ABSTRACT

In this study, I carried out source parameter estimation and strong motion simulation of the 2001 Geiyo earthquake (M$_{J}$6.7), Japan. Data obtained at 10 KiK-net stations located at 19 to 66 km in epicentral distance is used. To focus on the source modeling from near-field records without consideration about nonlinearity of soft surface layers, borehole records are targeted. First, to derive rough estimates of basic source parameters, I inverted spectral amplitude from the S-wave main portion of the mainshock and 12 aftershocks (M$_{J}$3.5 to 5.0). The moment magnitude, the corner frequency and the stress drop for the mainshock were estimated to be 6.3, 0.5 Hz and 377 bar, respectively. Next, using data from the largest aftershock (M$_{J}$5.0) as the empirical Green’s function, I estimated the relative moment release distribution on the fault plane and simulated the strong motion records targeting the mainshock in a range of 0.3 to 10 Hz. Waveform matching between synthesis and observed data seems to be satisfactory. The maximum amplitudes of observed horizontal components from 10 stations were in a range between 1.6 and 8.5 kine in velocity. At most of the stations, the observed maximum amplitudes were simulated within a factor of 2.
Strong Motion Simulation of the 2001 Geiyo (Mj6.7), Japan, Earthquake by Empirical Methods

M. Ohori1

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In this study, I carried out source parameter estimation and strong motion simulation of the 2001 Geiyo earthquake (Mj6.7), Japan. Data obtained at 10 KiK-net stations located at 19 to 66 km in epicentral distance is used. To focus on the source modeling from near-field records without consideration about nonlinearity of soft surface layers, borehole records are targeted. First, to derive rough estimates of basic source parameters, I inverted spectral amplitude from the S-wave main portion of the mainshock and 12 aftershocks (MJ3.5 to 5.0). The moment magnitude, the corner frequency and the stress drop for the mainshock were estimated to be 6.3, 0.5 Hz and 377 bar, respectively. Next, using data from the largest aftershock (MJ5.0) as the empirical Green’s function, I estimated the relative moment release distribution on the fault plane and simulated the strong motion records targeting the mainshock in a range of 0.3 to 10 Hz. Waveform matching between synthesis and observed data seems to be satisfactory. The maximum amplitudes of observed horizontal components from 10 stations were in a range between 1.6 and 8.5 kine in velocity. At most of the stations, the observed maximum amplitudes were simulated within a factor of 2.

Introduction

The 2001 Geiyo earthquake (Mj6.7) ruptured in the Philippine Sea slab beneath the Seto Inland Sea of Japan at a depth (51 km) on March 24, 2001. The source mechanism of the event was normal faulting. This earthquake released high frequency energy to the southwest Japan and caused 2 deaths and injured 288 people. 70 houses were collapsed and 774 houses were damaged (Cabinet Office, 2001). As intra-plate earthquakes including this event are considered to release relatively high frequency energy compared with crust earthquakes and inter-plate earthquakes, the study on both the source modeling and the broadband (e.g. 0.3 to 10 Hz) strong motion simulation for this event is significant from seismological and engineering points of views.

In this study, I carried out source parameter estimation and strong motion simulation with

1Associate Professor, Research Institute of Nuclear Engineering, University of Fukui, 1-2-4 Kanawa, Tsuruga, 914-0055, Japan (email: ohorim@u-fukui.ac.jp)

use of the empirical Green’s function method. Fortunately, the KiK-net, one of the strong motion networks operated by the National Research Institute of Earth Science and Disaster Prevention (NIED), has been just started since August, 2000, seven months before the event. I targeted 10 KiK-net stations located at 19 to 66 km in epicentral distance from the mainshock epicenter. Due to the strong shaking during the mainshock, nonlinear behavior of shallow soft surface layers were induced at many sites [e.g. Kanno and Miura (2005)]. To focus on the source modeling without any consideration about nonlinear characteristics, borehole records of the KiK-net were used.

First, I inverted spectral amplitude of the S-wave main portion from mainshock and 12 aftershocks (Mj 3.5 to 5.0) and derived rough estimates of basic source parameters characterizing the omega-square source spectrum by Brune (1970). Second, I carried out strong motion simulation based on the empirical Green’s function method. A simple rectangular fault plane of 30 by 18 km² with strike of 180 deg. and dip of 60 deg. was assumed with reference of previous source studies [e.g. Kikuchi and Yamanaka (2001), Sekiguchi and Iwata (2001), Nozu (2001), and Kakehi (2004)]. Using data from the largest aftershock as the empirical Green’s function, I performed waveform inversion and estimated the relative moment release distribution on the fault plane. Incorporating the inversion results with the empirical Green’s function [Dan and Sato (1998, 1999)], I simulated the strong ground motion during the mainshock in a range of 0.3 to 10 Hz.

Events and Stations

In Figure 1, locations of the mainshock (Mj 6.7, labeled as Event 1) and 12 aftershocks (Mj 3.5 to 5.0, Events 2-13) of the Geiyo earthquake are shown. The focal mechanism solutions of events determined by the F-net are inserted. Also, 10 KiK-net stations, which was used in Koketsu and Furumura (2002), are plotted with up-side-down solid triangles. These stations are surrounding the rupture area of the mainshock and their recordings are carried out not only at the surface but also at the borehole. They are located at epicentral distance from 19 km to 66 km for the mainshock, and the S-wave velocity at their boreholes (Vsmax) are ranging from 2000 m/s to 2900 m/s, except for two stations, HRSH07, EHMH04 with the Vsmax of 1200 m/s and 700 m/s, respectively. As for the mainshock, the nonlinear behavior of soft surface layers are pointed out [e.g. Kanno and Miura (2005)]. On the other hand, the data recorded at close distance from the source is considered to be rich in source characteristics. Therefore, to focus on the source modeling without any consideration about nonlinearity of surface layers, I used borehole data instead of surface data.

Inversion of Spectral Amplitude

Data Processing

To have rough estimates for the source parameters, the spectral amplitude inversion was carried out. I took 20 second time window for the S-wave portions from the NS and EW components. The beginning and the end of the window were tapered with 1 second cosine taper. Then, I calculate the Fourier transform from a complex signal \[ x(t) + iy(t), \] where \( x(t) \) and \( y(t) \) denote two orthogonal horizontal components. The amplitude spectrum was smoothed by a Parzen
window with a width having frequency dependence: given by 0.1f with the minimum of 0.1 Hz and the maximum of 1.0 Hz. The spectral amplitude between 0.1 and 20 Hz was targeted in the spectrum inversion.

Figure 1  Map showing location of epicenters and stations targeted in this study. Focal mechanism solutions determined by the F-net are also inserted. Note that a rectangle surrounding the rupture area denotes a fault plane used for the simulation based on the empirical Green’s function method with 30 km in length and 18 km in width. The strike and dip are set to 180 deg. and 60 deg.

Analytical Method

Analytical procedure of the spectrum inversion employed in this study was almost the same as the method by Iwata and Irikura (1986), except that \( Q_s \)-value (quality factor of the S-wave) along the propagation path was given a priori after preliminary analyses.

Let us consider the spectral expression of the ground motion. The spectral amplitudes at the j-th station from the i-th event, \( O_{ij}(f) \) can be given by

\[
O_{ij}(f) = S_i(f)G_j(f)\frac{1}{R_{ij}}\exp\left( -\frac{\pi fR_{ij}}{Q_s(f)V_s} \right)
\]

where \( S_i(f) \), \( G_j(f) \) and \( Q_s(f) \) represent the source spectrum, the site amplification, and quality
factor along the path from source to station. Also, \( R_{ij} \) and \( V_s \) represent the corresponding hypocentral distance and the average S-wave velocity from source and station. \( V_s \) was assumed to be 3.8 km/s.

The equation (1) can be rewritten as

\[
\overline{G}_{ij}(f) = S_i(f)G_j(f)
\]  

(2)

where \( \overline{G}_{ij}(f) \) is the path-effect corrected spectral amplitude given by

\[
\overline{G}_{ij}(f) = R_{ij}O_{ij}(f)\exp\left(\frac{\pi f R_{ij}}{Q_s(f)V_s}\right)
\]  

(3)

We take the logarithm of the equation (2) and derive the following expression:

\[
\log_{10} \overline{G}_{ij}(f) = \log_{10} S_i(f) + \log_{10} G_j(f)
\]  

(4)

The unknowns to be solved in the above equation are \( S_i(f) \), \( G_j(f) \) and \( Q_s(f) \). As previously mentioned, in this study, \( Q_s(f) \) was treated to be given. I tested several \( Q_s(f) \) models in preliminary analyses and examined the spectrum matching between the synthesized spectrum and observed ones. As a result, \( Q_s(f) = 81f^{0.85} \) was seemed to be appropriate in this study. Therefore unknowns were reduced to two parameters, \( S_i(f) \) and \( G_j(f) \). Considering \( M \) events and \( N \) stations in total, \( M \) by \( N \) simultaneous equations are constructed for each frequency. These equations can be solved with the nonnegative least square method by Lawson and Hansen (1974).

To solve the equations with a constraint of \( G_j(f) \geq 2 \), \( G_j(f) \) was substituted by \( 2G'_j(f) (= G_j(f)) \) because in solving the logarithmic solution, the nonnegative constraint of \( \log_{10} G'_j(f) \geq 0 \) corresponds to \( G_j(f) \geq 1 \). Moreover, the equation (1) was normalized by the minimum amplitude of \( \overline{G}_{ij}(f) \) for each frequency.

Results

In order to determine basic source parameters [the moment magnitude \( M_W \) (or the seismic moment), the corner frequency, the stress drop], I fit the theoretical source acceleration spectrum with inverted one. The source acceleration spectrum used here is the omega-square model by Brune (1970) combined with a high frequency cut-off filter, given by

\[
S(f) = \frac{r_s M_0}{4\pi \rho \beta^3 R} \left(\frac{2 \pi f}{f_c}\right)^2 \left(1 + \left(\frac{f}{f_c}\right)^2\right)^{- \frac{n}{2}}\left(1 + \left(\frac{f}{f_{\text{max}}}\right)^n\right)^{-1}
\]  

(5)
where \( r_s \) is the average radiation pattern for the S-wave, \( R \) is the hypocentral distance. \( \rho \) and \( \beta \) denote the density and the S-wave velocity in the source layer. \( f_{\text{max}} \) and \( n \) denote parameters for a high frequency cut-off filter. \( M_0 \) and \( f_c \) represent the seismic moment and the corner frequency. The stress drop is given by

\[
\Delta \sigma_s = \left( \frac{f_c}{4.9 \times 10^6 \beta} \right)^3 M_0
\]

(6)

where the unit of \( M_0 \) were dyne*cm. Here, \( r_s \), \( R \), \( \rho \) and \( \beta \) were assumed to be 0.63, 1 km, 3.1g/cm\(^3\) and 4.62 km/s, respectively. \( M_0 \) and \( f_c \) were determined by fitting the inverted source spectrum with the model. \( n \) was assumed to be 1 and \( f_{\text{max}} \) was determined in a range of 14 to 24 Hz by eye inspection.

Because of limited space, I neglect the figure showing the inverted source spectra and the model source spectra. The model spectra agree well with the inverted ones so that the scaling law based on the omega-square model was considered to be valid among targeted events in this study. In Table 1, the estimated results of source parameters are summarized. The moment magnitude (M\( _W \)), the corner frequency, and the stress drop were estimated to be 6.3, 0.5 Hz, and 377 bar for the mainshock, and 5.2, 0.8 Hz, and 32 bar for the largest aftershock (Event 7 in Figure 1).

<table>
<thead>
<tr>
<th>Event</th>
<th>JMA Date (y:m:d)</th>
<th>Clock (h:m:s)</th>
<th>Depth (km)</th>
<th>( M_J )</th>
<th>( M_W )</th>
<th>( f_c ) (Hz)</th>
<th>( \Delta \sigma ) (bar)</th>
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<td>4.2</td>
<td>1.6</td>
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</tr>
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</table>

Table 1 Source parameters of targeted events and results of spectral amplitude inversion.

**Simulation of the Mainshock**

**Fault Plane Discretization**

Referring to the focal mechanism solutions, aftershock distribution, and waveform inversion results in previous studies [e.g. Kikuchi and Yamanaka (2001), Sekiguchi and Iwata (2001), Nozu (2001), and Kakehi (2005)] , I assumed simple rectangular fault plane with 30 km in
length and 18 km in width, on which the mainshock hypocenter was located as a rupture point. See Figure 1. The strike and dip of the fault plane was set to 180 deg. and 60 deg., respectively. The depth of the fault plane is located in a range of 45 km to 60 km. To express rupture propagation from the hypocenter to the whole fault plane, it was divided into 10 by 6 subfaults with the size of 3 km by 3 km.

**Method and Analytical Condition**

Since a pioneering work by Hartzell (1978), the empirical Green’s function method has been recognized as a useful technique to synthesize strong ground motion and extended in various ways by various researchers. Among them, I selected the method proposed by Dan and Sato (1998), because theirs can easily incorporate the variable-slip rupture model with the empirical Green’s function method to simulate the broadband strong ground motion.

In this study, I used the data from the largest aftershock (Event 7) as the empirical Green’s function. Note that the mainshock and aftershock have difference in the moment magnitude (or the seismic moment), the corner frequency, and the stress drop, as summarized in Table 1. Also, the rupture area of the aftershock was evaluated to be 15 km$^2$ (2.2 km in equivalent radius for the circular fault, later called $\lambda_s$) whereas each subfault modeled here has the area of 9 km$^2$ (1.7 km in equivalent radius, later called $\lambda_{pq}$). The Dan and Sato’s method can provide the element wave from each subfault by taking into consideration the following difference between aftershock data and ground motion from each subfault, the medium property in source layers, the seismic moment, the corner frequency, the stress drop, the size of rupture areas. Although their original method can correct the difference of the medium of source layer, in this study, the whole fault plane is assumed to be embedded in the half-space with the S-wave velocity of 4.62 km/s, so that the correction concerned with the medium difference between the small event and subfault are not considered. Using the small event data as the empirical Green’s function, the spectrum of the ground motion from (p, q) th subfault is expressed as follows:

$$u_{pq}(f) = u_s(f) \frac{M_{0pq}}{M_{0s}} \frac{R_s}{R_{pq}} \frac{s_s}{1 + j \frac{f}{f_{c_{pq}}} \left(1 + j \frac{f}{f_{c_{pq}}}ight)} \exp \left[-\frac{\pi f (R_{pq} - R_s)}{Q_s(f) V_s}\right]$$

where $u_s(f)$ denotes the small event data used as an empirical Green’s function. $R_s$, $f_{c_s}$, and $M_{0s}$ denote the hypocentral distance, the corner frequency, and the seismic moment, respectively, for the small event. These will turn to be variables for the (p, q) th element with suffix ‘s’ by replaced ‘pq’. $s_s$ is a scaling factor, given by $\lambda_{pq}/\lambda_s$, where $\lambda_{pq}$ and $\lambda_s$ are equivalent radii of the circular fault for the (p, q) th subfault and the small event. $f_{c_{pq}}$ is the corner frequency defined by $V_{pq}/2\pi D_{pq}$, due to the temporal integration of the slip-velocity function, where $V_{pq}$ and $D_{pq}$ are the maximum slip velocity and the final slip, respectively.
$f_{c_{pq}}$ is another corner frequency defined by $\lambda_{pq}/\pi\beta_{pq}$, due to the spatial integration of the slip-velocity function on the subfault. Details are found in Dan and Sato (1998, 1999).

Based on the spectrum inversion results, $f_c$, $\lambda_S$, $M_{Q_S}$, and $f_{c_{pq}}$ are set to 0.8 Hz, 2.2 km, $7.9\times10^{23}$ dyne*cm, 0.5 Hz. $\lambda_{pq}$, $\beta_{pq}$ and $V_s$ are set to 1.7 km, 4.62 km/s, and 3.8 km/s. $M_{0_{pq}}$ are unknown to be solved by the waveform inversion. The strong ground motion from the whole fault plane can be calculated by summing up the element wave from each subfault. Prior to summation, the effect of the rupture propagation must be considered with adjustment in timing.

I confirmed that the source spectrum ratio between the mainshock and the largest aftershock seemed to obey the scaling law based on the omega-square model [Brune (1970)] at a frequency higher than 0.3 Hz. Also, as mentioned in previous chapter, $f_{\text{max}}$ is at least higher than 10 Hz, although it varies from event to event. In the following simulation, the data from the both mainshock and aftershock events was band-pass filtered between 0.3 and 1 Hz in waveform inversion and between 0.3 and 10 Hz in forward modeling.

![Figure 2](image)

Figure 2  Relative moment release distribution on the fault plane for the mainshock. Contour lines are plotted with an unit step corresponding to the seismic moment of the largest aftershock (Event 7). A solid star inserted represents a rupture starting point (the mainshock hypocenter)

**Relative Moment Release Distribution**

Firstly, prior to the waveform simulation. I carried out waveform inversion to derive the rupture model using the element wave from each subfault as the empirical Green’s function. The acceleration data was twice integrated into displacement with a bandpass-filter ranging from 0.3 to 1Hz. Simple inversion allowing each subfault to rupture once was carried out using the nonnegative least square method by Lawson and Hansen (1974).

Rupture velocity of 3.0 km/s was selected after testing the rupture velocity in a range of 2.5 km/s
to 3.5 km/s with a step of 0.1 km/s in the process of estimation for the seismic moment release distribution on the fault plane.

In Figure 2, the relative moment release $M_{pq}$ on the fault plane is shown. This result means relative strength on the fault against the largest aftershock. On the basis that the Event 7 is an earthquake of $M_W5.2$, the mainshock can be evaluated to be $M_W6.5$. As seen in Figure 2, present study resolved at least two asperities: the largest one is located at about 10 km south from the hypocenter, and second one is located at slightly north. As waveform inversion results highly depend on analytical conditions, previous studies [e.g. Kikuchi and Yamanaka (2001), Sekiguchi and Iwata (2001), Nozu (2001), and Kakehi (2005)] show somewhat resemblances and differences at the same time. Among them, the relative moment release distribution in Figure 2 is similar with the result from most detailed analysis [Figure 7 in Kakehi (2004)].

Simulation Results

Using the relative moment release distribution shown in Figure 2, the strong ground motion for the mainshock was synthesized in a frequency range from 0.3 to 10 Hz. Velocity waveforms for selected stations of our interest are shown in Figures 3. The maximum amplitudes of the synthesis and data are plotted in Figure 4. It is clear that simulation results seem to agree well with the observed data except for discrepancies found in some sites. As for the maximum acceleration (Figure 7a), simulation results underestimates the NS and EW components of HRSH01 and HRSH07 and overestimates the NS-component of HRSH08. As for the maximum velocity and displacement (Figures 7b and 7c), simulation results underestimates the NS and EW components of HRSH01 and HRSH07 and the NS-component of EHMH04. On the whole, the maximum amplitudes of observed horizontal components from 10 stations were in a range of 24 to 123 gal in acceleration and 1.6 to 8.5 kine in velocity. Present simulation reproduced most of the observed maximum amplitudes within a factor of 2.0.

Take a look at Figures 3a and compare the synthesized results for HRSH07, located at north from the fault. It is clarified that the simulation significantly underestimated the observed horizontal data in velocity and displacement waveforms. It may be partially attributed to isolated later phases appearing at around 25 sec. Results for HRSH01 also show similar characteristics. Sekiguchi and Iwata (2001) suggested that the more complex rupture history were required for the simulation of the stations located in the northern direction from the rupture area. Judging from the fact that such clear pulse is not so clear at the other stations, more complicated rupture process and/or the change of the focal mechanisms may be needed to explain such characteristics. As for HRSH08 and HRSH12, the synthesized waveforms reproduced well the observed data. Long duration characteristics found in the data is simulated successfully in the synthesis as well as the maximum amplitudes. At three stations located in west direction to the source area, YMGH03 (Figure 3b), YMGH04, and YMHH05, simulation results reproduced well the observed data for velocity. Above all, the degree of the waveform matching between data and synthesis is remarkable at YMGH03. At other stations located at southern area, EHMH02, EHMH04, and EHMH05, the agreement between the data and synthesis is satisfactory. Note that as for EHMH04, the NS component is reproduced well whereas the EW component are underestimated. It may imply that observed data needed the change of focal mechanism during the rupture process.
Figure 3  Comparison of synthesized velocity waveforms and observed data for HRSH07 (a), YMGH03 (b). For each site, top three traces are the observed data for the Event 7 (EGF), middle three are the synthesized ones for the mainshock (Syn.), and others are the observed data (Obs.). Numerals at the end of traces are absolute maximum amplitudes.

Figure 4  Comparison of the maximum amplitude for the mainshock between the synthesized waveform and observed data for acceleration (a), velocity (b), and displacement (c). Station index labeled on the horizontal axis is defined as the table above.

Conclusions

The source parameters of the 2001 Geiyo earthquake (M6.7) was estimated by the spectrum inversion using the KiK-net borehole data. The moment magnitude, the corner frequency, and the stress drop were estimated to be 6.3, 0.5 Hz, and 377 bar for the mainshock, and 5.2, 0.8 Hz, and 32 bar for the largest aftershock. Next, based on the obtained source parameters, the empirical Green’s function method was applied to simulate the strong ground motion for the mainshock. Element waves evaluated from the largest aftershock data were used for the waveform inversion and the strong motion simulation. Comparison of synthesized waveforms and observed data shows a good agreement except for discrepancies found in some sites. The maximum velocity from simulation underestimates the NS and EW components of HRSH01 and
HRSH07 and the NS-component of EHMH04. The maximum amplitudes of observed horizontal components from 10 stations were in a range between 1.6 and 8.5 kine in velocity. Present simulation reproduced most of the observed maximum amplitudes within a factor of 2. To enhance the accuracy of simulation, I consider that the more detailed fault rupturing should be investigated.

Acknowledgments

In this study, I used the strong motion data of the KiK-net and the source parameter information of the F-net, operated by the National Research Institute for Earth Science and Disaster Prevention. My sincere gratitude is given to whom it may concern.

References