Quick Slip Distribution Determination of Moderate to Large Inland Earthquakes Using Near-Source Strong Motion Waveforms

Kuo-Fong Ma 1)      Hsiang-Yi Wu 1)

1) Institute of Geophysics, National Central University, Tau Yuan, Taiwan

ABSTRACT

We developed a method on investigating the close-in displacement waveforms of moderate to large inland earthquakes from the deployed dense Taiwan Strong Motion Network (TSMN) to quickly determination of spatial slip distribution of earthquakes. The general well azimuthal coverage of the strong motion stations to the earthquakes provided us good opportunities to understand the detail characteristics of the earthquakes. On the basis of finite-fault modeling, we divided the fault into several subfaults and calculated its corresponding Green's function by considering a triangle source time function for a half-space media for the close-in stations to obtain the slip distributions on the faults for nine moderate-large (M5.0 ~ 7.3) earthquakes. The results provide the information on the spatial slip distribution with the actual ruptured dimension, average amount of slip and estimation of stress drop. In addition to that, this study also shows the possibility on determination of actual ruptured plane from focal mechanism by considering the fault rupture directivity. The quick determination of fault rupture will, thus, provide good information on understanding the rupture behavior of earthquakes in Taiwan. The subsequence studies on this analysis will, thus, provide the understanding of earthquake scaling characteristics in Taiwan.

INTRODUCTION

Since the deployment of the Taiwan Strong Motion Network (TSMN), hundreds and thousands earthquakes had been well recorded by the network [1,2]. For inland large earthquakes, near-source strong motion waveforms usually recorded very nice waveforms representing the source of the earthquake rupture. These waveforms provided good opportunities on quick analysis on fault rupture characteristics using finite-fault model. Finite-fault source studies have been important in providing information
beneficial to a wide range of seismological investigations and earthquake engineer applications. The fault rupture behavior analysis provided insight into understanding the consistencies and variations of rupture kinematics and dynamics from event to event. Although Taiwan region is a highly seismic activity region, the finite-fault rupture models studies for understanding the spatial and temporal details of the earthquake rupture process has not yet well developed. One reason for that is no well recorded waveform available for studying the detail source rupture process before the installation of TSMN.

The methodology employed in this study is a constrained, damped, least-squares inversion of waveform data for retrieval of the faulting history [3]. For inland moderate-large earthquakes, many near source strong motion stations, which having the epicentral distances of about 10 to 20km and have well azimuthal coverage to the epicenter of the earthquake, recorded nice waveform of the earthquakes. For such short paths, the propagation effects can be ignored, the strong motion waveforms, especially SH wave, exhibit clear source terms in their displacements waveforms. These waveforms provided us a good opportunity to understand the source parameters and the rupture process of the earthquake without needing the detail knowledge on the velocity structure, which is rather complex in the collision tectonic environment. In this study, for the finite-fault study, we considered the near source displacement waveforms, the waveforms of each subfault can be approximated by using a simple half space velocity model with a triangle source time function to resolve source properties of the earthquake. Figure 1 shows the distribution of the earthquakes investigated in this study. Table 1 lists the locations and magnitudes of the earthquakes. The magnitudes studied here ranged from 5.0 to 7.3.

Table 1  Earthquake locations, magnitudes, and focal mechanisms of nine moderate-large earthquakes

<table>
<thead>
<tr>
<th>No.</th>
<th>Time (yr/mon/day) (hr/min/sec)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>Magnitude (ML)</th>
<th>Focal Mechanism (dip, rake, strike)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93/12/15 09:23:00.00</td>
<td>23.194</td>
<td>120.507</td>
<td>15.21</td>
<td>5.7</td>
<td>(84, 48, 200)</td>
</tr>
<tr>
<td>2</td>
<td>94/04/06 01:12:11.09</td>
<td>23.533</td>
<td>120.421</td>
<td>13.44</td>
<td>5.03</td>
<td>(10, 70, 160)</td>
</tr>
<tr>
<td>3</td>
<td>94/06/05 01:09:30.09</td>
<td>24.468</td>
<td>121.787</td>
<td>5.13</td>
<td>6.2</td>
<td>(8, 81, 87)</td>
</tr>
<tr>
<td>4</td>
<td>95/07/14 16:52:46.48</td>
<td>24.368</td>
<td>121.743</td>
<td>9.83</td>
<td>5.8</td>
<td>(10, 90, 270)</td>
</tr>
<tr>
<td>5</td>
<td>95/10/31 22:27:06.94</td>
<td>23.291</td>
<td>120.359</td>
<td>10.65</td>
<td>5.19</td>
<td>(80, 50, 0)</td>
</tr>
<tr>
<td>6</td>
<td>98/07/17 04:51:14.96</td>
<td>23.500</td>
<td>120.660</td>
<td>6.02</td>
<td>6.2</td>
<td>(110, 50, 45)</td>
</tr>
<tr>
<td>8</td>
<td>99/10/22 02:18:56.90</td>
<td>23.515</td>
<td>120.426</td>
<td>16.64</td>
<td>6.4</td>
<td>(120, 50, 40)</td>
</tr>
<tr>
<td>9</td>
<td>99/10/22 03:10:17.48</td>
<td>23.533</td>
<td>120.431</td>
<td>16.74</td>
<td>6.0</td>
<td>(0, 80, 150)</td>
</tr>
</tbody>
</table>
Fig. 1 Locations of the moderate-large earthquakes used in the analysis and the distribution of Taiwan strong motion stations used in this study. The strong motion stations used for corresponding earthquakes are shown by different colors. The focal mechanisms of the earthquakes are also shown by lower hemisphere equal area projection.

DATA

For each earthquake, we chose the stations by considering the quality of data, epicentral distances and the azimuthal coverage to the earthquake. The stations are near source and have well azimuthal coverage to the earthquake. They usually have epicentral distances of less than 20km and have azimuthal coverage of about 200 degree to the earthquake. The stations used in the analysis for corresponding earthquakes are also shown in Fig. 1. We integrated the acceleration records twice into displacement and rotated them into radial and transverse components. Since the transverse component is the most pure path, where the P and S waves will not convert to each other to cause complicate waveforms, we concentrated our analysis in transverse component. We high pass the data with corner frequency of 0.05Hz using Butterworth filter to remove baseline drift. In order not to disturb the original signals as SH waveforms, the records after high pass filter still show the little baseline drift effect.

RUPTURE ANALYSIS

Using a finite fault inversion technique, we inverted the near source displacement waveform data to determine the slip distribution on the fault plane. We tested the focal mechanism parameters if it is necessary and rupture velocity to try to find the best fitting model for the waveforms. The focal mechanisms of the earthquakes (Fig. 1) used in this study were basically from first motion results of Central Weather Bureau (personal communication) or from moment tensor results of BATS (Kao and Jian, 2001). The determination of fault plane was from the distribution of the aftershocks. For the event, which fault plane was difficult to define, two fault planes were both examined in the analysis. We divided the fault area into several subfaults. The dimension of the subfault was determined arbitrarily depending on the size of the earthquake. We calculated the corresponding Green’s function of each subfault by considering a triangle source time function for a half-space media. The Green’s function, which is now a single triangle source time function, is simply based on the method developed by Ma and Kanamori.
For the short epicentral distance, the contamination from the path can be ignored and the waveforms present the effect of the source. Thus, the observed displacement SH waveforms can be modeled by considering the composing of the triangle source time functions on each subfault. This slip function was chosen based on a comparison of the synthetic displacement-pulse width for a single subfault with the shortest-duration displacement-pulse width observed. The directivity effect on the pulse width, \( W(\theta) \), at the stations are taken into account in the Green's function calculations as

\[
W(\theta) = \frac{L}{V_r} \left[ \cos(\theta) \sin(i_h) \sin(i_r) - \cos(i_h) \cos(i_r) \right] / \beta
\]

where \( \theta \) is the angle between stations and the strike of the fault, \( i_h \) is the take-off angle, and \( i_r \) is the rupture angle of the rupture front. \( L \) is the length of the fault. \( V_r \) is the rupture velocity. \( \beta \) is the S-wave velocity. The starting time of each subfault is computed by considering the circular rupture model with constant rupture velocity and the distance between the subfault and the station.

We apply the inversion procedure developed by Mori and Hartzell [6] to determine the slip distribution on the fault. The slip \( (x) \) was determined on each subfault by solving the following equation using a least squares inversion with a positive constraint [7].

\[
A x = B
\]

where \( A \) is the matrix of Green's functions and \( B \) is the vector containing the data. The fit of the data to the model was evaluated using the variance \( (\sigma) \).

\[
\sigma = \frac{(A x - B)^2}{N}
\]

where \( N \) is the number of degrees of freedom.

\[
N = n_{\text{data}} - n_{\text{sol}} - 1
\]

where \( n_{\text{data}} \) is the number of data points used in the time series and \( n_{\text{sol}} \) is the number of subfaults that had nonzero slip. For the inversion, all of the waveforms were normalized to the same moment, to give each station equal weight. The inversion result gives the amount of seismic moment \( (M_0) \) released on each subfault, \( i \). The amount of slip on each subfault \( (D^i) \) is then estimated by

\[
D^i = M_0^i / \mu S
\]

where \( \mu \) is the rigidity as \( 3 \times 10^{11} \) dyne/cm\(^3\) and \( S \) is the area of the subfault.

### SLIP DISTRIBUTIONS

(1) 1993/12/15 M5.7

This earthquake occurred at the latitude of 23.19° and longitude of 120.51° with focal depth of 15.21km. This earthquake has focal mechanism of strike = 200°, dip = 48°, rake = 84° [8]. The displacement SH waveforms are shown in Fig. 2(a). The aftershock distribution exhibited the western dipping plane as the possible rupture plane. Figure 3(a) shows the determined slip distribution of the fault plane. Most of the slip occurred within an area with a dimension of 7 \( \times \) 7km. This earthquake was bilaterally ruptured. The largest slip was about 3m located about 1km northeast of the hypocenter. Figure 2(a) also shows the comparison of the synthetics to the observed waveforms. The synthetics can explain the observations generally well. The seismic moment determined from this analysis is \( 3.8 \times 10^{24} \) dyne-cm. The average slip...
within the region of 9km in length and 7km in width is about 25.9cm. The corresponding stress drop using dip-slip model is about 27bars.

(2) 1994/04/06 M5.03

This earthquake occurred at the latitude of 23.53° and longitude of 120.42° with focal depth of 13.44km. This earthquake has a strike-slip focal with strike = 160°, dip = 70°, rake = 10° from first motion data of strong motion waveforms. The displacement SH waveforms are shown in Fig. 2(b).
The aftershock distribution is too less and sparse to determine the rupture plane. We did our calculations for the both fault planes. Figure 3(b) shows the determined slip distribution of the one fault plane with smaller variance. Figure 2(b) show the comparison of the synthetics to the observations. Actually, the results from both fault planes show a generally good fit to the observation. It implies the difficulty of determination of the real rupture plane for this earthquake. Both of the determined slip distributions exhibit a small rupture region with a dimension of only about $1 \times 1$ km. The average slips from both fault
planes are about 15cm and 21.5cm, respectively. The corresponding stress drops are 78.8bars and 143.6bars. The seismic moment is about $7.8 \times 10^{22}$ dyne-cm.

(3) 1994/06/05 M6.2

This earthquake occurred at the latitude of 24.47° and longitude of 121.79° with focal depth of 5.13km. This earthquake has focal mechanism of strike = 87°, dip = 81°, rake = 8° (Shin, 1996). The displacement SH waveforms are shown in Fig. 2(c). The aftershock distribution exhibited the east-west striking plane as the possible rupture plane. Figure 3(c) shows the determined slip distribution of the fault plane. Most of the slip occurred within an area with a dimension of 14 × 14km. This earthquake was bilaterally ruptured. The largest slip was about 6m located about 2km east of the hypocenter. Figure 2(c) shows the comparison of the synthetics to the observed waveforms. The synthetics can explain the observations generally well. This earthquake has a seismic moment of about $3.3 \times 10^{25}$ dyne-cm. The average slip is about 26.6cm for a dimension of 25km in length and 16km in width and with a stress drop of about 9.5bars. If we consider the fault with dimension of 15km in length and 13km in width, the average slip will be about 56.7cm and the stress drop will be about 29.7bars.
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(4) 1995/07/14 M5.8

This earthquake occurred at the latitude of 24.37° and longitude of 121.74° with focal depth of 9.8km. This earthquake has focal mechanism of strike = 270°, dip = 90°, rake = 10°. The aftershock distribution exhibited the east-west striking plane as the possible rupture plane. Figure 3(d) shows the determined slip distribution of the fault plane. Most of the slip occurred within an area with a dimension of 4 × 5km. The average slip in this region is about 11cm with a stress drop of about 20bars. Figure 2(d) shows the comparison of the synthetics to the observed waveforms.

(5) 1995/10/31 M5.2

This earthquake occurred at the latitude of 23.29° and longitude of 120.36° with focal depth of 10.6km. This earthquake has focal mechanism of strike = 0°, dip = 50°, rake = 80°. The aftershock distribution was rather sparse to determine the actual rupture plane. The results obtained from both fault planes reveal similar feature. Figure 3(e) shows the determined slip distribution of one of the two fault planes. Most of the slip occurred within an area with a dimension of 2 × 2km. The average slip in this region is about 20 ~ 25cm with a stress drop of about 67 ~ 88bars. Figure 2(e) shows the comparison of the synthetics to the observed waveforms.

(6) 1998/07/17 M6.2

This earthquake occurred at the latitude of 23.50° and longitude of 120.66° with focal depth of 6km. This earthquake has focal mechanism of strike = 45°, dip = 50°, rake = 110°. The displacement SH waveforms are shown in Fig. 2(f). The aftershock distribution suggests that a northeast-southwest striking plane as the possible rupture plane. The results from finite-fault modeling show most of slip occurred within 10km of the hypocentral area as shown in Fig. 3(f). The seismic moment is about $7.4 \times 10^{24}$ dyne-cm. This earthquake was bilaterally ruptured. The largest slip was about 5m. The slip distribution is rather heterogenous over the fault plane. Figure 2(f) also shows the comparison of the synthetics to the observed waveforms. The synthetics can explain the observations generally well. The average slip is about 30.6cm for a dimension of 10km in length and 8km in width and with a stress drop of about 25bars.

(7) 1999/09/21 M7.3

This earthquake is the largest earthquake in last century. It occurred at the latitude of 23.85° and longitude of 120.82° with focal depth of 8km. This earthquake was a best recorded earthquake in the world in the modern seismology. It also provides us an opportunity of testing our quick analysis technique for a large earthquake. This is also the only earthquake studied so far of producing surface rupture. This earthquake ruptured along Chelungpu fault with a length of approximately 80km in north-south strike direction and extended toward northeast for about 20km. The detailed study on the rupture behavior of earthquake can be seen in several recent studies (e.g., [9]). The present study of this earthquake is trying to obtain the spatial slip distribution on a quick slip determination basis. The result from this can be tested by detailed slip distribution analysis as studied by Ma, et al. [9,10].

The displacement SH waveforms are shown in Fig. 2(g). Since there are many very close by strong motion stations recorded the near-field static
displacement. For half-space far-field SH waveform modeling, for this earthquake, we high-passed the waveforms at the 0.1Hz. Also, for the quick analysis basis, we only consider single-planar fault for the finite-fault modeling. The results from finite-fault modeling show a large asperity within 30 to 60km north of the hypocenter as shown in Fig. 2(g). The largest slip is up to about 15m. Most of slip concentrates at the shallow region with depth less than focal depth. Compared with the results from Ma, et al. [10], the results obtained from the quick analysis basis show similar slip distribution pattern. It suggests the reliability of this technique. The seismic moment is about $2.8 \times 10^{27}$ dyne-cm. The average slip over the fault plane of 100km in width and 40km in width is about 2.4m with dynamic stress drop of about 27bars. Figure 2(g) also shows the comparison of the synthetics to the observed waveforms. The synthetics can explain the observations generally well.

(8) 1999/10/22 M6.4

This earthquake occurred one month after the occurrence of the 1999. Chi-Chi (921) earthquake. It occurred at the latitude of 23.52° and longitude of 120.43° with focal depth of 16.6km. The focal mechanism of this earthquake is not well determined. The strike was within $170^\circ \sim 180^\circ$, dip $= 33^\circ \sim 66^\circ$, rake $= 120^\circ \sim 143^\circ$. The displacement SH waveforms are shown in Fig. 2(g). The aftershock distribution suggests that a north-south striking plane as the possible rupture plane. We tested several different dip and rake angles and obtained the dip angle of 42° and rake of 60° having the best fit to the waveforms. The results from finite-fault modeling show most of slip occurred within 4km above the hypocentral as shown in Fig. 3(g). The seismic moment is about $2.2 \times 10^{25}$ dyne-cm. Figure 2(f) also shows the comparison of the synthetics to the observed waveforms. The synthetics show better fit for the stations in southwestern but for the stations in northeast. The average slip is about 127cm for a dimension of 8km in length and 7km in width and with a stress drop of about 125bars.

(9) 1999/10/22 M6.0

This is the largest aftershock of the occurrence of last discussed earthquake. This earthquake occurred at the latitude of 23.53° and longitude of 120.43° with focal depth of 16.7km. This earthquake has very similar location to the previous one. But, the focal mechanism shows a strike-slip fault mechanism instead of thrust fault as previous one. The focal mechanism determined from first motions has strike $= 60^\circ$, dip $= 90^\circ$, rake $= 170^\circ$. The displacement SH waveforms are shown in Fig. 2(h). The aftershock distribution is rather sparse to determine the rupture plane. We did the modeling for both fault planes. The results show that the fault plane with strike of 60° give better fit to the waveforms suggesting it is an actual rupture plane. This earthquake demonstrates the ability of determination of actually rupture plane through our slip distribution analysis. However, this ability is good for strike-slip focal mechanisms due to the consideration on fault rupture directivity. For thrust-fault mechanism, the directivity effects to the two faults are rather similar and it becomes difficult to deviate the actual rupture plane from the auxiliary fault plane. From the more detail waveform modeling, we modified the fault plane to 45°. The slip distribution show most of slip occurred at 5km
southwest of hypocenter as shown in Fig. 3(h). The seismic moment is about $7.9 \times 10^{24}$ dyne-cm. Figure 2(f) also shows the comparison of the synthetics to the observed waveforms. The synthetics in general have good fit to the observations. The average slip is about 117cm for a dimension of 5km in length and 4.5km in width and with a stress drop of about 180bars.

**CONCLUSIONS**

The results from the studies on nine moderate-large earthquakes show the ability of quick slip distribution of earthquakes on the basis of using near source strong motion SH waveforms. In addition to that, the rupture analysis also shows the possibility on the determination of actual rupture plane through the calculation of rupture directivity effect. The slip distribution determinations of moderate-large earthquakes provide the important information on the understanding of fault rupture behavior. The subsequent studies on the earthquake rupture behavior analysis can help us to understand the activity of the existed active faults and blind faults in Taiwan, which is important on evaluation of earthquake hazard. The static results of these studies also will provide the earthquake scaling information for further strong ground motion prediction studies. The future studies on this work will be continuous on analysis of slip distribution of earthquakes toward faster and reliable calculations.

**REFERENCES**