Empirical Green's function simulation of broadband ground motions on Genkai Island during the 2005 West Off Fukuoka Prefecture earthquake

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The 2005 West Off Fukuoka Prefecture earthquake caused serious damage to and on Genkai Island as well as to downtown Fukuoka City. There were no strong motion instruments on the island, therefore no one knows how the strong ground motion occurred during the mainshock. The ground motion simulation on Genkai Island is very important to our understanding of earthquake damage at the near-source region. We have conducted an aftershock observation on the island in order to verify site amplification due to steep topography and to record aftershocks for reproducing ground motion during the mainshock by the empirical Green's function method. The observed records of aftershocks show small variations in the input motions in the island, indicating that the amplification due to the topography seems to be small below 2 Hz. We first estimated the strong motion generation area for the mainshock using the observation records at stations surrounding the source region. We then carried out broadband ground motion simulation on Genkai Island by using the aftershock records as empirical Green's functions. The simulated ground velocities exceed 1 m/s with a dominant period of 1–2 s due to the forward rupture directivity, and the instrumental seismic intensity reaches 6.6.

Key words: Broadband ground motion simulation, empirical Green's function method, instrumental seismic intensity, forward rupture directivity, Genkai Island.

1. Introduction

An inland crustal earthquake ($M_{\mathrm{JMA}}7.0$, $M_{\mathrm{w}}6.6$, depth: 14 km) occurred at 10:53 on March 20, 2005, off the western part of Fukuoka Prefecture. It caused serious damage to and on Genkai Island as well as to downtown Fukuoka City. Most houses on Genkai Island were fully or partially destroyed by the earthquake.

The CMT solutions by the NEIC/USGS and F-net/NIED indicate a left-lateral strike-slip at a depth of 10∼11 km and a moment magnitude of 6.4∼6.5. The aftershocks are distributed along an NW-SE line about 20 km long. No major active faults were clearly expected in the region before the earthquake, except for the Kego fault beneath Fukuoka City.

Since the nationwide strong motion arrays, called K-NET and KiK-net by the NIED (Kinoshita, 1998; Aoi *et al.*, 2000), and seismic intensity meters by the JMA (JMA, 1996) and local governments have been installed, most of inland crustal earthquakes have been well captured at their near-source regions. The 2000 Western Tottori Prefecture earthquake was recorded at a KiK-net station in Hino, and the 2004 Mid-Niigata prefecture earthquake was recorded at a station in Kawaguchi with instrumental seismic intensities of over 6.5.

During the 2005 West Off Fukuoka Prefecture earthquake, some stations in downtown Fukuoka City recorded instrumental seismic intensities of 6- on the JMA scale; however, there were no strong motion instruments on Genkai Island. Consequently, no one knows how strong ground motion occurred during the mainshock at this near-source region. Most houses on the island were built on steep slopes, therefore, the question remains of whether input ground motions or the effects of the steep slopes caused the damage.

It is a crucial to examine the above questions, and broadband ground motion validation on the island is very important for gaining an understanding of the earthquake damage at near-source region. We focus on the source modeling using the empirical Green's function method, then apply the model to the broadband ground motion simulation on Genkai Island during the mainshock. We then discuss the variations in the site amplification on the island based on our aftershock observations.

2. Aftershock Observation

Just after the mainshock, several organizations started aftershock observations to capture aftershock activities and ground motions. JMA soon installed a seismic intensity meter on Genkai Island and started to report the seismic intensity as well as to record ground motions. Researchers at ERI, University of Tokyo, had deployed eight portable strong-motion seismometers (SMAR-6A3P) on Genkai Island and downtown Fukuoka City. Our objectives were to record aftershocks in order to verify site amplification due to the steep topography of the island and to reproduce ground motions during the mainshock using the empirical Green's function method. We began the aftershock obser-

Table 1. List of events (M_w over 3.0) recorded by JMA, Fukuoka city, and ERI, University of Tokyo, from March 20 till April 8 (for 20 days). Hypocenter information and moment magnitude are from the JMA and F-net of the NIED, respectively (o: observed, x: missing, -: not yet installed).

No	Date	Time	N	E	D	M_{JMA}	M_w	fuk01	fuk02	fuk03	gnk01	gnk02	gnk03	gnk04	gnk05	fty	fhi	1f5
01	2005/03/20	10:53:40	33.7392	130.1763	09.24	7.0	6.4	-	-	-	-	-	-	-	-	o		
02	2005/03/22	15:55:33	33.7253	130.1768	10.53	5.4	4.8	-	-	-	-	-	-	-	-	o	o	o
03	2005/03/24	23:38:43	33.7413	130.1713	11.05	4.3	3.6	o	o	o	-	-	-	-	-			o
04	2005/03/25	03:43:19	33.7220	130.2163	10.89	4.0	3.7	o	o	o	-	-	-	-	-			o
05	2005/03/25	06:05:00	33.7557	130.1527	12.51	3.6	3.2	x	o	o	-	-	-	-	-			
06	2005/03/25	18:13:14	33.7102	130.2610	13.07	3.5	3.1	x	o	o	o	o	o	o	o			
07	2005/03/25	20:09:54	33.7178	130.2838	14.18	3.5	3.2	x	o	o	o	o	o	o	o			
08	2005/03/25	21:03:20	33.7865	130.1178	12.07	4.1	3.8	o	o	o	o	o	o	o	o	o	o	
09	2005/03/26	05:45:40	33.7680	130.1227	15.86	3.7	3.2	x	o	o	o	o	o	o	o			
10	2005/03/26	09:27:59	33.6947	130.2717	07.61	3.5	3.2	x	o	o	o	o	o	o	o			
11	2005/03/26	11:18:42	33.7315	130.2373	14.97	3.8	3.4	x	o	o	o	o	o	o	o			
12	2005/03/26	20:01:04	33.6998	130.2703	14.57	3.5	3.3	x	o	o	o	o	o	o	o			
13	2005/03/27	07:58:48	33.7098	130.2528	05.65	3.3	3.2	x	x	o	o	o	o	o	o			o
14	2005/04/01	21:52:14	33.6730	130.3195	11.90	4.3	3.9	o	o	o	o	o	o	o	o	o	o	o
15	2005/04/05	05:21:04	33.7442	130.1612	08.74	3.5	3.3	x	o	o	o	o	o	o	o			
16	2005/04/05	21:49:59	33.7400	130.1692	12.47	3.5	3.1	x	o	o	o	o	o	o	o			
17	2005/04/06	07:59:54	33.7097	130.2550	13.62	4.1	3.5	o	o	o	o	o	o	o	o			o
18	2005/04/07	00:17:25	33.7078	130.2365	04.92	4.0	3.6	x	o	o	o	o	o	o	o			o
19	2005/04/07	01:09:49	33.6720	130.3205	11.82	3.5	3.1	o	o	o	o	o	o	o	o			
20	2005/04/08	09:16:20	33.7608	130.1347	12.63	3.7	3.2	x	o	x	o	o	o	o	o			
21	2005/04/08	13:03:14	33.7643	130.1193	13.12	3.9	3.5	x	o	x	o	o	o	o	o			

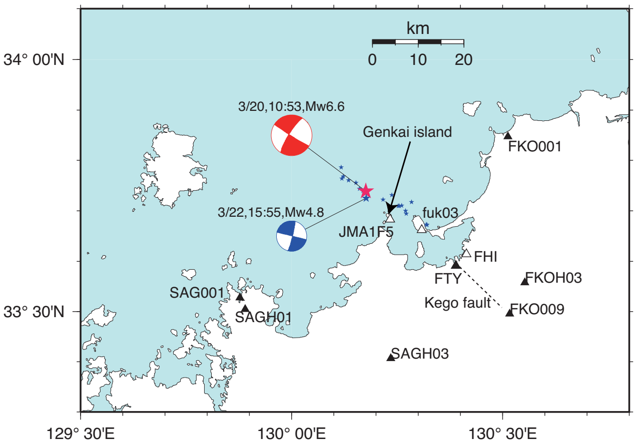

Fig. 1. Map showing the stations and focal mechanisms for the mainshock and aftershock. Black triangles are used for the source modeling. White triangles are stations without the mainshock records.

Table 2. List of stations.

Station Name	Code	Lat (deg.)	Long (deg.)	Alt (m)
Downtown Fukuoka City				
Maizuru Firehouse	fuk01	33.59072	130.38908	−37
Higashi Firehouse	fuk02	33.61428	130.41389	42
Shikanoshima Elementary School	fuk03	33.66189	130.30847	30
Genkai Island				
Fisherman's Union Office	gnk01	33.68350	130.23519	16
Genkai Nursery	gnk02	33.68581	130.23700	10
West Park	gnk03	33.68353	130.23222	20
Lodging House	gnk04	33.68447	130.23464	49
Raggage Rail	gnk05	33.68433	130.23581	20
JMA				
Maiduru Firehouse	fty	33.59072	130.38908	−37
Higashi Firehouse	fhi	33.61428	130.41389	42
Genkai Island	1f5	33.68289	130.23347	0

vation on March 24. Most of the aftershocks larger than M_w3.0 were recorded, as listed in Table 1.

Figures 1 and 2 display these stations in the Fukuoka region and Genkai Island, respectively. In downtown Fukuoka City, fuk01 and fuk02 were installed near the seismic intensity meters of the City of Fukuoka (FTY and FHI), which recorded the mainshock with a JMA seismic intensity of 6-. fuk03 was located on Shikanoshima Island because the aftershock activity was extending toward this island. Five seismometers were installed on Genkai Island to cover the village on the steep slopes (Fig. 2). Three of them were set in the center (gnk01), east (gnk02), and west (gnk03) of the village, at a low altitude, the remaining two were placed at a higher (gnk04) and middle altitude (gnk05). The locations of the stations are summarized in Table 2.

3. Source Modeling using the Empirical Green's Function Method

We first constructed the source model for broadband ground motions using the empirical Green's function method (Irikura, 1986; Irikura and Kamae, 1994). We used the hypocenter information for the mainshock (latitude 33.75N, longitude 130.16E, depth 14.0 km) by Kyushu University (Shimizu *et al.*, this issue). The records of the aftershock at 15:55 on March 22 (M_w4.8; No. 2 in Table 1) were selected for the empirical Green's functions, since the focal mechanism and hypocenter were similar to those of the mainshock. The aftershock is the largest one that satisfies the above conditions, so that we can expect high signal-to-noise ratio in a wider frequency range.

In the broadband ground motion simulation, the strong motion generation area in a rupture area plays a key role (e.g., Miyake *et al.*, 2003). This strong motion generation area is assumed to be a homogeneous rectangular area with large and uniform slip velocities, whose time functions were referred to Kostrov (1964). The area mainly reproduces strong ground motions in a frequency range of 0.1 to

Fig. 2. Stations plotted on the digital map of Genkai Island by the Geographycal Survey Institute (GSI) of Japan. Altitude contours are drawn every 10 m.

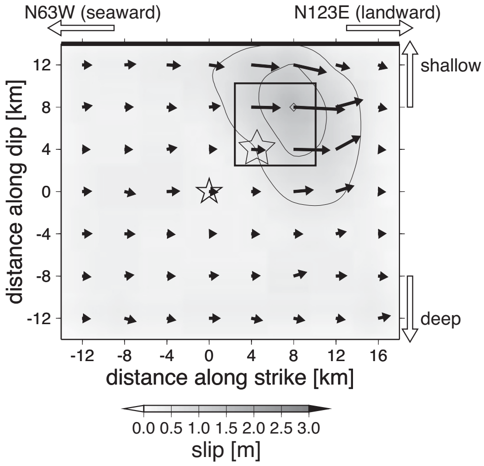

Fig. 3. Strong motion generation area (square in the fault) estimated by the empirical Green's function method, compared to the slip inverted by Kobayashi *et al.* (2006). The stars indicate the hypocenter and rupture starting point of the strong motion generation area, respectively.

10 Hz. This lower limit comes from the noise level of the aftershock records.

In order to estimate the strong motion generation area for the target earthquakes, we simulated acceleration, velocity, and displacement waveforms at stations surrounding the source area using the empirical Green's function method. We selected seven strong motion stations (Fig. 1) with records of both the mainshock and aftershocks. We used the source spectral ratio fitting method (Miyake *et al.*, 1999) for objective estimation of the parameters *N* and *C*, which are the ratios of fault dimension and stress drop, respectively, needed for the empirical Green's function method. The *N* and *C* are estimated to be 2 and 8.5, respectively. We took the source spectral ratios for different aftershocks (e.g., No. 3 in Table 1), and these also indicate *C* values larger than 7. Kamae *et al.* (2005) also derived *C* values of around 8. The large *C* value indicates a large stress-drop ratio between the mainshock and aftershock of the 2005 West Off Fukuoka Prefecture earthquake.

The parameters for the strong motion generation area, which are length, width, rupture starting point, rise time, and rupture velocity, were estimated by the forward modeling to fit simulated waveforms to observed ones. The length and width were examined for 1-km intervals, and the rupture starting point was tested for all subfaults (*N* by *N*). The rise time was searched for 0.1-s intervals. We changed rupture velocities between 2.1 and 3.5 km/s with increments of 0.1 km/s. We set the fault plane following the CMT solution by F-net. The size of the strong motion generation area is estimated to be 8 km long by 8 km wide (Fig. 3), which is slightly smaller than the estimation by Kamae *et al.* (2005). The rupture starting point is set 4 km in a shallower and 4 km southwestern position with respect to the hypocenter by the trial and error search. This rupture direction is coincident with the result of Kamae *et al.* (2005); however, it is different from that of Suzuki and Iwata (2006). The rupture started at the northwestern-bottom of the area and extended radially to the southeastern-upper direction. The rise time for the area is adopted to be 0.4 s. The rupture velocity is selected to be 3.1 km/s, where the *S*-wave velocity in the source region is 3.5 km/s. Based on the displacement spectral level and the size of the strong motion generation area for the aftershock (4 km long by 4 km wide), the stress drop for the aftershock is estimated to be around 2 MPa, assuming the circular crack model (Eshelby, 1957). We then multiply the *C* value (ratio of stress drop between mainshock and aftershock) for the stress drop of aftershock, then estimate the stress drop for the strong motion generation area for the mainshock to be around 17 MPa.

Figures 4 and 5 show waveform fittings for the stations in terms of acceleration, velocity, and displacement in the frequency range of 0.1 to 10 Hz. The overall fitting is not so good as that for recent earthquakes (e.g., Miyake *et al.*, 1999, 2003), but matching of the pulse width in the observation and simulation suggests the suitability of the estimation of the size for the strong motion generation area. The greatest limitation of our waveform fitting is that we had to choose an aftershock recorded after March 22 on Genkai Island because the objective of the paper is not only the source modeling, but also reproducing the unrecorded mainshock ground motions on Genkai Island. The difficulty of waveform fitting at station FKO001 may also come from its location close to the nodal plane of the focal mechanisms.

The source process of the 2005 West Off Fukuoka Prefecture earthquake was investigated by low-frequency (less than 1 Hz) waveform inversions (e.g., Asano and Iwata, 2006; Kobayashi *et al.*, 2006). According to these results, an asperity was found in a shallow part in the southeast of the hypocenter. Our strong motion generation area is roughly coincident with this asperity (Fig. 3), thereby supporting the applicability of the characterized source model for simulating broadband ground motions (e.g., Miyake *et al.*, 2003).

4. Broadband Ground Motion Simulation on Genkai Island

Based on the strong motion generation area obtained in the previous section, we simulate ground motions on

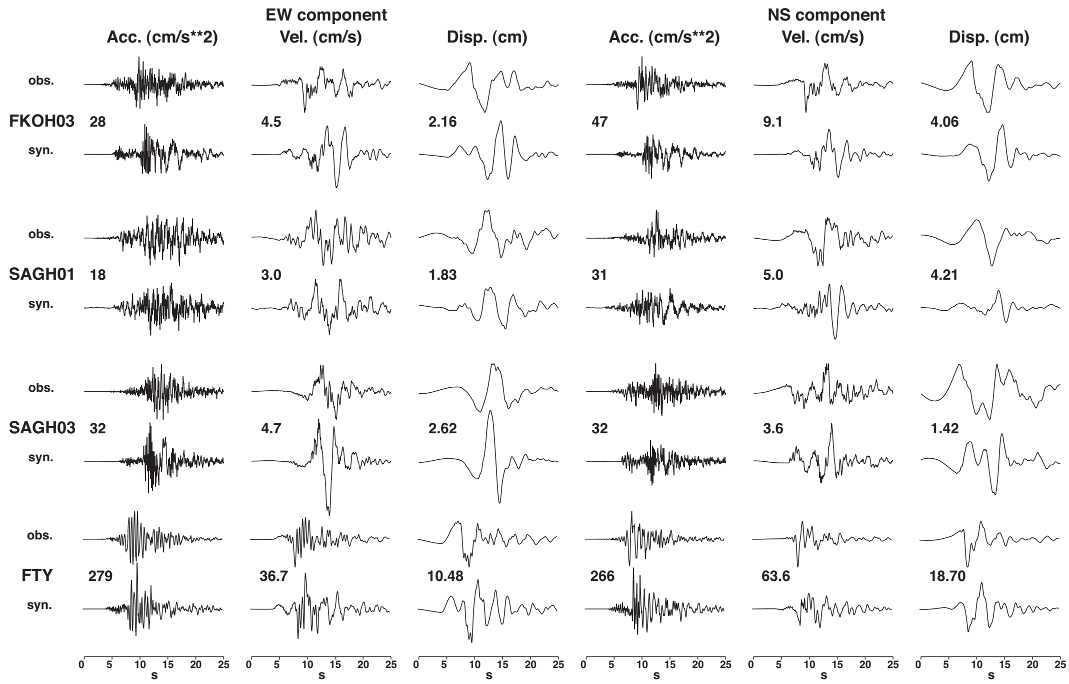

Fig. 4. Comparison of observed and synthetic waveforms of acceleration, velocity, and displacement for the 2005 West Off Fukuoka Prefecture earthquake at the stations of K-NET, KiK-net (borehole) and Fukuoka City (FTY; i.e., Maizuru Firehouse). Numbers show the maximum amplitude values of the observed waveforms.

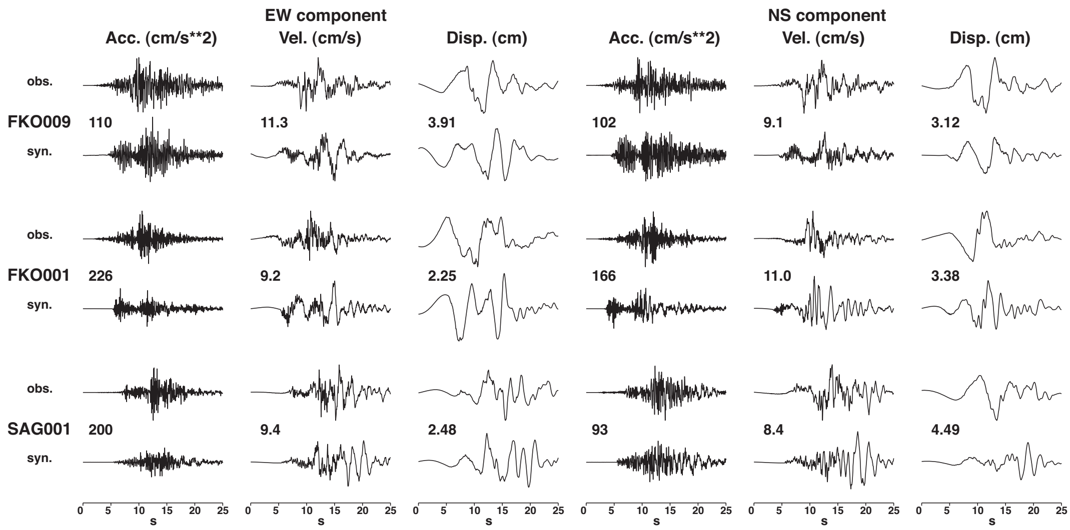

Fig. 5. (continued).

Genkai Island during the 2005 West Off Fukuoka Prefecture earthquake by the empirical Green's function method. We selected station JMA 1F5 as the target station because this is the only station to record the aftershock of 15:55 on March 22 (No. 2 in Table 1) on the island.

We applied 5-Hz low-pass filters for the simulated waveforms to avoid non-linear effects of the high-frequency ground motions in the near-source region (e.g., Chin and Aki, 1991; Yamamoto *et al.*, 1995). The simulated waveforms show the forward directivity pulse with a dominant period of 1–2 s, corresponding to the size of the strong motion generation area (e.g., Somerville, 2003). Even the low-pass-filtered ground velocities exceed 1 m/s (Fig. 6), and those response spectrum of NS components reaches 2 m/s (Fig. 7). The instrumental seismic intensity of the simulated records is over 6.6.

Even though the instrumental seismic intensity is large, it is not always used as a destructive index of strong ground motion. Kawase (1998) and Sakai *et al.* (2002) proposed response at the period of 0.5–2 s and 1.2–1.5 s as the destructive index, respectively. The velocity response at the period of 1–2 s at station JMA 1F5 is a match for that at station JMA Kobe during the 1995 Kobe earthquake (M_w6.9), but smaller than that at station Takatori during the Kobe earthquake. The peaks of the velocity response smaller than 0.5 s seem to correspond to the site amplification at station JMA 1F5 because several aftershocks show the same tendencies (an example is shown in Fig. 7). The seismic intensity at

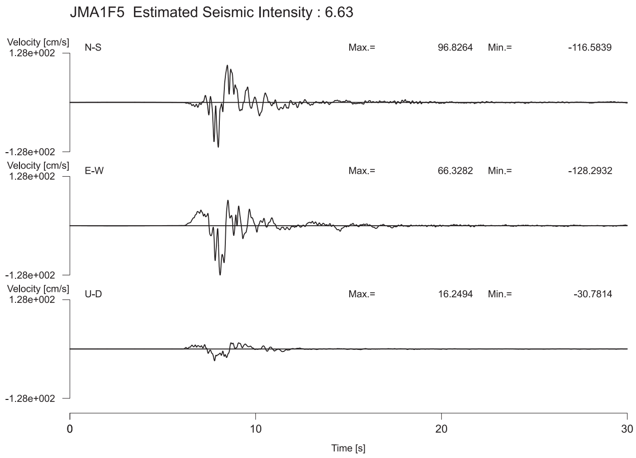

Fig. 6. Simulated ground motion at the station JMA 1F5 on Genkai Island.

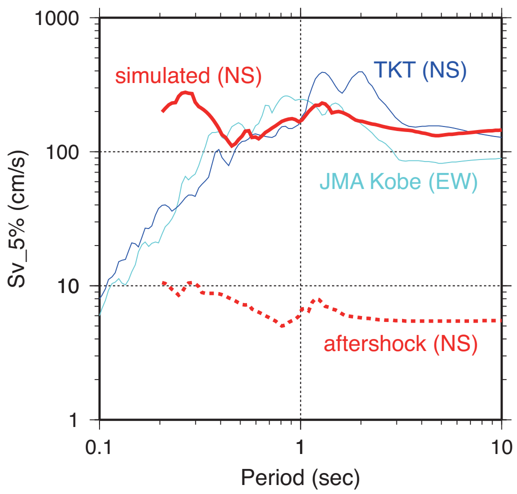

Fig. 7. Velocity response spectra for the simulated ground motion at the station JMA 1F5 (NS component, 5-percent damped) and its aftershock (No. 2). The spectra for the stations Takatori and JMA Kobe during the 1995 Kobe earthquake are shown for the comparison.

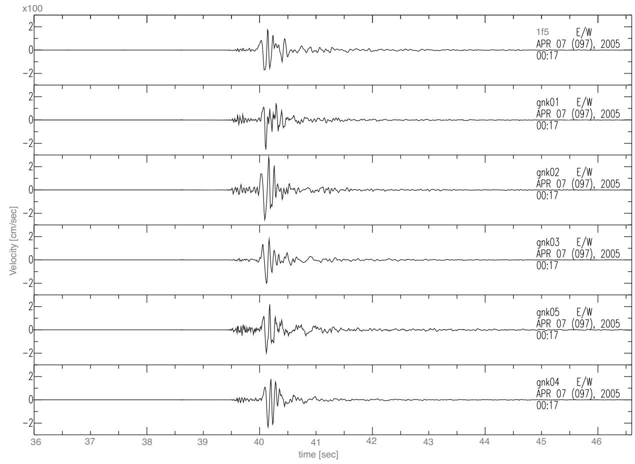

Fig. 8. Acceleration waveforms of the aftershock (No. 18) recorded on Genkai Island.

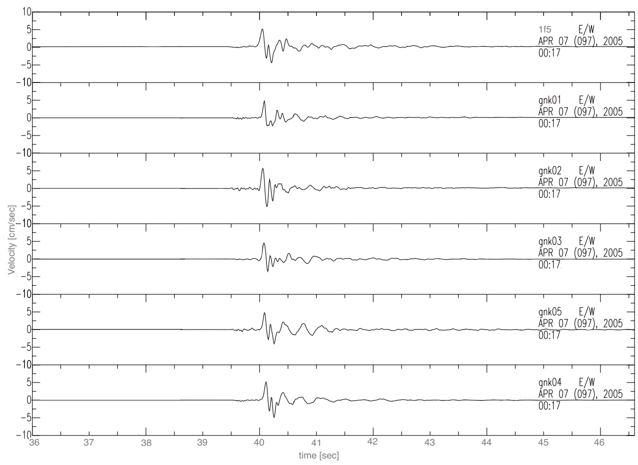

Fig. 9. Velocity waveforms of the aftershock (No. 18) recorded on Genkai Island.

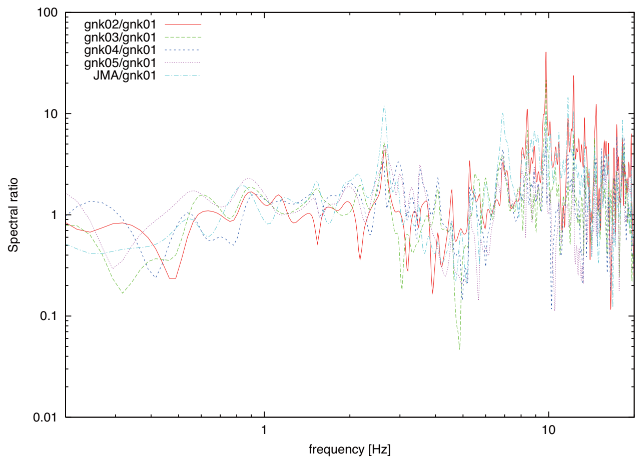

Fig. 10. Spectral ratios of the aftershock (No. 14) among the stations on Genkai Island respect to the station gnk01.

station JMA 1F5 may be affected by the both contribution from the 1–2 s ground motions mainly from the source and ground motions whose dominant periods are smaller than 0.5 s that are related to the site amplification.

As Somerville (2003) pointed out, the ground motions from the inland crustal earthquakes with subsurface faulting (M_w6.5–7.0) tend to have larger levels at the period of 1–2 s than those with surface faulting (M_w7.0–7.5) in the near-source region. This kind of seismic phenomenon may explain the large ground motion of the 2005 West Off Fukuoka Prefecture earthquake (M_w6.6). Discussion of the heterogeneous stress field will greatly improve our understanding of it.

5. Site Amplification on Genkai Island

We have carried out the ground motion simulation at station JMA 1F5 on Genkai Island. To understand its variations on the island, we investigated ground motion characteristics among stations JMA 1F5 and gnk01–gnk05 by the ERI, University of Tokyo. Figures 8 and 9 compare the non-filtered acceleration and velocity waveforms on the island stations of JMA 1F5 and gnk01–gnk05. Those waveforms look similar, especially in the amplitude and pulse width, even though the stations are several hundred meters apart from each other, at different altitudes.

We examined spectral ratios among the stations for the several aftershocks in order to identify the site amplification due to differences in altitude and location. Figure 10 displays spectral ratios among the stations and compares these to that of station gnk01 for the aftershock No. 14. Regardless of the different altitude and location of the stations, spectral ratios less than 2 Hz do not show large variations, so that the amplification due to the topography of the island is not so large. The variations seen in ratios higher than 5 Hz may relate to the local site effects around the stations. The H/V spectral ratios for the aftershocks show peaks around 1 Hz for all of the stations. This effect is considered large-scale site effects on Genkai Island.

6. Discussion and Conclusions

We performed the empirical Green's function simulation of broadband ground motions on Genkai Island during the 2005 West Off Fukuoka Prefecture earthquake. We first estimated the strong motion generation area, 8 km long by 8 km wide, that is almost compatible with the asperity estimated from the waveform inversions. The stress drop in the area is estimated to be around 17 MPa, which is higher than the standard values for the inland crustal earthquake (e.g., 10.5 MPa, after Miyake *et al.*, 2003). The rupture propagated in the southeast-upper direction and seemed to hit Genkai Island. The simulated waveforms by the empirical Green's function reproduce the larger N-S component and smaller E-W component at station FTY (Maizuru fire station) in downtown Fukuoka City. As pointed by Asano and Iwata (2006), the simulation of the larger NS component is difficult by the theoretical calculation in the low-frequency range with the 3D velocity structure. This may suggest the importance of the site and path effects as well as the source effects in the broadband frequency range.

Broadband ground motion simulations were performed for Genkai Island. The simulated waveforms show the forward directivity pulse with a dominant period of 1–2 s, corresponding to the size of the strong motion generation area, as well as the high-frequency ground motions. The velocity response is a match for that observed at station JMA Kobe, but it is not as large as that at station Takatori during the 1995 Kobe earthquake. Variations of the site amplification less than 2 Hz do not seem to be large on the island, so that the simulated velocities at station JMA 1F5 commonly correspond to the input ground motion in the village on the island at the frequency range.

In summary, we conclude that the close distance from the strong motion generation area toward the island and higher stress drop of the area with the forward rupture directivity strengthened the ground motions on Genkai Island during the 2005 West Off Fukuoka earthquake.

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