A new technique for moment tensor inversion with applications to the 2008 Wenchuan M_S 8.0 earthquake sequence*

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Abstract

A M_S 8.0 earthquake occurred in Wenchuan County, Sichuan Province, China, on May 12, 2008, and subsequently, numerous aftershocks followed. We obtained the moment tensor solutions and source time functions (STFs) for the Wenchuan earthquake and its seven larger aftershocks (M_S 5.0~6.0) by a new technique of moment tensor inversion using the broadband and long-period seismic waveform data from the Global Seismic Network (GSN). Firstly, the theoretical background and technical flow of the new technique was briefly introduced, and an aftershock of the Wenchuan earthquake sequence was employed to illustrate the real procedure for inverting the moment tensor; secondly, the moment tensor solutions and STFs of the eight events, including the main shock, were presented, and finally, the interpretation of the results was made. The agreement of our results with the GCMT results indicates the new approach is efficient and feasible. By using this approach, not only the moment tensor solution can be obtained but also the STF can be retrieved; the inverted STFs indicate that the source rupture process may be complicated even for the moderate earthquakes. The inverted focal mechanisms of the Wenchuan earthquake sequence show that the most of the aftershocks occurred in the main faults of the Longmenshan fault zone with predominantly thrusting with minor right-lateral strike-slip component, but some of them may have occurred in the sub-faults with strike-slip faulting in the vicinity of the main faults.

Key words: moment tensor inversion; Wenchuan earthquake; source time function; focal mechanism

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Introduction

At 14:28 on May 12, 2008 (Beijing Time), a M_S 8.0 major earthquake occurred in Wenchuan County, Sichuan Province, China. The earthquake caused 87 000 people dead and missing, more than 100 cities or towns collapsed or damaged, which has been the heaviest losses of lives and properties in Chinese mainland since the great 1976 Tangshan earthquake. After the main shock, thousands of aftershocks followed. By May 29, 5052 aftershocks had occurred, including 890 af-

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tershocks of $M_S \geq 3$, 156 aftershocks of $M_S \geq 4$, and nine aftershocks of $M_S \geq 5.4$. Because of the data quality, only seven of the $M_S \geq 5.0 \sim 6.0$ aftershocks and the main shock have been studied in this paper (Figure 1).

Figure 1 The epicentral distribution of the great Wenchuan earthquake of May 12, 2008, and its aftershocks. Green circles denote 890 $M_S \geq 3.0$ aftershocks determined by the Sichuan Province Seismic Network; red circles denote the main shock and strong aftershocks studied in this paper, and the corresponding numerals are referred in Table 1. Red lines and blue lines represent active faults and inactive faults, respectively.

Study on source parameters of earthquakes has been very important in seismological research, and furthermore the source parameters are important data to other studies. For example, the parameters obtained from moment tensor inversion have been used in the studies on the relation between seismic moment and occurrence frequency (Frohlich and Davis, 1993; Kagan, 1997; Sornette and Knopoff, 1996), the global distribution of non-double-couple sources (Kawakatsu, 1991), the earthquake classification (Reasenber, 1999), the variation of crustal potential energy (Tanimoto *et al*, 2000), the temporal correlations of focal mechanisms (Kagan, 2000). Therefore, accurate and fast determination of source parameters appears very important.

Soon after the Wenchuan earthquake, the Global Centroid Moment Tensor (GCMT) Project, the U.S. Geological Survey (USGS) and the Institute of Geophysics, China Earthquake Administration (CEA-IGP) released the moment tensor results rapidly. These results all indicated that the Wenchuan earthquake was a thrust faulting with a small right-lateral strike-slip component. However, these results were all obtained based on an assumption of triangular impulse source time function (STF). In order to investigate the complexity of STF, as well as to deeply study on the

focal mechanisms of the Wenchuan earthquake and its aftershocks, we took advantage of a newly developed technique to invert for the STFs and moment tensor solutions directly from the observed waveform data under the assumption that all the components of moment tensor have the same time history.

The epicenter of the Wenchuan earthquake was located in the Longmenshan fault zone, eastern edge of the Tibetan Plateau. The Longmenshan fault zone is a large one striking NE-SW direction, about 500 km long and 30~50 km wide (CHEN *et al.*, 2007). The Longmenshan fault zone contains the rear Longmenshan fault (Maoxian-Wenchuan fault), the central fault (Yingxiu-Beichuan fault) and the fore Longmenshan fault (Pengxian-Guanxian fault) (Figure 1). The faults are dominated by thrusting movement with right-lateral strike-slip component, and the right-lateral strike-slip component is getting more with going to northeast segment (CHEN *et al.*, 2007).

In this paper, firstly we will briefly introduce a new technique for moment tensor inversion, that is, the synchronous source, employed one of the aftershocks to illustrate the practice of the inversion process; and then we will present the moment tensor solutions, the STFs and the best double-couple (DC) solutions of the Wenchuan earthquake and its aftershocks, and others inverted using the new technique; finally, the interpretation on the results was made.

1 Data and its processing

The digital waveform data used in this study were all from the IRIS (Incorporated Research Institutions of Seismology) data center. The selection of data was made according to the following three criteria: ① high signal-to-noise ratio; ② evenly azimuthal coverage of stations; ③ 10° ~ 85° range of epicentral distances. In general, the greater the earthquake magnitude, the more the available stations. Thus, the epicentral distance range can be larger and the station coverage can be better for larger earthquakes. Since different earthquakes had different source sizes, which generate different dominant frequency signals, we used various parameters in processing waveform data of different earthquakes (Table 1). Considering the long duration of the Wenchuan main shock and its dominant low-frequency components, we selected the long-period (LP) recordings with the better low-frequency response in performing the moment tensor inversion of the main shock. And considering that the horizontal recordings get more interfered, we used the P-waveforms of the vertical component only.

In this study, we used the standard global velocity structure model (Kennett and Engdahl, 1991) and the reflectivity method (Kennett, 1983) to calculate the Green functions to be used.

Table 1 Origin times, epicentral locations and data-processing parameters of the great Wenchuan earthquake of May 12, 2008, and its seven larger aftershocks

Event No.	Date a-mo-d	Origin time (UTC) h:min:s	Epicentral location		M_s	Sampling rate/Hz	Frequency range/Hz	Data length/s	Number of stations used	Mean correlation coefficient
			$\lambda_E/^{\circ}$	$\varphi_N/^{\circ}$						
1	2008-05-12	06:28:00.00	103.367	31.021	8.0	1	0.0200~0.005	140	37	0.79
2	2008-05-12	20:08:48.73	103.834	31.428	5.6	5	0.0625~0.005	35	13	0.83
3	2008-05-13	07:07:08.26	103.113	30.734	5.9	5	0.0625~0.005	35	11	0.88
4	2008-05-14	02:54:38.00	103.495	31.332	5.4	5	0.0625~0.005	35	6	0.76
5	2008-05-16	05:25:19.22	103.336	31.333	5.5	5	0.0625~0.005	35	9	0.91
6	2008-05-17	05:25:19.22	104.883	32.155	5.7	5	0.0625~0.005	35	19	0.90
7	2008-05-25	08:21:48.00	105.456	32.577	5.8	5	0.0500~0.005	45	19	0.77
8	2008-05-27	08:37:51.00	105.618	32.730	5.7	5	0.0625~0.005	35	11	0.82

2 The technique of the synchronous source moment tensor inversion

In the case of the point source approximation, the ground motion caused by an earthquake is expressed by (Gilbert and Dziewonski, 1975)

$$U_i(\mathbf{r}, t) = \sum_{k=1}^6 G_{ik}(\mathbf{r}, t; \mathbf{r}_s) * M_k(t) \quad (1)$$

where $U_i(\mathbf{r}, t)$ is the i -th recorded seismic phase; $\mathbf{r}$, the station location; $\mathbf{r}_s$, the source location; $G_{ik}(\mathbf{r}, t, \mathbf{r}_s)$, the Green functions corresponding to the i -th record and k -th component of moment tensor; and $M_k(t)$ represents the six components of the moment tensor. Theoretically, the time-dependent components of moment tensor can be directly obtained according to equation (1). However, due to the large number of the unknowns and the errors in the Green functions and observed data, the inversion is often unstable.

The number of the unknowns should be rationally reduced to stabilize the inversion. In general, we assume all the components of moment tensor have the same time history, *i.e.*, synchronous source (Lay and Wallace, 1995), and in solving process based on the equation (1), we impose reasonable constraints to obtain the six independent moment tensor components with the same time history $s(t)$.

The constraint on STF function could be imposed with following iteration scheme (ZHANG, 2008)

Step 1. Separate the time history $s_k(t)$ and the amplitude M_k of the k -th component. In the following, the superscript n denotes the n -th iteration.

$$M_k^{(n)}(t) = \frac{\int M_k^{(n)}(t) dt}{\left| \int M_k^{(n)}(t) dt \right|} M_k^{(n)} s_k^{(n)}(t) \quad (2)$$

Step 2. Produce the same time history $s(t)$ from the time histories of the six components.

$$s^{(n)}(t) = \frac{\sum \{(M_k^{(n)})^2 [s_k^{(n)}(t) + s_k^{(n)}(t)] / 2\}}{\sum (M_k^{(n)})^2} \quad (3)$$

Step 3. Apply the same time history to the six components of moment tensor.

$$M_k^{(n+1)}(t) = \frac{\int M_k^{(n)}(t) dt}{\left| \int M_k^{(n)}(t) dt \right|} M_k^{(n)} s^{(n)}(t) \quad (4)$$

By the iteration scheme described by the equations (2) to (4), we can obtain the STF.

As the $s(t)$ is given, the ground motion can be rewritten into

$$U_i(\mathbf{r}, t) = \sum_{k=1}^6 [G_{ik}(\mathbf{r}, t; \mathbf{r}_s) * s(t)] \cdot M_k \quad (5)$$

where the unknowns becomes six scalars M_k , representing the amplitude of six moment tensor components. Following the inversion procedure described above, we can obtain the time dependent moment tensor solutions.

Comparing with the widely referenced GCMT solutions (Dziewonski and Woodhouse, 1983), our inverted results provide not only the STF but also the general moment tensor solution includ-

ing both deviation and isotropic (ISO) components.

In the next, we will take the $M_s 5.9$ event occurred at 15:07 on May 13, 2008, as an example to illustrate the general steps of the synchronous source moment tensor inversion.

1) Data selection. According to data quality, the stations with high quality data are selected. For this event, we selected 11 stations of the broadband recordings. The station distribution is showed in Figure 2a.

2) Calculation of Green functions for all the stations. Six sub-waveforms on the left of Figure 2c are the Green functions at the station TLY.

Figure 2 The stations and waveforms at the stations (a); the normalized source time function (NSTF) obtained by waveform inversion (b); the Green functions at the station TLY before and after convolving with the NSTF (c) for the $M_s 5.9$ aftershock of May 13, 2008, G_{11} to G_{33} denote the normalized Green functions at the station TLY, $s(t)$, the NSTF, asterisk, convolution in time domain

3) Cutting the observed data and Green functions to be used in the inversion. Generally, this step can be automatically completed by the computer according to the calculated theoretical travel time, which is derived from origin time, station position and source location. But for those with smaller magnitudes, the epicentral distances of the stations with the usable data are smaller, and the theoretical travel times based on IASPEI 91 velocity model (Kennett *et al*, 1991) are not accurate enough to account for, so we had to select the data manually.

4) Retrieval of the STF. Using the equations (2) to (4), we retrieve the normalized source time function (NSTF) (Figure 2b) from the Green functions and observed data by the non-negative conjugate gradient method (Ward and Barrientos, 1986).

5) Performing the inversion for moment tensor solution. We convolve the original Green functions with the NSTF to get the convolved Green functions as shown in the right of Figure 2. Then, we obtain the moment tensor solution by the STF-fixed moment tensor inversion method (XU *et al.*, 2004).

6) Evaluation of the results. After the inversion is completed, we have to evaluate the result by comparing the synthetic waveforms with the observed waveforms. If the synthetic waveforms are very similar to the observed waveforms, the results are thought to be acceptable. Figure 3 shows the comparison of the synthetic with observed waveforms of the $M_s5.9$ event occurred at 15:07, May 13, 2008. It can be seen that there is a good similarity between the synthetic and observed waveforms at most of the stations. Among 11 stations, the correlation coefficients at nine stations are larger than 0.8, and those at seven stations are larger than 0.9.

Figure 3 Comparison of the synthetic with observed waveforms calculated using the inverted moment tensor solution for the $M_s5.9$ ($M_w5.8$) aftershock of 2008-05-13

The thick lines denote the observed waveforms while the thin lines denote synthetic waveforms. On the left of the each pair of waveforms are the maximum amplitudes of observed waveforms, the correlation coefficients and the maximum amplitudes of synthetic waveforms from top to bottom, respectively. On the right are the station, component and phase names from top to bottom, respectively

3 Moment tensor solutions and STFs of the Wenchuan earthquake sequence

We applied the technique described above to the data of the Wenchuan earthquake and its seven larger aftershocks occurred before May 27, 2008. Table 1 shows the basic information, the data-processing parameters and the average correlation coefficients for these earthquakes. Tables 2 and 3 shows the moment tensor solutions, DC components, ISO components, CLVD components, moment magnitude, and the best DC solutions derived from the moment tensor solutions. Figure 4 depicts the STFs and the geometric representation of the moment tensor solutions and DC solu-

tions. Figure 5 compares the result obtained by this study with the GCMT solutions.

Figure 4 Moment tensor solutions, best double-couple solutions and NSTF of the great Wenchuan earthquake of May 12, 2008, and the seven larger aftershocks

Figure 5 Comparison among the best double-couple (DC) components, isotropic (ISO) components and compensated-linear-vector-dipole (CLVD) components in the moment tensor solutions

The dark lines denote the best DC components while the light lines denote the ISO components. The percentages are the ratio of the ISO components to the deviation components, the ISO components in GCMT solutions are constrained to be 0, and the differences of the unit 1 minus the best DC components are just the CLVD components (Dahm, 1996).

From Table 2 and Figure 5, we can see that the DC components and moment magnitudes in our results are very consistent with the GCMT's results. The difference in the magnitudes of the main shock is 0.2, the difference in the magnitudes of the four aftershocks is 0.1, and there is no

difference for the rest three aftershocks. The moment magnitude of the main shock is also close to the magnitude $M_W 7.9$ obtained by the finite fault modeling (ZHANG, 2008). Also, we notice that there is a considerable consistency in the CLVD components. Except that there is large difference in the CLVD component for the larger aftershock No.1, that is, the May 12 $M_S 5.6$ ($M_W 5.6$) event, there is little difference for the other events (Figure 5).

Table 2 Comparison of moment tensor solutions of the great Wenchuan earthquake of May 12, 2008, and its seven larger aftershocks obtained by GCMT and this study

Event	M_{rr}	M_{tt}	M_{pp}	M_{rt}	M_{rp}	M_{tp}	M_{DC}	M_{EXP}	M_{CLVD}	Scalar /N·m	M_W	Source
1	1.71	0.24	-1.22	-0.03	1.09	-0.76	1.97	0.24	0.10	10^{21}	8.1	This study
1	5.63	0.26	-5.89	-2.85	6.20	-3.13	9.43	0	0.48	10^{20}	7.9	GCMT
2	3.25	-1.10	-0.36	-0.54	2.72	-0.47	3.32	0.60	-0.87	10^{17}	5.6	This study
2	2.31	0.46	-2.77	-0.68	1.43	-1.47	3.34	0	0.21	10^{17}	5.6	GCMT
3	-0.01	2.20	-0.78	-6.45	-0.46	4.82	6.07	-0.55	0.52	10^{17}	5.8	This study
3	4.85	0.34	-5.19	-0.26	1.27	-2.20	5.57	0	-0.50	10^{17}	5.8	GCMT
4	1.72	4.08	-2.06	-0.16	-0.39	1.05	3.27	1.25	0.24	10^{17}	5.6	This study
4	-0.47	1.92	-1.45	-0.46	0.04	0.76	1.89	0	-0.26	10^{17}	5.5	GCMT
5	-0.32	2.93	-2.55	-0.34	1.11	-0.60	3.05	0.02	0.01	10^{17}	5.6	This paper
5	-0.29	3.04	-2.75	-0.40	1.00	-0.74	3.19	0	-0.03	10^{17}	5.6	GCMT
6	7.15	-3.76	-2.03	-0.40	-0.32	-3.68	6.9	0.46	0.21	10^{17}	5.8	This study
6	4.76	-2.46	-2.29	-0.19	0.45	-2.92	5.06	0	0.24	10^{17}	5.7	GCMT
7	0.84	9.2	-6.4	2.5	-2.7	-3.85	9.4	1.22	-0.40	10^{17}	5.9	This study
7	0.11	1.13	-1.24	0.261	-0.05	-0.62	1.37	0	0.03	10^{18}	6.0	GCMT
8	-0.53	-0.11	0.36	-0.89	-1.01	-0.95	1.63	0.26	0.34	10^{17}	5.4	This study
8	-0.02	0.37	-0.36	-0.87	-1.26	-1.6	2.11	0	0.45	10^{17}	5.5	GCMT

From Table 2 and Figure 5, we can also see that the ISO components are contained in the moment tensor solutions of the Wenchuan earthquake and its aftershocks. Especially, the ISO component of the $M_S 5.4$ ($M_W 5.6$) aftershock on May 14 is as large as 35.6%.

From Table 3, the best DC solutions obtained by the two techniques are very close to each other. The two results all indicate that the Wenchuan earthquake is a mainly thrusting with a small right-lateral strike-slip component. Among the seven larger aftershocks, the $M_S 5.4$ ($M_W 5.6$) event on May 14, the $M_S 5.5$ ($M_W 5.6$) event on May 16, and the $M_S 5.8$ ($M_W 5.9$) event on May 25 are the mainly strike-slip faulting, and the rest four events have the similar focal mechanism solutions to the main shock.

By the technique introduced in this paper, not only the DC, ISO, CLVD components, but also the STF can be retrieved. The STFs shown in Figure 4 indicate that the source rupture process may be complicated even for the moderate earthquakes. The STF retrieved by the method of finite fault modeling indicates that the rupture process of the main shock can be divided into five stages. Stage 1 was first 14 s after initial rupture, about 9% of total moment was released; Stage 2 was from 14 s to 34 s; 60% of total moment was released; Stage 3 was from 34 s to 43 s, releasing about 8% of the total moment; Stage 4 was from 43 s to 58 s, releasing about 17% of the total moment; Stage 5 was from 58 s to the end (about 90 s), rupture began to heal and released about only 6% of the total moment (ZHANG, 2008). Comparing above-mentioned result to the result in this study, the STF we inverted contains stages 1 to 3, which are the major process of seismic moment releasing, and both of the STFs have peak values at about 26 s; however, the inversion did not exhibit the stages 4 and 5 which were relatively smaller, that implies the point source approximation in this study has certain limitation on inverting source process of earthquake as large

as the great Wenchuan earthquake. The STFs of the seven aftershocks appear different in shape, indicating that they have different moment release processes and source geometry. The STFs of the $M_S5.9$ ($M_W5.8$) event on May 13, the $M_S5.5$ ($M_W5.6$) event on May 16 and the $M_S5.5$ ($M_W5.8$) event on May 17 are very similar to each other, and the shapes of the STFs indicate that the source

Table 3 Comparison of the best double-couple solutions of the great Wenchuan earthquake of May 12, 2008 and its seven larger aftershocks obtained by this study and the GCMT

Event No.	Nodal plane I			Nodal plane II			<i>P</i> axis		<i>B</i> axis		<i>T</i> axis		Source
	Strike/ $^{\circ}$	Dip/ $^{\circ}$	Rake/ $^{\circ}$	Strike/ $^{\circ}$	Dip/ $^{\circ}$	Rake/ $^{\circ}$	Az/ $^{\circ}$	Pl/ $^{\circ}$	Az/ $^{\circ}$	Pl/ $^{\circ}$	Az/ $^{\circ}$	Pl/ $^{\circ}$	
1	220	32	118	8	63	74	110	16	16	14	246	68	This study
1	229	33	141	352	70	63	103	20	2	25	227	57	GCMT
2	222	22	125	5	72	77	105	26	9	12	256	61	This study
2	228	41	134	356	61	59	108	11	13	27	218	60	GCMT
3	209	45	106	6	47	74	107	1	17	12	202	78	This study
3	209	40	105	10	52	78	109	6	18	9	230	79	GCMT
4	36	90	-173	305	83	0	261	5	37	83	170	5	This study
4	212	78	178	303	88	12	77	7	312	78	168	10	GCMT
5	233	69	-170	139	81	-21	95	22	297	67	188	8	This study
5	233	71	-173	141	83	-19	96	18	303	69	189	9	GCMT
6	232	47	90	52	43	90	322	2	52	0	142	88	This study
6	232	44	99	40	46	82	136	1	46	6	235	84	GCMT
7	58	68	178	148	88	22	281	14	153	68	15	17	This study
7	58	82	171	149	81	8	104	1	197	78	14	12	GCMT
8	207	82	65	100	27	161	318	32	211	25	91	47	This study
8	89	64	-161	351	73	-27	308	31	141	58	41	6	GCMT

Figure 6 Epicenters of May 12, 2008 Wenchuan earthquake and its aftershocks, and the best DC solution of the main shocks and its seven larger aftershocks

Green circles denote 890 $M_S \geq 3.0$ aftershocks, and red circles, the main shock and its seven larger aftershocks in this study; the numerals are referred in Table 1. Red lines and blue lines represent active faults and inactive faults, respectively

models could be of circular model (CHEN *et al.*, 1976). The STF of the rest events reflect more complex source processes. Especially, the STF of the $M_S5.4$ ($M_W5.6$) event on May 14 seems to imply a complex rupture process. Firstly, there was a small moment release; next, the moment release almost ceased; then, there occurred a strong moment release in a very short time period; and finally, the faulting healed and stopped.

4 Discussion and Conclusions

The agreement of the best DC solutions and the CLVD components obtained using the technique introduced in this paper with those from the GCMT results indicates that the new technique of the synchronous source moment tensor inversion is efficient and feasible. Comparing with the technique used in the GCMT project, our technique not only produces the moment tensor solution but also the point-source STF. It is worth noting that using the observed STF is more realistic than using the triangular impulse STF in moment tensor inversion, therefore, the moment tensor solutions obtained by our technique retrieve more information of the source. However, the point-source approximation is still in use, so the STF may not describe a complete process of moment release if the earthquake duration is too long or the rupture extent is too large.

The inverted results indicate that the 2008 Wenchuan earthquake is a mainly thrusting with small right-lateral strike-slip component; except that the $M_S5.4$ ($M_W5.6$) event on May 14, the $M_S5.5$ ($M_W5.6$) event on May 16 and the $M_S5.8$ ($M_W5.9$) event on May 25 are mainly strike-slip faulting, the other four events have very similar focal mechanisms to the main shock. The spatial distribution and focal mechanisms of these earthquakes well fit the local tectonic feature (CHEN *et al.*, 2007, Figure 6). However, the spatial distribution of the three mainly strike-slip events also reflects the complexity of the fault structure of the Wenchuan earthquake of May 12, 2008. The two mainly strike-slip aftershocks, the $M_S5.4$ ($M_W5.6$) event on May 14 and the $M_S5.5$ ($M_W5.6$) event on May 16, both occurred near the epicenter where the aftershock zone shoots toward northwest, implying that here appear to be a strike-slip fault perpendicular to the main shock fault; the $M_S5.8$ ($M_W5.9$) strike-slip aftershock on May 25 occurred at the northern end of the Longmenshan fault zone, which also implies that there is a strike-slip branch of the Longmenshan fault zone.

In addition, special attention should be paid to the $M_W5.6$ aftershock on May 14. This event occurred near the epicenter where the aftershocks distributed along the northwest, its ISO component is as large as 35.6% to the deviation component, and its STF shape is also very peculiar. There are lots of sources the ISO components come from, however for spontaneous earthquakes, the complexity in fault geometry, such as deflection or bending of the fault strike and so on, is considered to be the main causes (Lay and Wallace, 1995). Combining with the peculiarity of the STF, we can estimate that this event was possibly caused by the dislocations of two faults which are very near to each other, one stronger while the other weaker.

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