# Geophysical Journal International

*Geophys. J. Int.* (2013) **193,** 1713–1725 Advance Access publication 2013 April 04

# Imaging source slip distribution by the back-projection of *P*-wave amplitudes from strong-motion records: a case study for the 2010 Jiasian, Taiwan, earthquake

Wei-An Chao,<sup>1</sup> Li Zhao,<sup>2</sup> Yih-Min Wu<sup>1</sup> and Shiann-Jong Lee<sup>2</sup>

<sup>1</sup>Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan. E-mail: vvnchao@gmail.com <sup>2</sup>Institute of Earth Sciences, Academia Sinica, Nankang, Taipei 115, Taiwan.

Accepted 2013 February 28. Received 2013 February 27; in original form 2012 July 10

## SUMMARY

We propose an approach to imaging earthquake source rupture process by direct backprojection of local high-frequency (0.1-2.5 Hz) P-wave displacements from strong-motion records. A series of synthetic experiments are performed which demonstrate that our approach is capable of recovering the spatial-temporal distribution of the source slip with a good station coverage and a high average coherence value between the target and template waveforms. We demonstrate the effectiveness of our approach by applying it to image the slip distribution of an earthquake occurred on 2010 March 4, in Jiasian ( $M_{\rm w} = 6.0$  and  $M_{\rm L} = 6.4$ ) in southern Taiwan. The resulting moment-rate amplitude images show that the source rupture initiated at the vicinity of the hypocentre, followed by a moderate moment-rate release to the southeast of the hypocentre and a subsequent upward propagation, and finally propagated in the northwest direction, in agreement with the distribution of aftershocks. The majority of the slip at 17–20 km depth occurred to the west of the hypocentre, in a general agreement with the slip distributions obtained from dislocation model and finite-fault inversions. Our modified back-projection approach relies on seismic waveforms with the considerations of a recent 3-D structure model, high average coherence value, station correction factor and simplified amplitude correction. It is computationally efficient and allows for near real-time determinations of source slip distributions after earthquakes using strong-motion records. A quick result for the rupture model can be used in the calculation of strong ground-motion, providing important, useful and timely information for seismic hazard mitigation.

**Key words:** Earthquake dynamics; Earthquake source observations; Computational seismology; Asia.

#### **1 INTRODUCTION**

Conventional inversion schemes for earthquake finite source processes often require the calculation of Green's functions between the sources and seismic stations, which can be computationally demanding, and a priori knowledge of the fault-plane parameters (e.g. Mori & Hartzell 1990; Kuge 2003; Aoi et al. 2008; Lee et al. 2008). In contrast, the back projection method (BPM) provides a computationally less expensive means to image the kinematic source rupture processes, and it only relies on the observed waveforms and the estimated traveltimes between the sources and receivers. In recent years, this technique has been applied to relatively large earthquakes  $(M_{\rm w} > 7.5)$  to trace the source ruptures with dimensions of hundreds of kilometres using teleseismic P waveforms from seismic arrays (e.g. Ishii et al. 2005; Krüger & Ohrnberger 2005; Walker et al. 2005; Xu et al. 2009; Zhang & Ge 2010; Huang et al. 2011a; Ishii 2011; Kiser & Ishii 2011; Meng et al. 2011, 2012). Furthermore, Kao & Shan (2004, 2007) back-projects the amplitudes of *P*-wave envelopes using local seismic records to determine the orientations of the fault planes, while Pulido et al. (2008), and Allmann & Shearer (2007) and Honda & Aoi (2009) utilize the near-field P waves and S waves to map the rupture processes of moderate and shallow-focus earthquakes, respectively. Although there are various implementations of the BPM, the underlying concepts and assumptions are similar. Most of the aforementioned BPM implementations seek to determine only the relative slip intensities or grid brightnesses rather than absolute slip amplitudes on the fault plane due to normalization of records by the maximum amplitude so that geometrical spreading and other factors affecting amplitudes can be neglected. In this study, we develop a new and quantitative approach to the cross-correlation-based back-projection method with template waveform in which the absolute slip amplitude distribution in the source region is obtained after accounting for geometrical spreading, material properties in the source region and the nonuniform station distribution correction using local P wave absolute displacement amplitudes, without compromising the computational

efficiency. The cross-correlation approach with an allowance of time shift minimizes the effect due to imperfect velocity model and enhances the coherence in the stacking of the bursts of seismic energy corresponding to the same source asperity.

We conduct a series of synthetic tests to investigate the temporalspatial resolution of our back-projection approach, especially for examining how the distribution of seismic observations can influence the recovered rupture image. In addition, we also explore the importance of including a correction factor for non-uniform station distribution, which can significantly influence the accuracy of the result. In calculating slip amplitude, we define two threshold values  $\eta_{\rm R}$  and  $\eta_{\rm C}$  for the ratio of the moment-rate distribution and the average coherence value, respectively. These thresholds are discussed later in the synthetic test section. Then we apply it to the 2010 March 4 Jiasian earthquake ( $M_w = 6.0$  and  $M_L = 6.4$ ), the largest inland earthquake in southern Taiwan since the disastrous 1999 Chi-Chi earthquake. Fig. 1 shows the location of Jiasian earthquake as well as the locations of stations used in this study. These stations belong to the Taiwan Central Weather Bureau (CWB) real-time strongmotion network. The relocated epicentre of this event is located at 22.962°N and 120.699°E with a focal depth of 23 km (Huang et al. 2011b). The relocated aftershock distribution and the pattern

of the peak-ground acceleration (PGA) distribution suggest that the rupture initiated at the deeper part of the fault plane and propagated upward in northwest direction (Huang *et al.* 2011b).

In our back-projection study for the Jiasian earthquake, we use records from a number of stations with good distribution in both epicentral distance and azimuth around the source region, which can significantly reduce the biases caused by the lack of samples in the radiation pattern and local site effect as discussed in the section on synthetic tests. Anelastic attenuation is not included in our implementation, as our records are all from local stations so the effect of attenuation is insignificant compared to other uncertainties and simplifications and does not significantly change the estimated slip amplitudes (e.g. Aki & Richards 2002). We use our slip images together with relocated aftershock locations to infer the distribution of fault slip, and then compare our results with dislocation model and finite-fault joint inversion obtained using geodetic observations, and teleseismic body wave, GPS coseismic displacements and near-field strongmotion data, respectively. Due to simplicity amplitude correction and relatively fast computation, our approach is a good candidate for rapid determination of rupture process, slip amplitude distribution which can be used to estimate strong ground-motion. It is



Figure 1. Distribution of real-time strong-motion stations shown by triangles. Black triangles are stations used in the Jiasian case study. Black star indicates the relocated location of the 2010 March 4,  $M_L = 6.4$  Jiasian earthquake, and the circles show the relocated epicentres of its one-day aftershocks (Huang *et al.* 2011b). The focal mechanism for the main shock is from Hsu *et al.* (2011). Active faults published by the Central Geological Survey (CGS) of Taiwan are depicted by thick red lines. The 3-D spatial grids used in the synthetic tests and in the application to Jiasian earthquake are shown in the right panel. The black dots are the locations of two point sources in the synthetic tests. The source time function is shown in the lower right corner.

#### 2 METHOD

The seismic waves from a moderate-to-large-sized earthquake are generated by the spatial-temporal distribution of fault slips, with a slip patch moving in the direction(s) of rupture propagation. In our back-projection implementation, we focus on the *P*-wave train only. In a homogeneous elastic medium, the primary component of the far-field *P*-wave displacement from a point source is given by Aki & Richards (2002)

$$u \propto \frac{R^P}{4\pi\rho v_P^3 R} \dot{M}(t),\tag{1}$$

where  $\rho$  and  $v_P$  are the density and *P*-wave velocity at source region, respectively. *R* is the propagation distance from the source to the station.  $R^P$  is the *P*-wave radiation pattern. The first-arriving energy in the *P*-wave train comes from the initial rupture point, whereas later-arriving energy is due to slip at and behind the rupture front. The identification of a seismic asperity, as shown in Fig. 2(a), is based on the moment-rate releasing amplitude  $\dot{M}$ , which according to eq. (2) is proportional to the summation of the corrected absolute displacement of the *P*-wave amplitude in specific time windows.

Here we perform the amplitude correction based on the expression for homogeneous medium (eq. 1) to account for the effects of the geometry spreading (R), material properties ( $A^c$ ) at the source region and also a station-distribution (weighting) factor ( $S^c$ ). We neglect the influence of the source radiation pattern ( $R^P$ ) to minimize the computational demands and remove the requirement for a prior fault-plane solution. This should not introduce biases as long as records are available from a wide range of epicentral distances and azimuths as discussed in the section on synthetic tests.

For a given source location ( $\xi$ ), the filtered *P*-wave absolute amplitudes  $D_i$  of vertical-component displacement at all stations, after being applied the aforementioned corrections, are summed to approximate the moment-rate releasing  $\dot{M}_{\xi}$  as a function of the time *t*:

$$\dot{M}(\xi,t) \cong \frac{1}{N} \sum_{i=1}^{N} \left\{ \left( \frac{A_{\xi}^{c} S_{\xi i}^{c} R_{\xi i}}{R^{p}} \right) \sum_{k=-M}^{M} \frac{W_{k}^{G} D_{i}(t+T_{\xi i}^{p}+k\Delta t+t_{i}^{\text{corr}})}{\sum_{k=-M}^{M} W_{k}^{G}} \right\},$$
(2)

where  $R_{\xi i}$  and  $T_{\xi i}^p$  are the propagation distance and the theoretical *P*-wave traveltime from the source point  $\xi$  to the *i*th station, respectively;  $\Delta t$  is the sampling interval and  $W^G$  is a Gaussian weighting function. The number of samples around the predicted arrival times  $(T_{\xi i}^p)$  included in the summation in eq. (2) is 2M and the stacking length of the time window is equal to  $2M \times \Delta t$ . *N* is the number of stations. The correction for the material property at the source point  $\xi$ ,  $A_{\xi}^e$ , is defined as,

$$A^c_{\xi} = 4\pi\rho v^3_p. \tag{3}$$

Jakka *et al.* (2010) introduced a non-uniform station distribution factor that can be used to prevent the final slip image from being dominated by a particular station cluster. Here, we apply the same station-weighting factor  $S_{\xi i}^{c}$  calculated from the expression,

$$S_{\xi i}^{c} = \left(\sum_{j=1}^{n} \frac{\phi_{ji}}{\sum_{k=1}^{N} \phi_{jk}}\right),\tag{4}$$

where  $\phi_{ii}$  is the angle between the *j*th bisector and the *i*th station  $(0 \le \phi_{ii} < 180)$ . N represents the number of stations. n is the number of angular bisectors between consecutive stations. Regions in space and time that show high relative moment-rate releasing amplitude indicate constructive interference and can be considered as potential rupture locations. Ishii (2011) concluded that the conventional BPM relies heavily on seismic stations with relatively large bursts of seismic energy, which may obscure weak energy releases, and assumes that the asperity-induced amplitude bursts are similar in waveform among stations and that they are well-recorded with high signal-to-noise ratio (SNR) to warrant cross-correlation. Here, we adopt the cross-correlation approach to enhance the coherence of stacks. Thus, the time correction  $t_i^{\text{corr}}$  in eq. (2) is the time-point for the highest waveform similarity as defined by the cross-correlation between the template  $u_g$  and the *i*th target  $u_f$  displacements within the specific time windows (2M time-points). The cross-correlation coefficient also provides the relative amplitude information of each stacked target waveform with respect to the template waveform. Each corresponding maximum cross-correlation coefficient ( $C_{\rm fg}$ ) is normalized by the maximum auto-correlation coefficients  $C_{\rm ff}$  and  $C_{\rm gg}$  of the target and template displacements, respectively, as follows:

$$NCC = \frac{C_{\rm fg}}{\sqrt{C_{\rm ff}C_{\rm gg}}},\tag{5}$$

where NCC is the normalized cross-correlation coefficient. The average coherency value ( $C_0$ ) is defined as:

$$C_{0} = \frac{1}{N} \sum_{i=1}^{N} NCC_{i} = \frac{1}{N} (NCC_{1} + NCC_{2} + \dots + NCC_{N}),$$
(6)

where the sum is over the number of stations *N*. If a target waveform has a *NCC* value below 0.7, then the corresponding grid-point is not utilized in the stacking. In this study, waveform at Station CHN1 is selected as a template for its high SNR value and the earliest *P*-wave arrival time. Fig. 2(b) displays an illustration of the different quantities and an example of calculating the cross-correlogram and maximum cross-correlation coefficient ( $C_{\rm fg}$ ) between isolated *P*-wave amplitudes in the target and template waveforms  $u_{\rm f}$  and  $u_{\rm g}$ , respectively.

#### **3 SYNTHETIC TESTS**

To investigate how the non-uniform station distribution and the radiation pattern effect contribute to the resulting back-projection image, we perform a series of synthetic experiments. Fig. 1 shows the spatial discretization of our synthetic tests corresponding to source rupture points in 3-D volume. The source volume is gridded by a mesh with an interval of  $0.01^{\circ}$  in both latitude and longitude, and 1 km interval in depth. A sampling interval of 0.1 s in rupture time is used in all calculations throughout this study.

To investigate the spatial and temporal resolvability of our BPM approach, we use the spectral-element method (Komatitsch *et al.* 2004; Lee *et al.* 2009) to generate synthetic Green's functions in the 3-D velocity model of Wu *et al.* (2007, 2009). The *P*-wave velocity at source area in the 3-D velocity model of Wu *et al.* (2007, 2009) and 1-D layer model of Chen & Shin (1998) are ~6.3 km s<sup>-1</sup> and ~6.6 km s<sup>-1</sup>, respectively. The 1-D layer model of Chen & Shin (1998) is used by the CWB for locating regional earthquakes. Using the *P*-wave velocities in the two models in eq. (3), there is only ~10 per cent difference in the resulting correction factors,



**Figure 2.** (a) Two rupture points on the fault-plane are back-projected by the corresponding energies arriving in vertical-component records at two different stations. (b) An example of cross-correlation scheme between the truncated target  $(u_f)$  and template  $(u_g)$  waveforms with 2*M* time-points in length. (c) An example of stacking the absolute amplitude of filtered *P*-wave displacement around its predicted arrival-time. Solid black and red curves are the original filtered waveform and its absolute values after windowing.

which is small enough to satisfy the assumption of a homogeneous velocity model in eq. (3). Synthetic seismograms at 32 selected stations are computed from two input source points (black dots in Fig. 1) using the 3-D synthetic Green's functions with the focal mechanism (strike 324°, dip 39° and rake 67°) determined by Hsu et al. (2011). The simulations provide accurate waveforms up to 1 Hz. The finite-source synthetic seismograms are calculated by the summation of the two point-source synthetic waveforms convolved with the corresponding source-time functions (Fig. 1) with proper delay times discussed later. The seismic moment of the secondary point-source is twice as large as the first source point, corresponding to moment magnitudes of  $M_w = 6.3$  and  $M_w = 6.08$ , respectively. We integrate the vertical-component synthetic velocity seismograms to displacement, and then apply a bandpass filter with corner frequencies of 0.1 and 1.0 Hz. The absolute waveforms used in calculating the cross-correlagrams are obtained from the filtered seismograms after applying a 1-s Cosine taper at the end of the time window, chosen to be the predicted S-wave arrival time. Fig. 2(c) displays an example of the filtered synthetic seismogram and the corresponding windowed absolute waveform.

Assuming a rupture velocity of 2.5 km s<sup>-1</sup>, two asperities separated by 1 km will generate a waveform with two peaks separated by about 0.4 s. This implies that the time window in calculating the cross-correlations should be less than 0.4 s to achieve sufficient resolution of source process. The length of each input waveform depends on the duration of the source-time function, which can be roughly estimated from the corresponding magnitude, for example, about 6 s long for  $M_{\rm w} = 6.0$  (Kanamori & Brodsky 2004). Here we use 0.3 s  $(2M \times \Delta t)$  as the length of stacking time window and at least 5 s as the length of 32 input P-wave seismograms. The locations of the energy sources are specified in the synthetic calculation, which are compared with images recovered from the back-projection of the synthetic seismograms. In the first part of the synthetic experiment, we remove several stations located to the east of the Jiasian earthquake to explore the influence of imperfect station coverage, as shown in Fig. 3(a). The results when considering non-uniform station distribution are presented in Fig. 3(b). The two locations of the maximum moment-rate amplitude at two specific time-steps are not able to adequately recover the input asperities. In contrast, when station correction factor in eq. (4) is considered (Fig. 3c), the resulting image, although still shifted but is not very far from the input point-source locations. Shift of the two locations of the maximum moment-rate amplitude is perhaps due to a large number of stations located to the west of the Jiasian earthquake. Next, we consider a case with 32 stations distributed around the source at a distance range of 30–115 km, providing a nearly perfect coverage in epicentral distance and azimuth (Fig. 3d). The resulting images before (Fig. 3e) and after (Fig. 3f) correcting for station distribution using station correction factor both correctly identify two asperities. Thus, the station correction factor is not required when a large number of well-distributed stations are available. These synthetic experiments demonstrate the importance of applying a station distribution correction to prevent a particular station cluster from dominating the final image. If the effect of the radiation pattern is considered, the moment-rate release  $\dot{M}_{\xi}$  is calculated by a further division by the radiation patterns ( $R^{P}$  in eq. 2). The results are shown in Fig. 3(g), the locations of the asperities remain unchanged from the previous results (Fig. 3f). However, there is  $\sim$ 8 per cent amplitude change in the average moment-rate compared to results in Fig. 3(f) at two specific time-steps. This difference is small and acceptable for imaging the rupture process rapidly without the consideration of the radiation pattern.

The distribution of real-time strong-motion network is sparse in the central mountain region in Taiwan. In addition, for Jiasian earthquake the data stream from Station ALS was not useable because of transmission problems. To examine a more realistic station distribution, we conducted a synthetic test by excluding Station ALS. Without Station ALS, a larger station gap (59°) exists in the northeast direction. Here, we back-project the source using only 31 stations without Station ALS. The images recovered in this experiment (Fig. 3h) show relatively large smearing effect in the dip direction. However, this artefact has relatively small influence on slip image in Jiasian earthquake because its major rupture front is in the northwest direction. For the realistic case of Jiasian earthquake, we used relatively high-frequency (0.1-2.5 Hz) displacement to increase the spatial resolution and reduce the smearing effect. Such synthetic tests provide a first-order understanding of the recovery ability of our approach for the geometry of the asperity sources and stations.

We further investigate how the choice of template waveform influences the final resulting image. Here four template stations are selected in different quadrants. Results of the synthetic experiments are displayed in Fig. 4(a). In all synthetic experiments, the directions of point-source propagation and the amplitudes of moment-rate release, shown in Fig. 4(a) are all consistent with the input configurations. The seismograms in Fig. 4(b) are arranged in the order of increasing values in the auto-picking P-wave arrival times in the input waveforms, and the corresponding arriving energies from the two asperities are indicated by thick gray lines. The relative timing clearly changes with both epicentral distance and azimuth. By considering a wide range of epicentral distance from 30 to 115 km, and applying the average coherence value  $(C_0)$  and station distribution factor ( $S^c$ ), our back-projection approach significantly reduces the smearing effect. In the application to Jiasian earthquake discussed later, we back-project the P-wave amplitude in a 3-D volume with the same station geometry available in the synthetic tests except for Station ALS.

After obtaining the back-projected images as shown in Fig. 4(a) using the waveform at CHN1 as the template, for each time step we sum the moment-rates and grid areas with moment-rate values  $(\dot{M})$  larger than the threshold of moment-rate  $\eta_{\rm M}$  and average coherence values  $(C_0)$  higher than the threshold of average coherence value  $\eta_{\rm C}$  to estimate the total average moment-rate  $(\dot{M})$  and the total source area. Fig. 5(a) displays an example of the threshold of moment-rate  $\eta_{\rm M}$  determination. The ratio of moment-rate distribution  $(\dot{M}_R)$  is defined as,

$$\dot{M}_R = \sum_{i=1}^{N_C} \left( \frac{\dot{M}_S^i}{\dot{M}_T} \right), \, \dot{M}_T = \sum_{i=1}^{N_P} \dot{M}_S^i,$$
(7)

where  $N_p$  is the total number of grid-points at a specific rupture time-step and  $\dot{M}_S^i$  is the sorted moment-rate amplitude of the *i*th point. The sorted moment-rate value of first grid-point  $(\dot{M}_S^1)$  has the largest moment-rate amplitude.  $N_c$  is the point corresponding to the threshold values of  $\eta_R$  and  $\eta_M$ .  $\eta_R$  is the threshold of the ratio of moment-rate distribution  $(\dot{M}_R)$ . We have experimented with different  $\eta_R$  and  $\eta_C$  values, and found that  $\eta_R = 0.8$  and  $\eta_C = 0.9$  (Fig. 5a) lead to similar slip values of ~40 cm for the moment magnitude of  $M_w = 6.0$  (1.26 × 10<sup>25</sup> dyne-cm), as predicted by the empirical scaling relationship of Yen & Ma (2011). Based on physical explanation, the threshold values of  $\eta_R$  must be located on the first 80 per cent of moment-rate distribution. It indicates that most of the moment-rate amplitude larger than  $\eta_M$  value with



**Figure 3.** Left panels show the station configurations (white triangles) of (a) imperfect and (d) good station coverages in our synthetic tests with waveform at Station CHN1 as a template. Shown in the right panels are results of the major moment-rate release amplitude satisfying the  $\eta_R$  (0.8) and  $\eta_C$  (0.9) thresholds projected onto the corresponding fault-plane solution at two specific time-steps in the input model when considering no station correction (b and e), correction for station distribution (c and d), radiation pattern effect (g), and the synthetic case without Station ALS (h). Two white dots depict the input source locations. The stars indicate the locations of maximum moment-rate release amplitude. Gray scale represents the moment-rate amplitude.



**Figure 4.** (a) From left to right are station configuration and results of the major moment-rate release amplitude satisfying the  $\eta_R$  (0.8) and  $\eta_C$  (0.9) thresholds projected onto the corresponding fault-plane solution at two specific time-steps in the input model with the different template waveforms. Two white dots depict the input source locations. The stars indicate the locations of maximum moment-rate release amplitude. Gray scale represents the moment-rate amplitude. (b) Filtered and absolute waveforms at several stations. The stacking windows around the predicted arrival times from two asperities are marked by thick vertical gray lines with indices 1 and 2 as shown in (a). Asperity No. 1 corresponds to the location of the initial rupture. The station name, azimuth (in degrees) and epicentral distance (in km) with respect to the initial rupture are given beside the waveforms for each station. The thin vertical gray lines indicate the time points of the *P*-wave arrival determined by the auto-picker and the predicted *S* arrival.

high signal coherence ( $C_0 > \eta_C$ ). For real earthquakes, these gridpoints might correspond to the source complexity. In contract, the rest of the grid-points contribute only a small fraction of moment-rate release, perhaps due to artefacts and can be ignored. Finally, the total average seismic moment ( $\overline{M}_0$ ) can be determined from the integral of the average moment-rate ( $\overline{M}$ ) within the specific 0.4-s time interval *T*:

$$\bar{M}_0 = \int_T \bar{\dot{M}}(t) dt.$$
(8)

The average value of slip (S) obtained within the specific time interval corresponding to the average seismic moment can be calculated by,

$$S = \frac{\bar{M}_0}{\mu A},\tag{9}$$

where  $\mu$  is the shear modulus at source region ( $\mu = 3.0 \times 10^{11}$  dyne cm<sup>-2</sup>), *A* is the total source area (km<sup>2</sup>) during the specific time interval *T*. Fig. 5(b) displays the resulting average value of slip distribution for the two time intervals, which corresponds to the first and second input source points.

# 4 APPLICATION TO JIASIAN EARTHQUAKE

The synthetic tests not only confirms the effectiveness of our backprojection approach in resolving the spatial-temporal features of the source process, but also enable us to calibrate the parameters  $\eta_{\rm R} =$ 0.8 and  $\eta_{\rm C} = 0.9$  in our algorithm. With similar station configuration, spatial-temporal source discretization and filtering frequency band, these empirical parameters are suitable for back-projecting



Figure 5. (a) The left panel displays an example of  $\eta_M$  threshold determination. The dots are the ratio of moment-rate distribution in the sorted moment-rate amplitude accumulated from the maximum moment-rate release. The moment-rate amplitudes for the gray dots are larger than  $\eta_M$  threshold. Residuals between the average slip values and the empirical ones obtained with different  $\eta_R$  and  $\eta_C$  thresholds are shown in the right panel. Black dot indicates the location with minimum residual value. (b) The average values of the slip distribution for the two time intervals. The two white dots depict the input source locations.

the source ruptures of moderate earthquakes  $(M \sim 6)$ , and they can be tuned to accommodate earthquakes of larger or smaller magnitudes. Next, we apply our back-projection approach to the 2010 March 4 Jiasian earthquake ( $M_w = 6.0$  and  $M_L = 6.4$ ). To image the source process of this earthquake, we collected waveforms recorded at 31 real-time strong-motion stations, the same stations used in our synthetic tests except for Station ALS. Epicentral distances of these stations range from 30 to 115 km, far enough from the epicentre to allow an adequate separation between P- and S-wave arrivals yet not too far so as to avoid interference from secondary phases (e.g. scattering and converted waves). Each station has a three-component force-balanced accelerometer with a 16-bit resolution, a sampling rate of 50 Hz, and a full dynamic range of  $\pm 2g$ . In data processing we remove the mean and linear trend before the time point of *P*-wave arrival, then double integrate the vertical-component acceleration seismograms to displacement, and apply a bandpass filter with corner frequencies of 0.1 and 2.5 Hz. The lower corner frequency of 0.1 Hz is chosen such that there are at least two to three wavelengths between each subfault and station to maintain the far-field condition. The higher corner frequency of 2.5 Hz is chosen to minimize the influence from local small-scale structures. The final absolute waveforms are obtained by applying a boxcar time window which ends with a 1-s Cosine taper right before the predicted *S*-wave arrival time. Fig. 6 displays examples of the original strong-motion accelerograms as well as the double integrated displacements and corresponding absolute waveforms at selected stations. The *P*-wave arrivals were detected from the vertical-component accelerograms by an auto-picker (Allen 1978).

All the controlling parameters and spatial-temporal discretization in our back-project process for Jiasian earthquake are set according to the synthetic tests described in previous section. However, here we use 0.2 s as the length of time window for each rupture time-step (sampling interval of 0.1 s) and consider a 4-D grid of points uniformly spaced in latitude, longitude, depth and time. Fig. 7(a) shows the maximum moment-rate amplitude as a function of time and the relationship between the rupture time and hypocentral distance from the initial rupture point. The resulting images for six time steps with major moment-rate release amplitude ( $\dot{M}$ ) and



013

Figure 6. Strong-motion accelerograms and filtered displacement seismograms. The vertical gray lines indicate the time points of the *P*-wave and *S*-wave arrivals. The absolute displacement waveforms are shown in red lines.

average coherence value ( $C_0$ ) larger than the  $\eta_M$  and  $\eta_C$  thresholds, are shown in Fig. 7(b).

In our back-projection images of the moment-rate release for the Jiasian earthquake, the initial ruptures surround the hypocentre, followed by a moderate value of moment-rate appearing in the southeast and below the hypocentre, and then propagate upward. Finally, the ruptures propagate toward the northwest direction. This picture is generally consistent with the trend of aftershock distribution. The time from initial rupture point is shown as a function of the hypocentral distance in Fig. 7(a). It appears that initial ruptures are located at the vicinity of the hypocentre, and a significant westward propagation begins at ~2.5 s with an approximate rupture velocity of 3.0 km s<sup>-1</sup>. For most large crustal earthquakes, the rupture velocity falls in 75–95 per cent of the *S*-wave velocity at the depth where the largest slip occurs (Kanamori & Brodsky 2004). The *S*-wave velocity in our source area is ~3.5 km s<sup>-1</sup> in the velocity model of Wu *et al.* (2007, 2009). Thus, the estimated rupture velocity (3.0 km s<sup>-1</sup>) is reasonable (not a super-shear event). In Fig. 8 we show examples of the absolute *P*-wave displacement amplitude (vertical component) at several stations used for source imaging, aligned at the *P*-wave onset and ordered by increasing arrivals times. We highlight the arrival-times corresponding to the specific asperities by thick vertical gray lines with a thickness of 0.2 s, the time window used for cross-correlation around the predicted arrivals. We can



Figure 7. (a) Upper panel shows the maximum moment-rate amplitude as a function of time. Rupture time versus hypocentral distance is shown in the lower panel. The colour denotes azimuth with respect to the epicentre of initial rupture point (No. 1 asperity). The slope of the gray lines indicate rupture speeds of  $1 \text{ km s}^{-1}$ ,  $2 \text{ km s}^{-1}$ ,  $3 \text{ km s}^{-1}$  and  $4 \text{ km s}^{-1}$ . (b) The panels show the locations of major moment-rate releasing amplitudes satisfying the  $\eta_R$  threshold (0.8) and the  $\eta_C$  threshold (0.9) projected onto the surface and the corresponding fault-plane solutions at six specific time steps. The white and red stars indicate the locations of maximum moment-rate releasing amplitude and the relocated location of the Jiasian earthquake, respectively. Colour scale shows the moment-rate amplitude. Asperity No. 1 corresponds to the location of the initial rupture. The white dots show the distribution of relocated Jiasian one-day aftershocks (Huang *et al.* 2011b). The red rectangle shows the projection of the northeast-dipping fault-plane onto the surface.

observe that these windows in general include wavelets of higher amplitudes radiated from the asperities. The directivity effect of the rupture propagation can be visually confirmed by the relative timing of the phases associated with individual asperities. Specifically, stations to the northwest of the epicentres (e.g. WTP) have shorter time separations between the phases of the fourth and fifth asperities than stations at other azimuths. In the imaged slip distribution result shown in Fig. 9, rupture initiated from the hypocentre, and the large slips occurred both around and to the west of the hypocentre, in general agreement with the dislocation model and finite-fault model obtained from geodetic observations (Hsu *et al.* 2011) and a jointinversion of near-field strong-motion data, teleseismic body waves and coseismic displacement (Lee *et al.* 2013). In addition, most of the aftershocks are located surrounding the larger slip region.

#### **5 DISCUSSION AND CONCLUSIONS**

We have developed a new and quantitative implementation of the back-projection method for imaging the source rupture processes of moderate and large earthquakes using local *P*-wave records. From a series of synthetic tests, we demonstrate that our back-projection approach can recover the source spatial-temporal processes very well with a good distribution of seismic stations and relative high coherency value ( $C_0 > 0.9$ ). These cases also demonstrate the importance of applying a station correction factor to down-weight a large number of stations in one region. In the case where station distribution is less than optimal (Figs 3a and c), our approach identifies two asperities when the station correction is considered. The recent vast expansion of real-time broadband seismic networks in Taiwan provides additional aid with near-real-time earthquake CMT solutions as part of their routine operations (Zhao *et al.* 2011). Thus we can use earthquake focal mechanisms to ensure a good resolution, and quickly delineate the slip distributions on the two nodal planes.

In a practical application to the Jiasian earthquake, our results clearly show that back-projecting the real-time strong-motion data provides an effective way for imaging rupture propagation and determining asperity locations, even in the case of a relatively deep (>20 km) and moderate-sized earthquake. The overall pattern of



**Figure 8.** Filtered and absolute waveforms at several stations. The stacking windows around the predicted arrival times from different asperities are marked by thick vertical gray lines with indices 1-6 as shown in Fig. 7. Asperity No. 1 corresponds to the location of the initial rupture. The station name, azimuth (in degrees) and epicentral distance (in km) with respect to the initial rupture are given beside the waveforms for each station. The thin vertical gray lines indicate the time points of the *P*-wave arrival determined by the auto-picker and the predicted *S* arrival.



Figure 9. Left panel shows the average moment-rate function (dash line). Rupture process snapshots of the Jiasian earthquake with cumulative average slip for the four time-periods are shown in the right panel. The red star depicts the relocated location of Jiasian earthquake. The dashed contour is a large patch of slip in the finite-fault model of Lee *et al.* (2013).

the imaged asperities generally coincides with the slip distribution determined using more elaborate methods (Hsu *et al.* 2011; Lee *et al.* 2013). The slip amplitudes in these studies are in general agreement, which indicates that the parameters  $\eta_{\rm R} = 0.8$  and  $\eta_{\rm C} =$ 

0.9 derived from fitting empirical slip values are appropriate. Nevertheless, a large patch of slip in the finite-fault model of Lee *et al.* (2013) is mostly located at to the north of our back-projection result (Fig. 9). Several factors may contribute to this discrepancy. In the finite-fault technique, the fault geometry is often assumed, and the slip is prohibited to occur behind a healing front. The BPM, on the other hand, does not impose these *a priori* constraints, but it does depend on the station distribution. The discrepancy may also imply a complex source process, where different source processes are responsible for the radiations of high and low frequencies. The BPM result presumably includes the effect of relatively high frequency radiation in comparison to the finite-fault model (0.01– 0.5 Hz). Ideally, both approaches can be combined to provide a robust and complete image of the earthquake rupture.

After a moderate-to-large-sized earthquake, one of the most important tasks is to determine a source rupture model as quickly as possible. It can not only help us establish a better understanding of the earthquake and evaluate the potential of any further seismic risk, but also assist in emergency response and rescue by providing crucial information on possible strong shaking caused by source directivity. In the case of Jiasian earthquake, one of the Taiwan High Speed Rail (THSR) trains 50 km from the epicentre went off the rails during the Jiasian mainshock because of the high PGA value northwest of the epicentre, in the rupture direction (Wu et al. 2011). Currently, the earthquake early warning system operated by the CWB of Taiwan has an average reporting time of about 22 s for the earthquake hypocentres and magnitudes (Wu et al. 1998; Hsiao et al. 2009). Our approach uses the early warning location and magnitude of an earthquake as a priori constraints to ensure that the epicentral distance must be large enough to have a good separation between P- and S-wave trains (with the source duration taken into account), and perform the source discretization. However, we can directly obtain the location of the initial rupture point from our back-projection procedure, and the source duration can be estimated from the earthquake magnitude. Thus, our improved BPM provides a means to obtain a relatively detailed source process very quickly without the need for obtaining the focal mechanism as discussed in the synthetic test section. Once the seismic wave (local P-wave in this study) arrives at a number of seismic stations, it merely takes 10-20 min on a desktop computer to perform the back-projection scheme. The total amount of time required to obtain a source rupture image is proportional to the number of trial grid-points, a scenario suitable for parallelization. If an adequate station coverage is available, our approach allows for a rapid determination of the source slip distribution after an earthquake using real-time strong-motion records. It facilitates forward ground-motion simulations and the calculations of shake maps, providing important, useful and timely information for seismic hazard mitigation.

#### ACKNOWLEDGEMENTS

The authors wish to thank two anonymous reviewers for their constructive comments that helped improve the manuscript. This research has been supported by the CWB and the National Science Council of the Republic of China. The authors acknowledge the CWB for providing the real-time strong-motion data. The software package GMT (Wessel & Smith 1991) was used in making some of the figures in this paper.

## REFERENCES

- Aki, K. & Richards, P.G., 2002. *Quantitative Seismology*, 2nd edn, University Science Books, Sausalito, California.
- Allen, R.V., 1978. Automatic earthquake recognition and timing from single traces, Bull. seism. Soc. Am., 68, 1521–1532.

- Allmann, B.P. & Shearer, P.M., 2007. A high-frequency secondary event during the 2004 Parkfield earthquake, *Science*, **318**, 1279–1283.
- Aoi, S., Sekiguchi, H., Morikawa, N. & Kunugi, K., 2008. Source process of the 2007 Niigata-ken Chuetsu-oki earthquake derived from near-fault strong motion data, *Earth Planets Space*, **60**, 1131–1135.
- Chen, Y.L. & Shin, T.C., 1998. Study of the earthquake location of 3-D velocity structure in Taiwan are, *Meteorol. Bull.*, 42, 135–169.
- Honda, R. & Aoi, S., 2009. Array back-projection imaging of the 2007 Niigataken Chuetsu-oki earthquake striking the world's largest nuclear power plant, *Bull. seism. Soc. Am.*, **99**, 141–147.
- Hsiao, N.C., Wu, Y.M., Shin, T.C., Zhao, L. & Teng, T.L., 2009. Develop of earthquake early warning system in Taiwan, *Geophys. Res. Lett.*, 36, L00B02, doi:10.1029/2008GL036596.
- Hsu, Y.J., Yu, S.B., Kuo, L.C., Tsai, Y.C. & Chen, H.Y., 2011. Coseismic deformation of the 2010 Jiashian, Taiwan earthquake and implications for fault activities in southwestern Taiwan, *Tectonophysics*, **502**, 328– 335.
- Huang, B.S., Huang, Y.L., Leu, P.L. & Lee, S.J., 2011a. Estimation of the rupture velocity and fault length of the 2004 Sumatra-Andaman earthquake using a dense broadband seismic array in Taiwan, *J. Asian Earth Sci.*, 40, 762–769.
- Huang, H.H., Wu, Y.M., Lin, T.L., Chao, W.A., Bruce, J., Shyu, H., Chan, C.H. & Chang, C.H., 2011b. The Preliminary Analysis of the 2010 Mw6.3 Jiasian, Taiwan, Earthquake Sequence, *Terr. Atmos. Oceanic Sci*, 22, 283– 290.
- Ishii, M., Shearer, P.M., Houston, H. & Vidale, J.E., 2005. Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hinet array, *Nature*, 435(16), 933–936.
- Ishii, M., 2011. High-frequency rupture properties of the  $M_w$  9.0 off-the-Pacific-coast-of-Tohoku earthquake, *Earth Planets Space*, **63**, 609–614.
- Jakka, R.S., Cochran, E.S. & Lawrence, J.F., 2010. Earthquake source characterization by the isochrone back projection method using near-source ground motions, *Geophys. J. Int.*, 182(2), 1058–1072.
- Kanamori, H. & Brodsky, E.E., 2004. The physics of earthquakes, *Rep. Prog. Phys.*, 67, 1429–1496.
- Kao, H. & Shan, S.-J., 2004. The source-scanning algorithm: mapping the distribution of seismic sources in time and space, *Geophys. J. Int.*, 157(2), 589–594.
- Kao, H. & Shan, S.-J., 2007. Rapid identification of earthquake rupture plane using source-scanning algorithm, *Geophys. J. Int.*, 168(3), 1011–1020.
- Kiser, M. & Ishii, M., 2011. The 2010 M<sub>w</sub> 8.8 Chile earthquake: triggering on multiple segments and frequency-dependent rupture behavior, *Geophys. Res. Lett.*, 38, L07301, doi:10.1029/2011GL047140.
- Komatitsch, D., Liu, Q., Tromp, J., Süss, P., Stidham, C. & Shaw, J.H., 2004. Simulations of ground motion in the Los Angeles basin upon the spectral-element method, *Bull. seism. Soc. Am.*, **94**, 187–206.
- Krüger, F. & Ohrnberger, M., 2005. Tracking the rupture of the Mw = 9.3 Sumatra earthquake over 1150 km at teleseismic distance, *Nature*, **435**, 937–939.
- Kuge, K., 2003. Source modeling using strong-motion waveforms: toward automated determination of earthquake fault planes and moment-release distributions, *Bull. seism. Soc. Am.*, 93, 639–654.
- Lee, S.J., Liang, W.T. & Huang, B.S., 2008. Source mechanisms and rupture processes of the 26 December 2006 Pingtung earthquake doublet as determined from the regional seismic records, *Terr. Atmos. Oceanic Sci*, **19**, 555–565.
- Lee, S.J., Komatitsch, D., Huang, B.S. & Tromp, J., 2009. Effects of topography on seismic wave propagation: an example from northern Taiwan, *Bull. seism. Soc. Am.*, 99, 314–325.
- Lee, S.J., Mozziconacci, L., Liang, W.T., Hsu, Y.J., Lu, C.Y., Huang, W.G. & Huang, B.S., 2013. Source complexity of the 4 March 2010 Jiasian, Taiwan earthquake determined by joint inversion of teleseismic and nearfield data, *J. Asian Earth Sci.*, 64, 14–26.
- Meng, L., Inbal, A. & Ampuero, J.-P., 2011. A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake, *Geophys. Res. Lett.*, 38, L00G07, doi:10.1029/2011GL048118.
- Meng, L., Ampuero, J.-P., Luo, Y., Wu, W. & Ni, S., 2012. Mitigating artifacts in back-projection source imaging with implications on frequency-

dependent properties of the Tohoku-Oki earthquake, *Earth Planets Space*, **64**(12), 1101–1109.

- Mori, J. & Hartzell, S., 1990. Source inversion of the 1988, Upland, California earthquake: determination of a fault plane for a small event, *Bull. seism. Soc. Am.*, **80**, 507–518.
- Pulido, N., Aoi, S. & Fujiwara, H., 2008. Rupture process of the 2007 Notohanto earthquake by using an isochrones back-projection method and K-net and KiK-net data, *Earth Planets Space*, **60**, 1035– 1040.
- Walker, K.T., Ishii, M. & Shearer, P.M., 2005. Rupture details of the 28 March 2005 Sumatra M8.6 earthquake imaged with teleseismic *P* waves, *Geophys. Res. Lett.*, **32**, L24303, doi:10.1029/2005GL024395.
- Wessel, P. & Smith, W., 1991. Free software helps map and display data, EOS, Trans. Am. geophys. Un., 72(41), 441–446.
- Wu, Y.M., Shin, T.C. & Tsai, Y.B., 1998. Quick and reliable determination of magnitude for seismic early warning, *Bull. seism. Soc. Am.*, 88, 1254– 1259.
- Wu, Y.M., Chang, C.H., Zhao, L., Shyu, J.B.H., Chen, Y.G., Sieh, K. & Avouac, J.P., 2007. Seismic tomography of Taiwan: improved constraints from a dense network of strong-motion stations, *J. geophys. Res.*, **112**, B08312, doi:10.1029/2007JB004983.

- Wu, Y.M., Shyu, J.B.H., Chang, C.H., Zhao, L., Nakamura, M. & Hsu, S.K., 2009. Improved seismic tomography offshore northeastern Taiwan: implications for subduction and collision processes between Taiwan and the southernmost Ryukyu, *Geophys. J. Int.*, **178**, 1042–1054.
- Wu, Y.M., Lin, T.L., Chao, W.A., Huang, H.H., Hsiao, N.C. & Chang, C.H., 2011. Faster short-distance earthquake early warning using continued monitoring of filtered vertical displacement: a case study for the 2010 Jiasian, Taiwan, earthquake, *Bull. seism. Soc. Am.*, **101**(2), 701–709.
- Xu, Y., Koper, K.D., Sufri, O., Zhu, L. & Hutko, A., 2009. Rupture imagining of the Mw 7.9 12 May 2008 Wenchuan earthquake from back projection of teleseismic P-waves, *Geochem. Geophys. Geosyst.*, 10, Q04006, doi:10.1029/2008GC002335.
- Yen, Y.T. & Ma, K.F., 2011. Source-scaling relationship for M 4.6–8.9 earthquakes, specifically for earthquakes in the collision zone of Taiwan, *Bull. seism. Soc. Am.*, **101**(2), 464–481.
- Zhang, H. & Ge, Z., 2010. Tracking the rupture of the 2008 Wenchuan earthquake by using the relative back-projection method, *Bull. seism. Soc. Am.*, **100**, 2551–2560.
- Zhao, L., Hsieh, M.C., Liang, W.T. & Tsai, C.L., 2011. An automatic system for the determination of earthquake focal mechanism and ground motion in Taiwan, S52A, 2011 AGU Fall Meeting, San Francisco, CA, USA.