$ km$^3$ from the one-day aftershock area and the tsunami source area. Using this size, we obtain $M_e=0.6 \times 10^{28}$ dyne·cm; this value is proved to be almost the same moment as derived from surface-wave analysis by SHIMAZAKI (1974). The fault size of this earthquake is about one-half the predicted value, and therefore the moment is almost one-third. It follows that much of the accumulated strain energy still remains unreleased. Based on such a quantitative comparison, ABE and YOKOYAMA (1974) assumed that this
energy would be released in future either by a large earthquake or by a large amount of creep without generating major earthquakes.

5. Summary

The relationship between seismic moment and fault size has been determined on the basis of several remarkable features common to large earthquakes on the Pacific coast. This relationship is proposed for assignment of reliable moments to large earthquakes for which detailed mechanism studies cannot be made. In this method, the fault size inferred from seismic, tsunami-genetic, and geologic evidence is used instead of the conventional magnitude scale. The assignment of moment to a particular earthquake may be uncertain by a factor of two or so at the most. This uncertainty is much less than that in estimating moments from the earthquake magnitude. The method presented here has been applied to past and future large earthquakes in the northeastern Japan.

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REFERENCES


