Scale-dependence of seismic energy-to-moment ratio for strike-slip earthquakes in Japan

Yasuo Izutani and Hiroo Kanamori
Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

Abstract. We analyzed four pairs of a large (Mw = 6) and a small (Mw = 3.5 to 4) shallow strike-slip earthquakes to investigate the scale-dependence of the seismic energy-to-moment ratio, an important macroscopic parameter which reflects the basic physical process of seismic slip. These earthquakes occurred in the south-western part of Japan, and high-quality close-in records (epicentral distance < 50 km) are available for both the small and large earthquakes. The paired events have almost the same focal mechanism and hypocenter location. We used the spectral ratio of the paired events in order to remove the effects of attenuation along the wave propagation path and the station site response. We then estimated the seismic energy from the source spectra estimated from the spectral ratio. The energy-to-moment ratio increases with the earthquake size. This scale-dependence is very similar to that found earlier for earthquakes in Southern California.

Introduction

The seismic moment, M0, and the radiated seismic energy, E, are among the most fundamental macroscopic parameters for understanding the physical process of earthquake source. The seismic energy reflects the dynamic characteristics of earthquake source while the seismic moment does the static ones. The ratio of seismic energy to seismic moment, \( \varepsilon = E / M_0 \), can be interpreted as the radiated energy per unit area and per unit slip on the fault plane. This ratio, multiplied by rigidity \( \mu \), has long been used in seismology as apparent stress [Aki, 1966; Wyss and Brune, 1970]. This ratio was recently used for interpretation of dynamic source processes of earthquakes [Kanamori and Heaton, 2000].

The energy-to-moment ratio, \( \varepsilon = E / M_0 \), estimated for earthquakes in Southern California increases with the earthquake size [Thatcher and Hanks, 1973; Kanamori et al., 1993; Mayeda and Walter, 1994; Abercrombie, 1995]. Similar scale-dependence in energy-to-moment ratio was also found for earthquakes in the eastern Mediterranean region [Hofstetter and Shapira, 2000] and in Japan [Kobayashi et al., 2000]. The scale-dependence suggests that the dynamic source process is different between small and large earthquakes.

In practice, correction for attenuation along the path poses a severe difficulty in estimating seismic energy accurately, especially for small earthquakes. In order to overcome this difficulty Venkataraman et al. [2001] estimated the seismic energy for the 1999 Hector Mine, California, earthquake using its foreshock and aftershock records as empirical Green's functions (EGF). They removed the effects of attenuation along the path and local site condition at regional stations by taking the spectral ratio of the main shock record to EGF. The estimate using EGF is probably more accurate than those estimated with other methods.

Recently Ide and Beroza [2001] pointed out that the seismic energy currently estimated for small earthquakes tend to be underestimated because of the limited frequency band of instruments and unreliable corrections for attenuation along the wave propagation path. They evaluated the missed energy using the \( o^2 \) source spectral model and concluded that the energy-to-moment ratio is essentially constant over a 17 orders of magnitude range of seismic moment.

Thus, whether the energy-to-moment ratio is scale dependent or not is still in question because of the large scatter in the available data set. It is important to accumulate more accurate measurements to address this question. To this end, we used the high-quality close-in records which have only recently become available in Japan to accurately estimate seismic energy for 4 earthquakes in Japan; we specifically investigate whether the energy-to-moment ratio is scale-dependent or not.

Data and Analysis

We analyzed four pairs of a large and a small shallow strike-slip earthquakes which occurred in the south-western part of Japan. Table 1 lists all the earthquakes studied. The source mechanisms and the seismic moments of these events have been determined by the National Research Institute for Earthquake Science and Disaster Prevention, Japan (NIED) [Fukuyama et al., 2000, 2001]. The epicenters of the

Table 1. List of earthquakes

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Mw</th>
<th>Strike (deg)</th>
<th>Dip (deg)</th>
<th>Rake (deg)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1997 03 26</td>
<td>6.1</td>
<td>103</td>
<td>88</td>
<td>-9</td>
<td>10</td>
</tr>
<tr>
<td>A2</td>
<td>1997 06 01</td>
<td>3.7</td>
<td>290</td>
<td>90</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>B1</td>
<td>1997 05 13</td>
<td>6.0</td>
<td>101</td>
<td>85</td>
<td>-2</td>
<td>8</td>
</tr>
<tr>
<td>B2</td>
<td>1997 06 11</td>
<td>3.6</td>
<td>281</td>
<td>82</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>C1</td>
<td>1997 06 25</td>
<td>5.8</td>
<td>319</td>
<td>89</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>C2</td>
<td>1997 06 26</td>
<td>3.9</td>
<td>139</td>
<td>71</td>
<td>-15</td>
<td>6</td>
</tr>
<tr>
<td>D1</td>
<td>2000 10 06</td>
<td>6.6</td>
<td>150</td>
<td>85</td>
<td>-9</td>
<td>16</td>
</tr>
<tr>
<td>D2</td>
<td>2000 10 06</td>
<td>3.9</td>
<td>159</td>
<td>87</td>
<td>10</td>
<td>16</td>
</tr>
</tbody>
</table>

M0 and focal mechanism solutions are evaluated by National Research Institute for Earth Science and Disaster Prevention, Japan. N is number of records.

1On leave from Department of Architecture and Civil Engineering, Shinshu University, Nagano, Japan

Copyright 2001 by the American Geophysical Union.
earthquakes and the stations used are shown in Figure 1. The large events are strike-slip with $M_c = 5.8$ to 6.6 and the small events are also strike-slip with $M_c = 3.6$ to 3.9. The paired events have almost the same focal mechanism and hypocenter location. We used the spectral ratio of the paired events in order to remove the effects of attenuation along the wave propagation path and the station site response. We then estimated the seismic energy from the source spectra estimated from the spectral ratio following the method of Venkatakrishnan et al. [2001].

We used the accelerograms recorded at K-NET and KIK-NE relationship between the seismic moment and the high-frequency portion of the source spectrum is expressed as

$$ M_s(f) = M_0 [1 + (f/f_0)^n]^2 $$

where the suffixes 1 and 2 stand for the large and small events, respectively.

The corner frequencies, $f_{01}$ and $f_{02}$, and $n$ are estimated by minimizing the sum of squared residuals between the logarithmic amplitude of the observed spectral ratio and that for the source spectral model. This method for estimating the corner frequency is the same as that used by Hough and Kanamori [2001]. Since the signal-to-noise ratio for small events at long periods is poor, the spectral ratio at frequencies lower than 0.5 Hz is not reliable, and the spectral ratio often falls in the low frequency range because of the increased noise for the small events, as shown in Figure 2. In the high frequency range above 5 Hz, the observed spectral ratios for the same paired events vary considerably from station to station, probably because the path effect cannot be completely removed in this frequency range.

We used the spectral ratio over the frequency range from 0.5 Hz to 5 Hz to estimate $f_{01}$, $f_{02}$ and $n$ using a grid search method. The search windows are from 0.02 to 2 Hz for $f_{01}$, 0.2 to 20 Hz for $f_{02}$, and from 1.7 to 2.3 for $n$.

The observed and the best fit theoretical spectral ratios are shown in Figure 2. The optimal values for $f_{01}$, $f_{02}$ and $n$ are listed in Table 2.

**Seismic Energy-to-Moment Ratio**

Radiated energy for S-wave, $E_s$, is given by

$$ E_s = \frac{4\pi}{5\rho d^2} \int_{f_0}^{f_o} |f M(f)|^2 df $$

where $M_0$ is the seismic moment, $f_0$ is the corner frequency and $n$ is the power for the spectral decay in the frequency range above $f_0$. The spectral ratio for a pair of events is then expressed as

$$ M_s(f) = M_0 [1 + (f/f_0)^n]^2 $$

**Figure 1.** Locations of epicenters and stations used shown for the four pairs of a large event and a small event listed in Table 1.

**Figure 2.** Source spectral ratio for the four pairs of events. The solid curves show observed spectral ratios. The dashed curves represent theoretical spectral ratios expressed by equation (2) and the parameters in Table 2.
where \( \rho \) is the density and \( \beta \) is the S-wave velocity in the source region, here assumed to be 2.7 g/cm\(^3\) and 3.3 km/s, respectively [e.g., Vassiliou and Kanamori, 1982]. We assume that the source spectrum is expressed by equation (1) and used the parameters listed in Table 2. Although we assumed a particular form (equation (1)) for the source spectrum, the energy is computed by integration of the source spectrum, so that the estimate does not depend much on the particular form of the source spectrum.

Since the radiated energy for \( P \)-wave from a double-couple source is small compared with that for \( S \)-wave, it is ignored here [Haskell, 1964]. Energy estimation for the large events is more reliable than that for the small events, because the source spectra for the large events are well approximated by the theoretical ones at least in the frequency range up to 5 Hz. The theoretical source spectra are extrapolated in the high frequency range over 5 Hz in estimating the seismic energy for the small events. However, since the corner frequencies are lower than 3.2 Hz and \( n \) is about 2 (see Table 2), this extrapolation would not introduce significant errors in energy estimates.

The energy-to-moment ratio, \( E_R/M_o \), is between \( 10^{-4} \) to \( 10^{-2} \) for the large events, and is \( 10^{-5} \) to \( 10^{-4} \) for the small events. Figure 3 shows our results together with those from several previous studies for earthquakes in Southern California. Although the energy-to-moment ratios for the earthquakes in Japan are somewhat smaller than those for the earthquakes in Southern California, the scale-dependence is similar between Japan and California. If we combine our results with those from Matsuzawa [2001] and Matsuzawa et al. [2001] for small earthquakes in the central part of Japan, the similarity in the scale-dependence between Japan and California becomes even clear.

**Scale-Dependence of Energy-to-Moment Ratio**

The power for the source spectral decay in the high frequency range, \( n \), in Table 2 is very close to 2, which suggests that the source spectra for these events are well approximated by the \( \omega^2 \) source spectral model [Aki, 1967]. For the \( \omega^2 \) source spectral model,

\[
E_R/M_o \propto M_o f_0^3
\]  

(4)

Thus, if \( E_R/M_o \) is scale independent, then the commonly used scaling relation

\[
M_o \propto f_0^{-3}
\]  

(5)

holds. However, if \( E_R/M_o \) increases with \( M_o \), as shown in Figure 3, this scaling relation no longer holds. For example, if \( E_R/M_o \propto M_o^{\alpha} (\alpha > 0) \), then \( M_o \propto f_0^{3(1-\alpha)} \). As shown in Figure 4, the relationship between \( M_o \) and \( f_0 \), taken from Table 2 exhibits a slope steeper than -3, though the trend is marginally significant.

Ide and Beroza [2001] state that the energy-to-moment ratio is almost constant over 17 orders of magnitude in seismic moment. However, their conclusion relies heavily on the result by Pérez-Campos and Beroza [2001] in which the energy-to-moment ratio varies over a large range from \( 3 \times 10^{-4} \) to \( 3 \times 10^{-7} \). The large scatter may be due to inclusion of events with various fault types in various tectonic environments [Choy and Boatwright, 1995]. The energy-to-moment ratio is controlled by static and dynamic source process which may vary for different tectonic environments.

Kanamori and Heaton [2000] and Brodsky and Kanamori [2001] explained the scale-dependence of energy-to-moment ratio in terms of sudden change in friction due to microscopic mechanisms such as shear melting, fluid pressurization and elastohydrodynamic lubrication. For earthquakes with \( M_o \) larger than 5 to 6, dynamic friction may drop due to shear melting, fluid pressurization, and elastohydrodynamic lubrication.
Table 2. Corner frequency and radiated energy

<table>
<thead>
<tr>
<th>Event</th>
<th>$n$</th>
<th>$f_0$</th>
<th>$E_R$</th>
<th>$M_0$</th>
<th>$E_{d}/M_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(Hz)</td>
<td>(J)</td>
<td>(Nm)</td>
<td>(x10^3)</td>
</tr>
<tr>
<td>A1</td>
<td>2.1</td>
<td>0.27</td>
<td>7.3x10^13</td>
<td>1.40x10^14</td>
<td>5.2</td>
</tr>
<tr>
<td>A2</td>
<td>2.1</td>
<td>3.2</td>
<td>3.4x10^10</td>
<td>7.5x10^14</td>
<td>2.1</td>
</tr>
<tr>
<td>B1</td>
<td>1.9</td>
<td>0.20</td>
<td>3.4x10^13</td>
<td>1.22x10^14</td>
<td>2.8</td>
</tr>
<tr>
<td>B2</td>
<td>1.9</td>
<td>3.2</td>
<td>6.3x10^9</td>
<td>3.13x10^14</td>
<td>2.0</td>
</tr>
<tr>
<td>C1</td>
<td>2.1</td>
<td>0.26</td>
<td>1.0x10^13</td>
<td>5.66x10^17</td>
<td>1.8</td>
</tr>
<tr>
<td>C2</td>
<td>2.1</td>
<td>1.2</td>
<td>1.6x10^9</td>
<td>8.26x10^14</td>
<td>0.19</td>
</tr>
<tr>
<td>D1</td>
<td>1.9</td>
<td>0.12</td>
<td>3.0x10^14</td>
<td>8.62x10^15</td>
<td>3.5</td>
</tr>
<tr>
<td>D2</td>
<td>1.9</td>
<td>1.5</td>
<td>4.1x10^9</td>
<td>7.59x10^14</td>
<td>0.54</td>
</tr>
</tbody>
</table>

$n$ is the power for the decay of the source spectrum in the frequency range higher than the corner frequency, $f_0$. $E_R$ is the seismic energy. $M_0$ is the energy-to-moment ratio.

lubrication and the radiated energy per unit area per unit slip becomes larger than that for smaller earthquake. Aki [2000] argues, on the basis of the size of breakdown zones and barrier intervals on a fault plane, that large ($M_0>5$) and small earthquakes in California are fundamentally different. Knopoff [2000] suggests that the magnitude-frequency relationship for southern California earthquakes has two segments with different slopes, and suggests that earthquake process is scale dependent. The transition occurs at around $M_0=4.5$. The scale-dependence of energy-to-moment ratio in Figure 3 does not show a simple proportionality to the earthquake size. For events with $M_0>5$ the ratio is between $10^4$ and $10^5$ while the ratio for events with $M_0<5$ shows a larger scatter between $10^2$ and $10^3$. This result suggests that the rupture process of small earthquakes may be controlled by various mechanisms.

The scale-dependence of energy-to-moment ratio would provide an important clue to the difference in dynamic source process of large and small earthquakes. Also, regional variations in the scale-dependence may reflect the difference in seismogenic processes in various tectonic environments.

Acknowledgements. We thank T. A. Matsuzawa and M. Takeo who kindly sent us their unpublished data on $E_d/M_0$. Accelerograms from K-NET and KIK-NET stations operated by the National Research Institute for Earth Science and Disaster Prevention, Japan, are used in this study. Y. I. was supported by the scholarship from the Ministry of Education, Culture, Sports, Science and Technology, Japan. This research was partially supported by NSF Cooperative Agreement EAR-9909371. This is contribution 8807 of the Caltech Division of Geological and Planetary Sciences.

References

Abercrombie, R. E., Earthquake source scaling relationship from -1 to 5 using seismograms recorded at 2.5-km depth, J. Geophys. Res. 100, 24,015-24,036, 1995.


Y. Izuani, Faculty of Engineering, Shinsyu University, 4-17-1, Wakasato, Nagano, 380-8553, Japan. (ldpp0008@ipwsh.shinsyu-u.ac.jp)

H. Kanamori, Seismological Laboratory MC 252-21, California Institute of Technology, Pasadena, CA 91125. (hirono@gps.caltech.edu)

(Received May 7, 2001; accepted July 31, 2001)