Rapid estimation of fault rupture extent using envelopes of acceleration

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Abstract We present a new strategy to estimate the geometry of a rupture on a finite fault for rapid reporting of seismic intensity. We use envelope attenuation relationships which were presented by Huo et al. (Acta Seismol Sin 16:519–525, 1994). An important base of this work is the fault finiteness theory. We propose a new model to simulate high-frequency motions from earthquakes with large rupture dimension. The envelope of high-frequency ground motion from a large earthquake can be expressed as a root-mean-squared combination of envelope functions from smaller earthquakes. We use simulated envelopes of ground acceleration to estimate the direction and along-strike length of a rupture. Using the Wenchuan and Jiji (Chi-Chi) earthquake dataset, we parameterize the fault geometry with an epicenter, a fault strike, and along-strike rupture lengths. So this methodology seems quite appropriate for the rapid reporting systems of seismic intensity.

Keywords Rapid reporting of seismic intensity · Envelope · Direction and along-strike length of a rupture · Wenchuan and Jiji (Chi-Chi) earthquake

1 Introduction

Recently, with advances in broad-band and high-sampling-rate seismometers, the rapid reporting systems of seismic intensity has attracted more research attention, and various methods have been proposed from seismologists and engineers (Nakamura 1988; Li et al. 2002; Jin et al. 2003, 2004a, 2008; Wu and Kanamori 2005; Yamada 2008; Kang

and Jin 2009), and some have already been put into trial operation in many countries. Currently, the most successful system is the rapid reporting system of seismic intensity provided by USGS, which was released to the public in 1996. The system had a wide reach, and it attracted considerable attention entire world. The goal of quick reporting is to calculate the intensity in certain areas. The messages are very useful to the government and rescue teams, and to achieve this target, the rapid reporting systems of seismic intensity must collect and quickly analyze seismic data. In principle, this work could be rapidly achieved in a very short time. However, for large earthquakes, if we hope to get a better precision, there are advantages in involving characterization of the earthquake source. As we know, the seismic intensity distribution has a tight relationship with the seismic source characteristics. Ideally, the rapid reporting systems of seismic intensity would provide the best estimate of intensity distributed in space (Böse and Hauksson 2012; Jin and Kang 2009; Zeng et al. 1993). We introduce a three-step strategy to accomplish this: (1) we rotate and move the subsources, from which we can obtain all the possible rupture extent, (2) we determine the spatial and temporal extent of a rupture by analyzing waveform envelopes of high frequency shaking, and (3) we search for the minimum deviations that are calculated between the observed envelope and attenuation relationships envelope.

However, for large earthquakes, rupture length can be in the order of 10–100 km. For example, the fault rupture in the 1999 Jiji (Chi-Chi) earthquake was longer than 80 km, and in the Wenchuan it earthquake was longer than 250 km, and the main loss was along with the fault. It would be difficult, if not impossible, to estimate in a few seconds after the earthquake such large shaking at considerable distances from the epicenter.

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In this article, we introduce a methodology to determine the direction and along-strike length of the rupture from high-frequency ground motions. We construct a model to describe high frequency motions from earthquakes with large fault dimensions. By applying this model to high-frequency ground motions, it becomes possible to estimate the geometry of an earthquake in a short time.

2 Data

The data for this analysis are the strong-motion dataset from the 21 September 1999 Jiji (Chi-Chi) Earthquake which occurred in central Taiwan (Lee et al. 2001; Wang et al. 2005). The epicenter was located at 120.82°N, 23.85° E, with a focal depth of 8 km and magnitude (M_w) 7.6, according to the Central Weather Bureau (CWB) of Taiwan (Shin and Teng 2001). It is currently the largest well-recorded earthquake. A total of 441 strong-motion stations recorded the main event, and 69 of those were at distances of less than 50 km from the epicenter. We use three-component (north–south, east–west, and up–down) strong-motion records from the dataset collected by COSMOS. The distribution of stations is shown in Fig. 1b. The other plot is the strong-motion dataset from the 12 May 2008 Wenchuan Earthquake, the epicenter of which was located at 103.4°N, 31.0°E, and the focal depth was 14 km (Wang

et al. 2008), all records from the stations in Sichuan province were chosen, plus some others in the provinces of Gansu and Shanxi. The distribution of the stations is shown in Fig. 1a.

We use envelopes of acceleration records in horizontal and vertical components. The horizontal components are calculated from the east–west and north–south components, respectively. Acceleration envelopes are obtained by taking the maximum absolute amplitude of the ground-motion time history over a 1-s window (Fig. 2). These 1-s sampling acceleration envelopes reduce the computational efforts.

3 Methods

3.1 Ground-motion models

Huo et al. (1994) and Huo (1989) examined a few hundred seismograms in America and developed relationships that predict waveform envelopes and peak ground acceleration. Each waveform envelope is parameterized with a set of 3 parameters, and each parameter is characterized as a function of magnitude and epicentral distance. This ground-motion model is similar to the traditional strong-motion attenuation relationships with time domain transition. However, unlike attenuation relationships that have been developed primarily from local earthquakes, the

Fig. 1 Distribution of the epicenter (black circle) and stations (black up-pointing triangle) from the Wenchuan (a) and Jiji (Chi-Chi) (b) earthquakes

Fig. 2 An acceleration record (a) and its envelope (b). The envelope is obtained by taking the maximum absolute amplitude of the ground motion time history in 1-s window

Fig. 3 The geometry of fault segments of our preferred fault source model showing all possible ruptures along-strike length (a) and direction (b). The epicenter is initial rupture point; it is a fixed point in the inversion process

dataset of Huo et al. (1994) included earthquakes in America because of too few data in China (Jin and Kang 2009). In order to characterize this data, it was essential to utilize relationships in which the distance decay of amplitudes changes as a function of magnitude.

Based on the strong ground-motion records, Huo et al. (1994) presented the envelope function of the acceleration time history scaled in terms of magnitude, distance, and site condition. The function is composed with rising (t_1), stationary ($t_2 - t_1$) and descending (c) stages and all the

model parameters are expressed as the function of M and R . The function can be written as:

$$f(t) = \begin{cases} \left(\frac{t}{t_1}\right)^2 & t \leq t_1 \\ 1 & t_1 < t \leq t_2 \\ \exp[-c(t - t_2)] & t > t_2 \end{cases} \quad (1)$$

The coefficient of t_1 , t_2 and c can be given as:

$$\begin{cases} \log t_1 = -1.074 + 1.005 \log(R + 10) \\ \log(t_2 - t_1) = -2.268 + 0.3262M + 0.5815 \log(R + 10) \\ \log C = 1.947 - 0.2817M - 0.5670 \log(R + 10) \end{cases} \quad (2)$$

3.2 Subsource model

We introduce a line source model to express the fault finiteness based on the ground-motion models. The fault surface is divided into subfaults, and each subfault is represented by a single point source, called the subsurface (Fig. 3). To simplify the problem, we assume that the dimensions of all subsources are uniform. Each source nucleates, and the waves are radiated when the rupture front arrives at the subsources. The ground motion at a site is modeled as the combination of the responses of each subsurface. An envelope of the i th subsurface is expressed as follows:

$$E_i = f(M_i, R_i), \quad (3)$$

Fig. 4 The predicted result of acceleration envelope for Wenchuan earthquake. N is the number of the north subsources and the q_0 is the azimuth angle of arranged subsurface

Fig. 5 The predicted result of acceleration envelope for Jiji (Chi-Chi) earthquake. N is the number of the north subsources and the q_0 is the azimuth angle of arranged subsurface

where M_i is the magnitude of the subsurface i , and R_i is the distance between the station and subsurface i .

For high-frequency motions with approximately random phase, the square root of the sum of the squares of the envelope amplitudes from each subsurface provides a good estimation of an acceleration envelope (Cocco and Boatwright 1993):

$$E_{\text{total}}(t) = \sqrt{\sum_{i=1}^N E_i^2(t|M, R)} \quad (4)$$

where N is number of the point sources, and E_{total} is the estimated envelope as a function of time. E_i is actually a fairly complex function of time, magnitude, and distance, although its forward calculation is very fast because it only involves analytic functions. This model only works for high-frequency ground motions. Unlike longer-period ground motions, high-

Table 1 The predicted results

Earthquake	Source	Direction	Rupture length (km)	Along-strike length	
				One side	Other side
Wenchuan	This paper	50°	260	20 km	240 km
	USGS	49°	260	–	–
Jiji (Chi-Chi)	This paper	10°	110	50 km	60 km
	USGS	357°	110	–	–

frequency motions seem to be insensitive to either radiation pattern (Liu and Helmberger 1985) or directivity (Boatwright and Boore 1982). Based on this theoretical interpolation, we estimated the ground-motion envelopes with the subsurface model for the Wenchuan and Jiji (Chi-Chi) earthquakes. First, we calculate the rupture length with the empirical relationship (Wells and Coppersmith 1994): the Wenchuan rupture length is 260 km, and Jiji (Chi-Chi) earthquake is 110 km. We then consider every 10 km simplified to one subsurface, so N is 1, 2, 3, ..., 26 and 1, 2, 3, ..., 11, respectively. Second, we fix the epicenter and move the subsurface of one side to the other, so that we can get the all possible N . In the same way, we circumrotate the arranged subsurfaces with 10° as a unit, and define θ as an azimuth angle, so that θ is 0, 10, 20, ..., 170. The fault extent in the earthquake must be one of each possible N and θ , corresponding to the N and θ which must form the most likely source model.

4 Results

We assume a symmetrical velocity model and a constant rupture velocity, so we can use t_1 , t_2 , and C to obtain the subsurface of the envelopes then synthesize them for each N and θ , and compare them to the total observed envelopes. The best estimate of the model parameters minimizes the residual sum of the squares (RSS) between the observed ground-motion envelopes and the predicted envelopes from the subsurface model (Figs. 3, 4). The misfit function as a measure of goodness of fit is defined as follows:

$$\text{RSS}(t) = \sum_{i=1}^s \sum_{j=1}^3 \sum_{k=1}^t (E_{ijk} - \hat{E}_{ijk})^2 \quad (5)$$

where s is the number of stations, t is the time in 1-s intervals from the event onset, and E_{ijk} and $\hat{E}_{ijk}$ are observed and predicted envelopes of component j at station i at time $k\Delta t$. In this section, we show the results. We use the horizontal and vertical records of the stations. To simplify the problem, we assume each subsurface has the same magnitude of 6.0 and 6.3, with the same spacing of 10 km (Fig. 5).

The total results can be collected as shown in Table 1.

5 Discussion and conclusions

A key aspect of this strategy is to map the location of the rupture using envelopes of high-frequency acceleration data. We circumrotate the arranged subsurface with the azimuth angle, move one subsurface to the opposite side, and then we can get the total possible fault extent. This misfit function tends to emphasize the importance of fitting stations with large accelerations. As we know, the nearest source stations will record a large acceleration, and the RSS could be a huge figure if there are serious discrepancies; on the other hand, some more distant stations have a small acceleration, and there is a lesser impact on the inversion even though these have serious discrepancies. So an adequate near-source station distribution is important. Our strategy for using high-frequency radiation to determine the N and θ of the rupture relies on the observation that high-frequency seismic waves can be modeled as random-phase waves. By using this assumption, we show that we can simulate the ground motion of a large earthquake with smaller events and then sum the random-phase signals from the smaller events. In our example of the Wenchuan and Jiji (Chi-Chi) earthquakes, we showed that a sum of 10-km interval subevents provided a good prediction of the acceleration envelopes for these two earthquakes. The best estimate of the model parameters minimizes the residual sum of the squares between the observed ground-motion envelopes and the predicted envelopes from the subsurface model. Based on the analysis of the strategy from the Wenchuan and Chi-chi earthquakes, the following conclusions can be drawn.

- (1) We present a simple method to search a minimum residual by comparing the observed and predicted envelopes; the results show less distinction from some public conclusions in academia. Better achievements can be obtained from some other examples, which will be introduced in another paper.
- (2) There are some advantages that apply to the digital seismic network, which begin to work after gathering the accelerations, epicenter, and magnitude. That is a new strategy for networks in the background, and our country is engaged in constructing such networks.
- (3) The time consumed is 2 min, which may be shortened if we can promote the computer configurations or improve the program efficiency, so that the strategy must be completely satisfied with regards to the systems of rapid reporting of seismic intensity.

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