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STRONG MOTION FROM A MODERATE SIZE CRUSTAL EARTHQUAKE AND ITS SOURCE CHARACTERISTICS

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SUMMARY

It is important for the quantitative strong ground motion prediction to model the earthquake source processes accurately. The 2001 Hyogo-ken Hokubu earthquake (Mw 5.2) occurred in the northern part of the Hyogo prefecture in southwest Japan. We estimate the source process of this event from inversion using the waveform data of the high-density strong ground motion observation networks. The source model obtained from the 0.4-2.0 Hz waveforms is relatively simple. In estimating the source process using waveform inversion, we calibrate the different velocity structures at the different stations from the forward modeling the observed waveforms of small aftershocks. This calibration enables us to estimate the accurate source model. The characteristics of the obtained source model of this event are consistent with the conventional scaling relations. The high-density strong motion records of this event will be an important dataset for studying the path and site effects in Kansai Area, since this study has presented the accurate source model.

INTRODUCTION

The Hyogo-ken Hokubu earthquake (Mw 5.2, M_{JMA} 5.6) occurred at 08:00:04.25 on 12 January 2001 JST (11 January, 23:00:04.25 UTC) in the northern part of Hyogo prefecture of southwest Japan. The 4th degree on the Japan Meteorological Agency (JMA) seismic intensity scale (the 6-7th degree on the modified Mercalli seismic intensity scale) was observed near the focal area and landslides were generated in two places.

The strong ground motions from crustal large earthquakes tend to cause huge urban disasters especially near the source fault. They are generally characterized by the three effects of source, path, and site. The strong ground motion data from moderate earthquakes can be used for the studies of path and site effects, since their source processes are relatively simple. On the other hand, the conventional studies have shown that the source effects on the strong ground motion are very large. Therefore, accurate modeling of the source processes of moderate size events is very important for quantitative strong ground motion prediction.

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However, few studies have ever tried to estimate the source processes of moderate or small earthquakes. One of the reasons for this is that the quantity and amount of the observed waveform data are not enough to study the source processes of small earthquakes. In Japan, National Institute of Earth Science and Disaster Prevention (NIED) developed the high-density strong ground motion observation networks of K-NET (Kinoshita [1]), KiK-net (Aoi [2]), and F-net (Fukuyama [3]). These networks provide us the strong ground motion data dense and high-quality enough to estimate source processes of moderate earthquakes. We estimate the source process of the 2001 Hyogo-ken Hokubu earthquake from inversion using these high-quality strong ground motion waveform data.

STRONG GROUND MOTION DATA USED FOR THE WAVEFORM INVERSION

We apply a waveform inversion to the near-source ground motion data of the 2001 Hyogo-ken Hokubu earthquake and estimate its detailed source process. We use strong ground motion data at five K-NET stations and one F-net station for analysis. The distribution of used stations is shown in Figure 1. The nearest station, HYG004, was only 8 km away from the source fault plane.

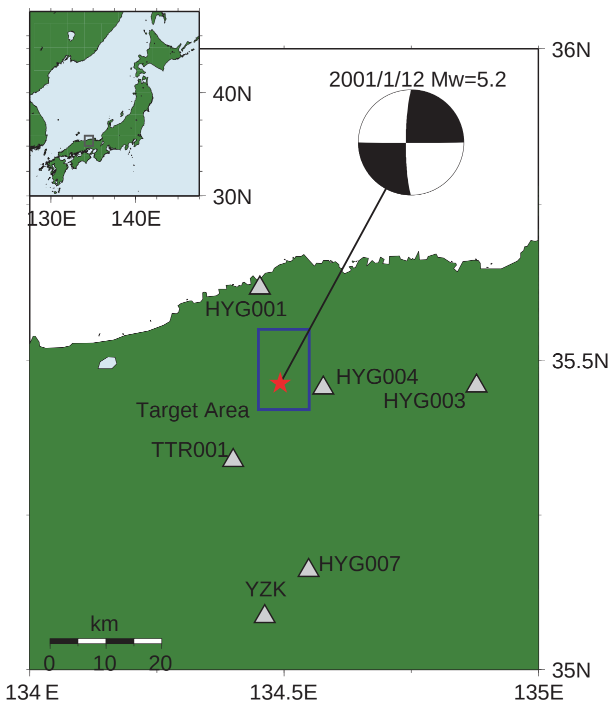

Figure 1. Station distribution used for the waveform inversion. The area in the blue rectangle is magnified in Figure 2. The red star shows the epicenter. Its focal mechanism is also shown. Triangles indicate the strong ground motion stations.

We use S-wave portion with time length of 4.0 sec of the 0.4-2.0 Hz velocity waveforms as the inversion data. Since theoretical Green's functions were unable to model the later phases of S-wave at HYG001 and TTR001, we use shorter time lengths of 2.7 sec and 2.5 sec, respectively, at these two stations. This will be described in more detail in the later part on the modeling the velocity structures for calculating Green's functions.

FAULT MODEL AND INVERSION METHOD

We adopt strike = 90°, dip = 89°, and the size of 6.0 × 5.0 km^2 for the fault plane model used for waveform inversion. We plot the epicenters of aftershocks for a month after the mainshock from the integrated hypocenter database by JMA in Figure 2. Although the distribution of aftershocks indicates two clear trends striking EW and NW-SE, respectively, we adopt the former strike by taking into account the focal mechanism of F-net shown in Figure 2. We divided this fault plane into 12 × 10 subfaults. The hypocenter of JMA database is used as the rupture starting point (longitude = 134.4928°, latitude = 35.4628°, depth = 10.59 km).

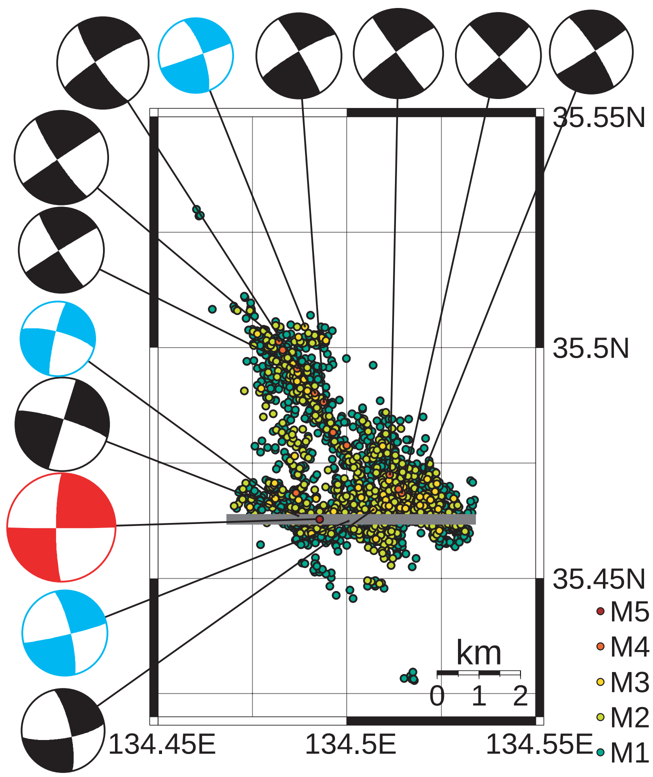

Figure 2. Epicentral distribution of aftershocks for a month after mainshock. The focal mechanism of the mainshock is red, aftershocks larger than Mw 4.0 are black and the events used for calibration of the velocity structures are blue. Gray rectangle shows the projection of the fault plane of the mainshock used for the waveform inversion.

We invert the waveform data using the multiple time-window analysis (Hartzell [4]). We put four time-windows with duration of 0.4 sec on each subfault. We constrain the rake angle variation within 172° +/- 45° using the non-negative constraint (Lawson [5]). The central rake angle of 172° is adopted from the focal mechanism of F-net. We adopted 2.4 km/sec (69 % of the S-wave) as the propagation velocity of the first time-window.

CALIBRATION OF STRUCTURE MODELS

In estimating source process using the waveform inversion, it is very important to use adequate Green's functions to extract information of source from the observed waveform data. For example, if the effect of amplification caused by sedimentary layers of the path is underestimated, the moment release on the source fault plane may be overestimated. Therefore, we search for different appropriate 1-D velocity structures at different stations from the forward modeling of the observed waveform of aftershocks. Selected aftershock events (Mw = 3.6, 20 January 2001; Mw = 3.6, 21 January 2001; Mw = 4.1, 1 February 2001), which are small enough to be modeled with a point source and close to the target event, are shown in Figure 2. We calibrate 1-D velocity structure models so that the theoretical waveform can fit the observed by trial and errors.

The small aftershocks used for the structure calibration are shown as gray focal mechanisms in Figure 2. We use F-net solution for the focal mechanisms and seismic moments in calculating the theoretical waveforms. In the structure model calibration based on forward modeling using the observed waveforms of small events, the velocity structure by Oike [6] and K-NET borehole drilling information are also referred to. Figure 3 shows the comparison of the observed waveforms and the two kinds of the theoretical waveforms at HYG001, HYG004, and TTR001. One theoretical waveform is for the modified velocity structure, and the other is for the structure of Oike [6], which has no soft layers. The theoretical waveform of HYG004, which is the closest station to the target event, is greatly improved by this structure model calibration. On the other hand, for HYG001 and TTR001, there still remain unnegligible misfits between the observed and theoretical waveforms in the later phases of S-wave. Therefore, for these two stations, we use shorter data time length for the waveform inversion so that these misfits in the later parts do not come into the time-window of the inversion target data. This is to avoid obtaining an inadequate source model due to the unmodeled S-wave later phase. The parameters of the velocity structure for each station used to calculate Green’s function are shown in Table 1.

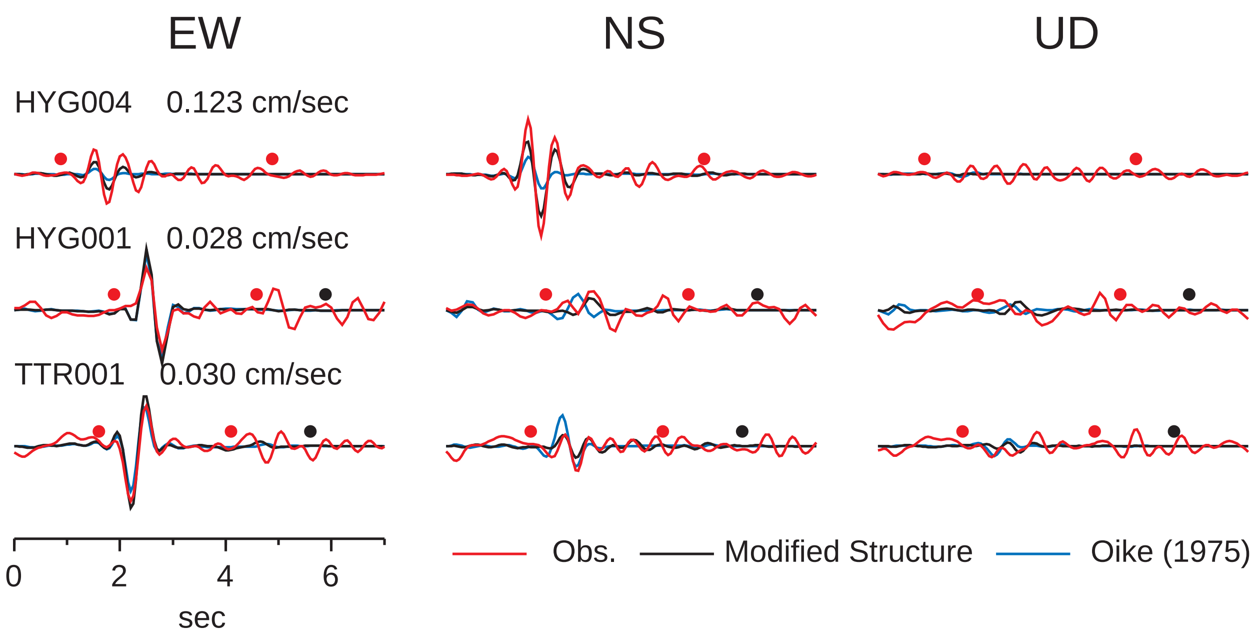

Figure 3. Comparison of the observed waveforms, the theoretical waveforms for the modified velocity structures, and the theoretical waveforms for the structure without surface layers (Oike, [6]) at HYG004, HYG001 and TTR001. The part between two red circles indicates the part of S-wave component used for the waveform inversion at each station. The part between the left red circle and black circle indicates the part of S-wave with time length of 4.0 sec at HYG001 and TTR001.

Table 1
Parameters of the velocity structures used to calculate Green's function

Depth (km)	Vp (km/sec)	Vs (km/sec)	Density (g/cm^3)	Qp	Qs	Depth (km)	Vp (km/sec)	Vs (km/sec)	Density (g/cm^3)	Qp	Qs
		HYG001						HYG003			
0.00	2.27	0.69	2.10	100	50	0.00	2.10	0.41	2.00	100	50
0.01	4.00	2.00	2.45	140	70	0.02	3.00	1.50	2.20	140	70
0.50	5.30	2.65	2.50	180	90	0.80	4.90	2.45	2.40	180	90
0.90	5.50	3.18	2.60	200	100	1.40	5.20	2.65	2.40	180	90
3.00	6.05	3.50	2.70	300	150	1.60	5.50	3.18	2.60	200	100
16.00	6.60	3.82	3.00	500	250	3.00	6.05	3.50	2.70	300	150
32.00	8.00	4.62	3.50	1000	500	16.00	6.60	3.82	3.00	500	250
						32.00	8.00	4.62	3.50	1000	500
		HYG004						HYG007			
0.00	2.06	0.78	2.20	100	50	0.00	2.00	0.71	2.17	100	50
0.11	4.90	2.45	2.50	180	90	0.02	4.70	2.35	2.45	160	80
1.20	5.50	3.18	2.60	200	100	0.40	5.10	2.55	2.50	180	90
3.00	6.05	3.50	2.70	300	150	0.50	5.20	2.60	2.50	180	90
16.00	6.60	3.82	3.00	500	250	0.60	5.30	2.65	2.50	180	90
32.00	8.00	4.62	3.50	1000	500	1.50	5.50	3.18	2.60	200	100
						3.00	6.05	3.50	2.70	300	150
						16.00	6.60	3.82	3.00	500	250
						32.00	8.00	4.62	3.50	1000	500
		TTR001						YZK			
0.00	1.58	0.30	2.30	100	50	0.00	1.20	0.60	2.00	100	50
0.01	4.10	2.05	2.40	160	80	0.06	1.40	0.70	2.05	110	55
1.90	4.80	2.40	2.50	180	90	0.07	5.10	2.55	2.50	180	90
2.80	5.50	3.18	2.60	200	100	0.60	5.50	3.18	2.60	200	100
3.00	6.05	3.50	2.70	300	150	3.00	6.05	3.50	2.70	300	150
16.00	6.60	3.82	3.00	500	250	16.00	6.60	3.82	3.00	500	250
32.00	8.00	4.62	3.50	1000	500	32.00	8.00	4.62	3.50	1000	500

INVERSION RESULTS

Figure 4 shows the slip distribution on the fault plane obtained from waveform inversion. The slip distribution is relatively simple. The largest slip occurs near the rupture starting point. Small slip is seen on the eastern part of the fault plane. This small slip is necessary especially to explain the waveform at HYG004. The maximum slip is 0.79 m. The total seismic moment is 1.3×10^{17} Nm (Mw 5.3). Figure 5 shows the comparison between the observed and synthetic waveform at each station. The waveform fitting is good. Figure 7 shows the snapshots of rupture propagation with 0.3 sec interval. The large slip near the rupture starting point lasts for about 1.0 sec and the total source duration time is about 2.4 sec.

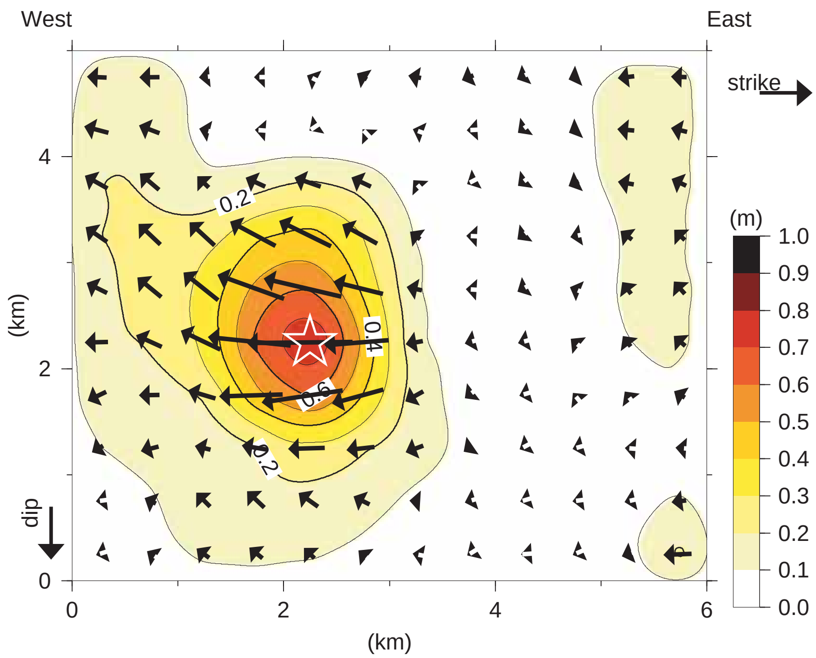

Figure 4. Slip distribution on the fault plane of the mainshock obtained from waveform inversion. The outlined star shows the rupture starting point. Vectors indicate the rake and amount of slip on each subfault.

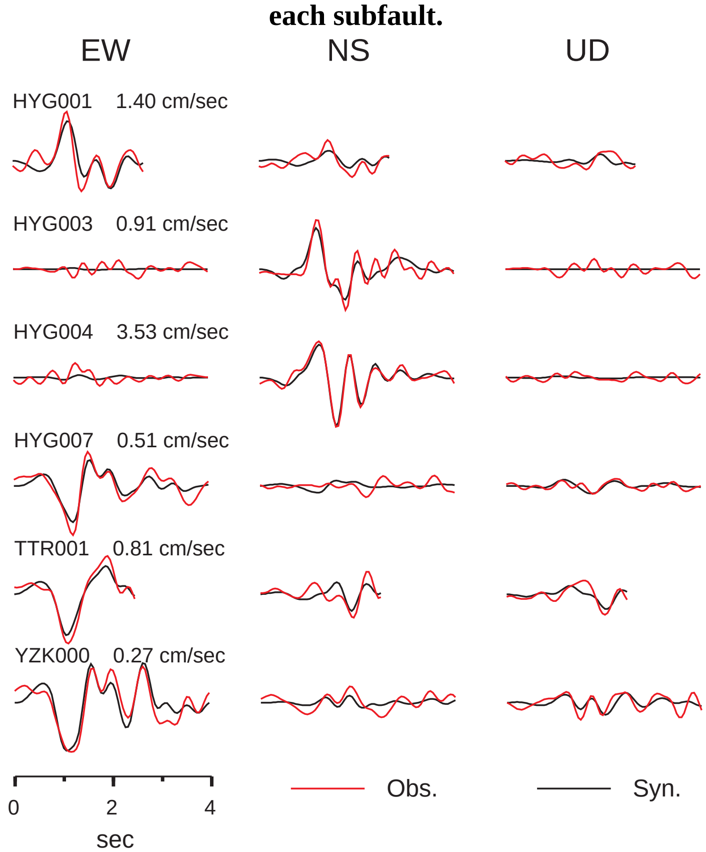

Figure 5. Comparison between the observed and synthetic waveforms. The value on the right-hand side of station name indicates the maximum amplitude of the observed waveform.

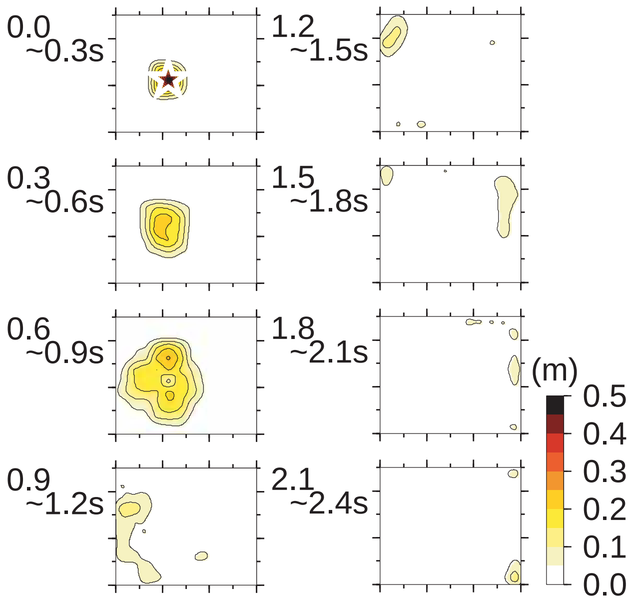

Figure 6. Snapshots of rupture propagation for every 0.3 sec. The interval of contour is 0.05 m.

Following Somerville [7], we extract an asperity area from the slip model of the 2001 Hyogo-ken Hokubu earthquake. Figure 7 shows the relation between the combined area of asperities and seismic moment of the events in California, Japan, etc. The value of the 2001 Hyogo-ken Hokubu earthquake is consistent with the relation of Somerville [7]. As to the scaling relation between the average slip and seismic moment, the 2001 Hyogo-ken Hokubu earthquake is consistent with the conventional relation, though its figure is not shown. Therefore, this earthquake can be concluded to have a typical source factor.

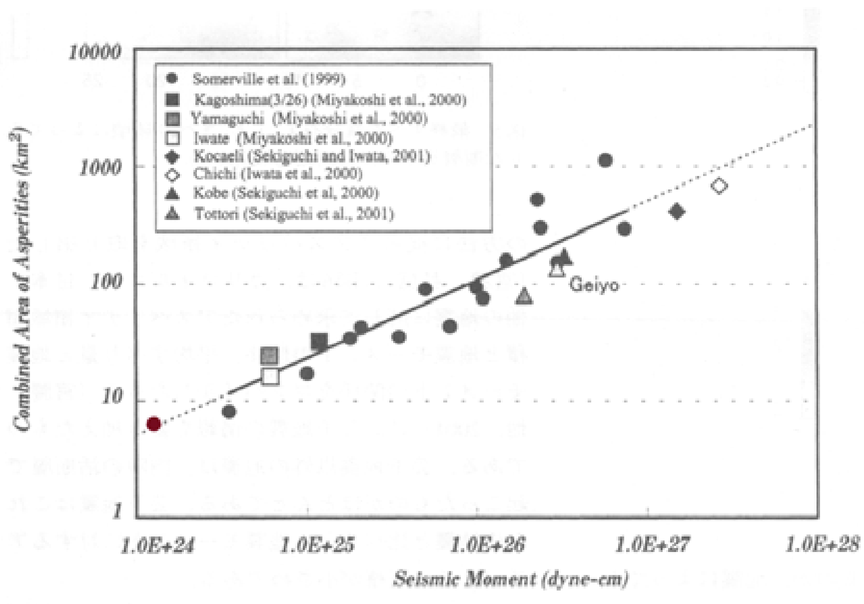

Figure 7. Relation between combined area of asperities and seismic moment. Red circle indicates the 2001 Hyogo-ken Hokubu earthquake. We add it to the Figure 6 (bottom) of Sekiguchi [8]. The line indicates the relation obtained originally by Somerville [7].

DISCUSSION

We estimate the source process of the 2001 Hyogo-ken Hokubu earthquake from waveform inversion using near-source strong ground motion data. The obtained source process is relatively simple. One of the reasons for this is that we can avoid inadequate complex source process by modeling the adequate 1-D velocity structures. In the preliminary study, we estimated the source process using the velocity structure without soft surface layers. As a result, we obtain more complex source process which has three large slip areas on the fault plane. The main cause of this is the neglect of reverberation and amplification due to the surface soft layers, especially at HYG004, which is the closest station to the target event. Thus, we see that using an inadequate simple velocity structure can bring an overestimation of heterogeneity and slip amount of source.

Since we have estimated the accurate source model from waveform inversion using the near-source strong ground motion data at the frequency band of 0.4-2.0 Hz, we will be able to evaluate the path and site effects in Kansai Area from the observed waveform data of this event. In fact, the strong ground motion data of this event were observed at many stations in Osaka basin including Kobe city and Kyoto basin.

However, if waveforms including higher frequencies than 2.0 Hz are used for the inversion, the more complex source process may be seen. Therefore, in the studies on the strong ground motion at such higher frequency band, effects of complex source process may be not neglect.

CONCLUSIONS

We have estimated the source process of the 2001 Hyogo-ken Hokubu earthquake from the inversion of the high-quality strong ground motion data. The slip distribution estimated from the inversion of the 0.4-2.0 Hz waveforms is relatively simple. The large slip area on the fault plane is seen around the rupture starting point. The characteristics of the obtained source model are consistent with the conventional scaling relations of Somerville [7].

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