Discussion on the dynamic corner frequency in the case of 2011 Great East Japan Earthquake

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Abstract. For the simulation of broadband near-fault ground motion, one of the key points is to start with a reasonable source spectral model. Corner frequency is a parameter of source spectrum. We redefined the parameter \( N_{RIJ} \) of the dynamic corner frequency as the number of rupturing sub-faults, rather than that of ruptured ones, in the model of Motazedian and Atkinson (2005). Four sizes of sub-fault are given, and ground motion on 51 bedrock stations is simulated randomly by a finite fault model, in the case of the 2011 Great East Japan Earthquake. The variation with sub-faults size is reduced to a certain extent, and the improvement is more obvious at the periods of 0.1-1s. By comparing with the response spectra of strong ground motion records, the long-period parts fit better, and the short-period (≤0.1s) parts are lower than the observed spectra, while for several stations, the simulated spectra fit with the observed ones over the periods to 10s. And, the influence of the corresponding energy conservation factor (or scaling factor) on the simulated ground motion is analysed. Compared with strong ground motion records, the dependence on sub-fault size is further weakened, and the simulated spectra fit with the observed ones at the periods of less than 0.1s.

1. Introduction

Following Brune (1970, 1971), Aki and Richards (2002) defined a corner frequency as the frequency at the intersection of the low- and high-frequency asymptotes in the far-field displacement spectrum. And, Boore (1983) expressed the corner frequency \( f_0 \) in the stochastic point-source approach as

\[
 f_0 = 4.9 \times 10^6 \beta (\Delta \sigma / M_0)^{1/3} \tag{1}
\]

where \( \beta \) is the shear wave velocity (km/s), \( \Delta \sigma \) is the stress drop (bars), \( M_0 \) is the seismic moment (dyne·cm).

In a stochastic finite-fault simulation method to generate stochastic acceleration time histories from each subfault, Beresnev and Atkinson (1997) assumed that slip at every point on the subfault continued until the rupture reached its periphery and stopped. The corner frequency \( f_0 \) in terms of the dimension of the subfault \( \Delta l \) is

\[
 f_0 = \frac{y \beta}{\pi \Delta l} \tag{2}
\]

where \( y \) is the ratio of the rupture velocity to the shear wave velocity, which is a constant; \( z \) is arbitrarily defined. It indicates that the corner frequency and the simulated ground motion depend on...
$\Delta l$, in which some inaccuracies are discussed in some studies, like Beresnev and Atkinson (1998), Motazedian and Atkinson (2005) and Sun et al. (2010).

Motazedian and Atkinson (2005) defined a dynamic corner frequency $f_{0ij}(t)$ of the $ij$th subfault as a function of the cumulative number $N_R(t)$ of ruptured subfaults at time $t$.

$$f_{0ij}(t) = N_R(t)^{-\frac{1}{3}} \cdot 4.9 \times 10^6 \cdot \beta \cdot (\Delta \sigma f_{\text{ave}})^{\frac{1}{3}}$$ (3)

However, the corner frequency is not related with the slip of subfaults in this model, and the corner frequency of the latter ruptured subfault is always lower than that of the former ruptured one. Chen (2011) introduced the improvement of the Masuda source spectra, and the corner frequency of subfault was determined by its seismic moment assigned as the slip distribution.

$$M_{0ij} = \frac{M_0 D_{ij}}{N_i N_j \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} D_{kl}}$$ (4)

where $N_i$ and $N_j$ are the number of subfaults along the length and width of the whole fault; $D_{ij}$ denotes the slip of $ij$th subfault. However, the corner frequency of the last ruptured subfault is still the lowest value on the whole fault.

2. Redefinition of the dynamic corner frequency
We redefined the $N_R(t)$ in equation (3) as the number of rupturing subfaults, since the energy is radiated from these subfaults. As the rupture propagates across the fault, the number of rupturing subfaults increases and then decreases till the rupture stops. Correspondingly, the corner frequency of the subfaults decreases and then increases, rather than decreases monotonously, as shown in Figure 1.

![Figure 1. Diagram of the corner frequency.](image)

We use the same method with Chen (2011) to observe the influence on simulated ground motion, and both results are compared with the recorded strong ground motion. The 2011 Great East Japan Earthquake, with magnitude 9.0 and depth of 24 km, is our case. It occurred on March 11, 2011, off the Pacific coast of the northeastern part of the Japanese mainland (38.103°N, 142.860°E), which is the largest earthquake recorded in Japan (Japan Meteorological Agency, 2011). The slip distribution of the fault is from Ide (2011). The parameters for simulation are listed in Table 1.

| Parameters               | Values                  |
|--------------------------|-------------------------|
| Moment magnitude         | 9.0                     |
| Strike /Dip              | 189.78°/15.3°           |
| Depth of upper edge      | 2.648 km                |
| Distance-dependent duration | $T_0+0.1R$            |
Geometric spreading

Quality factor

$Q_0 = 167.89, \eta = 0.78$

Crustal shear-wave velocity

3.7 km/sec

Crustal density

2.8 g/cm$^3$

Strength factor

1.6

Stress drop

119 bars

The subfault size is set as 5km×5km, 7.5km×7.5km, 10km×10km or 20km×20km. Ground motion on 51 bedrock stations, with hypocentral distance less than 200 km, are simulated, including that on 33 bedrock K-NET stations and 18 KiK-net borehole stations. On each period, the ratio of the recorded response spectral amplitude to the average simulated one of the four subfault sizes. The result of Chen (2011) is shown as Figure 2(a), and the result from our research is shown as Figure 2(b).

The red shadowed areas are for the 95% confidence interval of the mean value, and the green lines are for the mean value±one standard deviation. The influence of subfaults size is weakened during the periods of 0.1s-1.0s. We compare the results with the strong motion records on the 51 stations. On 22 stations, the spectral amplitude of simulated ground motion matches well with the recorded one at long period (>0.1s). At short period (≤0.1s), the simulated amplitude is lower than the recorded one. Those on two stations are examples and shown in Figure 3, in which the thick lines are the recorded spectra and the thin lines are the simulated spectra.
3. Conservation of the total radiated energy at high frequencies
The low estimation at short periods might be caused by the dynamic corner frequency concept (Motazedian and Atkinson, 2005), and we borrow the scaling factor to conserve the total radiated energy of subfaults at high frequencies.

The source spectrum is multiplied by two scaling factors $H_{ij}$ of Motazedian and Atkinson (2005) and Boore (2009), respectively. The spectral amplitude of simulated ground motion matches well with the recorded one at short period ($\leq 0.1s$); at long period (>0.1s), the simulated amplitude is higher than the recorded one. And, the ratios of response spectra, corresponding to the scaling factor of Motazedian and Atkinson (2005) and Boore (2009), are shown as Figure 4(a) and Figure 4(b).

![Figure 4](image)

Figure 4. Comparison of the response spectral amplitude ratio.

In Figure 4, the blue shadowed areas are for the 95% confidence interval of the mean value, and the blue lines are for the mean value±one standard deviation, after multiplied by the scaling factors; the red ones are the same with Figure 2(b). The influence of subfault size is weakened further, and the difference from these two scaling factors is slight.

4. Conclusions
$N_{Rij}$ of the dynamic corner frequency model is redefined as the number of rupturing subfaults, rather than that of ruptured ones. Ground motion on 33 K-NET bedrock stations and 18 KiK-net borehole stations is simulated randomly, based on a finite fault model, in the case of the 2011 Great East Japan Earthquake, under the assumption of four different subfault sizes. The influence of subfault size on the simulated ground motion is weakened, especially at the periods of 0.1s-1.0s. Compared with the recorded response spectra, the long-period parts fit better. Since the total radiated energy of subfaults at high frequencies is considered as a scaling factor, the simulated spectra fit with the recorded ones at the periods of less than 0.1s.

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