SOURCE MODELING AND STRONG GROUND MOTION SIMULATION OF THE 2007 NIIGATAKEN CHUETSU-OKI EARTHQUAKE (Mj=6.8) IN JAPAN

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ABSTRACT :

The Niigataken Chuetsu-oki earthquake (M_j=6.8) occurred on July 16, 2007, northwest-off Kashiwazaki in Niigata prefecture, Japan. In this earthquake, severe damages of fifteen people dead, about 1319 collapsed houses and so on around Kashiwazaki have been caused. In particular, strong ground motions struck the Kashiwazaki and Kariwa nuclear power plant (hereafter KK-site), and triggered a fire at an electric transformer and other troubles. although the all nuclear reactors in operation shut down safely and the damages fortunately appeared less than expected from the seismic design level by the design safety margin. The source mechanism of this earthquake is a reverse fault with the fault plane of SW-NE strike and SE dip. In this study, we tried to construct the source model by the forward modeling approach using the empirical Green's function method. Finally, we proposed the best model consisting of three asperities on the fault. In particular, we pointed out the significant pulse observed at KK-site was generated from the asperity located SW direction of the site and amplified by the folded underground structure between the asperity and the site region though the 3-D finite difference computation.

KEYWORDS: source modeling, Niigataken Chuetsu-oki earthquake, strong ground motion, empirical Green's function method, 3-D simulation

1. INTRODUCTION

The Niigataken Chuetsu-oki earthquake (M_j=6.8) occurred on July 16, 2007, northwest-off Kashiwazaki in Niigata prefecture, Japan. Severe damages of fifteen people dead, about 1319 collapsed houses and so on around Kashiwazaki have been caused. In particular, strong ground motions struck the Kashiwazaki and Kariwa nuclear power plant (hereafter KK-site), and triggered a fire at an electric transformer and other troubles. although the all nuclear reactors in operation shut down safely and the damages fortunately appeared less than expected from the seismic design level by the design safety margin. The source mechanism of this earthquake is concluded to be a reverse fault with the fault plane of SW-NE strike and SE dip from the aftershock distribution determined by a number of temporal observations including the OBS (ocean bottom seismometer). To reconfirm the seismic safety of the nuclear power plants based on new guidelines for seismic design which had been issued in September, 2006, it is very important to estimate the source process of this earthquake that radiated the strong ground motion at KK-site. From this point of view, we tried to construct the source model by the forward modeling approach using the empirical Green's function method (Irikura, 1986). The advantage of this method is that it includes the propagation path and local site effects and estimates basically broad-band ground motions as long as the aftershock recordings are accurate enough in broad-frequency band. Furthermore, this method is convenient and robust in case of having difficulty in calculating the theoretical Green’s functions because of complicated underground structure around the corresponding region. We used the main-shock and the aftershock data by K-NET, KiK-net, F-net of the National Research Institute for Earth Science and Disaster Prevention (NIED), and by Tokyo Electric Power Company (TEPCO) at KK-site. Furthermore, we verified the source model from the 3-D finite difference computation using the complicated folded underground structure model derived from the deep borehole data, reflection wave seismic surveys and so on.

2. STRONG GROUND MOTION DATA

We used broad-band acceleration data at NIG005, NIG016 and NIG025 by K-NET , at NIGH07, NIGH15 and NIGH16 by KiK-net, at KZK by F-net, and at KKZ1R2 and KKZ5R2, which are located at basement in underground of Unit 1 and Unit 5, respectively, in KK-site. The locations of these stations are shown in Fig. 1 together with the epicenters of the mainshock and the aftershock used here as the empirical Green's function. Table 1 and Table 2 show the information of the mainshock and the aftershock, respectively. The source parameters of the aftershock were estimated roughly from the displacement source spectra calculated by the borehole data of KiK-net which are not affected strongly by the reflected wave from the ground surface. We use the mainshock and aftershock data bandpass-filtered 0.2 to 10.0 Hz depending on the quality of the aftershock waveform data.

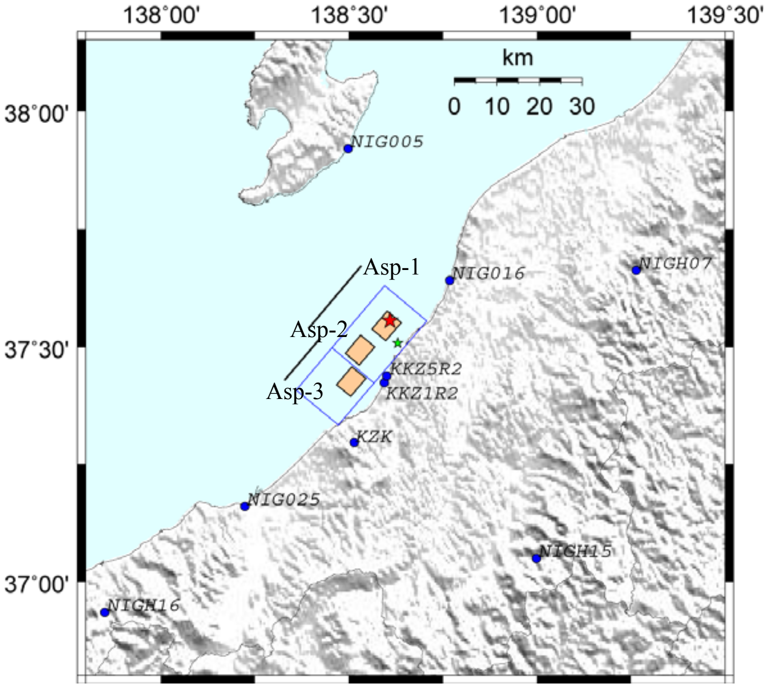

Figure 1 Map showing the location of the epicenters of the mainshock and the aftershock, observation stations and asperities. The red star, green star and blue circles indicate the location of the epicenters of the mainshock, the aftershock, and observation station respectively. The rectangular box depicts the region for the asperities.

Table 1 Information of the mainshock

Origin Time (JST)	2007/7/16 10:13
Latitude (deg)	37.557
Longitude (deg)	138.610
Depth (km)	16.8
M_{JMA}	6.8

Table 2 Source parameters of the aftershock

Origin Time (JST)	2007/7/16 21:08
Latitude (deg)	37.509
Longitude (deg)	138.630
Depth (km)	20.4
M_{JMA}	4.4
Seismic moment (Nm)*	5.21×10^{15}
Focal Mechanism Solution* [Strike/Rake/Dip] (deg)	187/54/70
	39/41/115
Area (km2)	1.4 × 1.4
Stress Drop (MPa)	4.6

* Source parameters estimated by F−net

3. SOURCE MODELING

Several inverted source models have already been proposed from teleseismic data or/and strong ground motion data (Hikima and Koketsu (2008), and Aoi (2008), Nozu (2008)). These models present two or three regions with a relatively large slip – in the part near the hypocenter, one or two parts of south-west direction of the hypocenter –. Firstly, we assumed a simplified source model composed of asperities located on three regions referring to the inverted source models. This assumption is based on the recent studies (i.e. Kamae and Kawabe (2004)) that strong ground motions near source are controlled by the asperities. Finally, we adjusted the locations, sizes, and stress parameters of those three asperities shown in Fig. 1 to fit the simulated motions to the observed ones using a forward modeling approach. In special, we regarded the fitting at KK-site near source as the important. We assumed an S-wave velocity of 3.5 km/s along the wave propagation path and a rupture velocity of 2.7 km/s on the fault plane. Furthermore, we assumed that the rupture should start from red star inside Asp-1 and propagate radially. The ruptures of Asp-2 and Asp-3 restart from each green stars after the rupture reaches each green stars and propagate radially. After several trials, we obtained the best source model shown in Fig. 1 and Fig. 2. The source parameters for each asperity are summarized in Table 3. The stress parameters (stress drop) of these asperities are 1.5- 2.0 times larger than the averaged one (About 12 MPa) for past inland earthquakes (Somerville *et al.*, 1999). As examples, the synthesized motions at KKZ1R2 and KKZ5R2 in KK-site, NIG016 of K-NET and NIGH15 of KiK-net are compared with the observed ones in Fig. 3. Fig. 4 shows the comparison between those synthetic and observed pseudo-velocity response spectra (PVRS) with a damping factor of 0.05. The synthesized waveforms and the PVRS agree with the observed ones fairly well. In particular, separate contributions from each asperity at KKZ1R2 and KKZ5R2 are well produced in the synthesized velocity and displacement waveforms. However, the synthesized ground motion from Asp-3, which is an important and destructive pulsive waveform, is slightly overestimated at KZK5R2 and is estimated well at KZK1R2. Such a discrepancy at both sites might suggested to use more appropriate aftershock data under considering the realistic propagation path effect of the seismic waves from Asp-3.

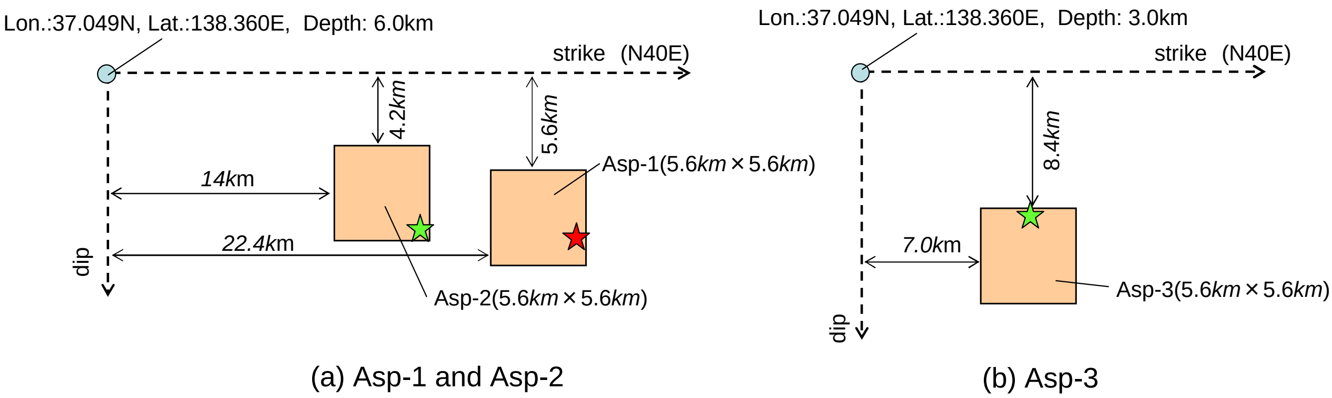

Figure 2 Source model of the Niigataken Chuetsu-oki earthquake (M_j=6.8). The red star and green stars indicate the location of the epicenter (the rupture start point of Asp-1) and the rupture start points of Asp-2 and Asp-3, respectively.

Table 3 Source parameters of the Niigataken Chuetsu-oki earthquake (M_j=6.8)

	Strike (°)	Dip (°)	Rake (°)	S (km^2)	Mo (Nm)	Δσ (MPa)
Asp−1	40	40	90	5.6 × 5.6	1.33×10^{18}	18.4
Asp−2	40	40	90	5.6 × 5.6	2.00×10^{18}	27.6
Asp−3	40	40	90	5.6 × 5.6	1.67×10^{18}	23.0

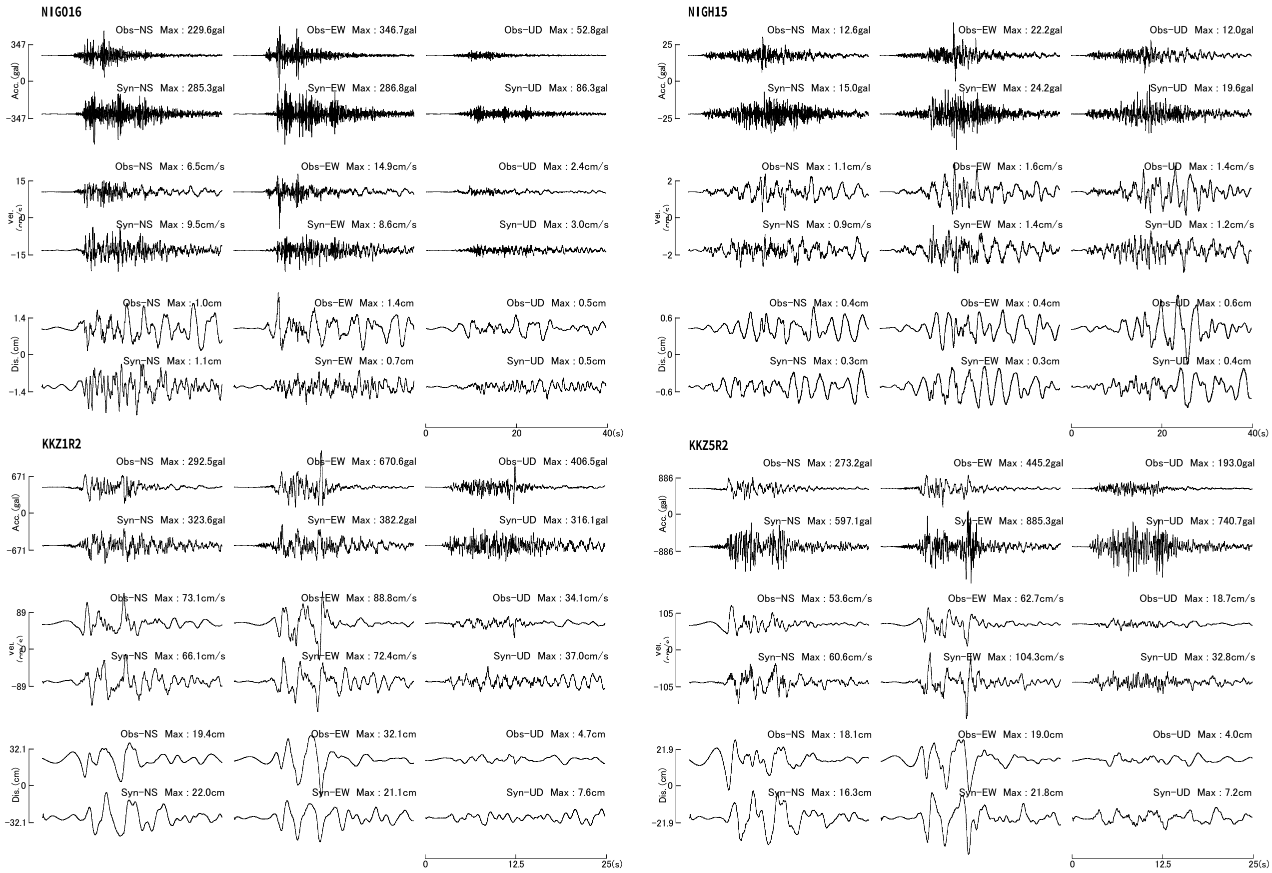

Figure 3 Comparison between the synthesized and observed motions at NIG016, NIGH15, KKZ1R2 and KKZ5R2.

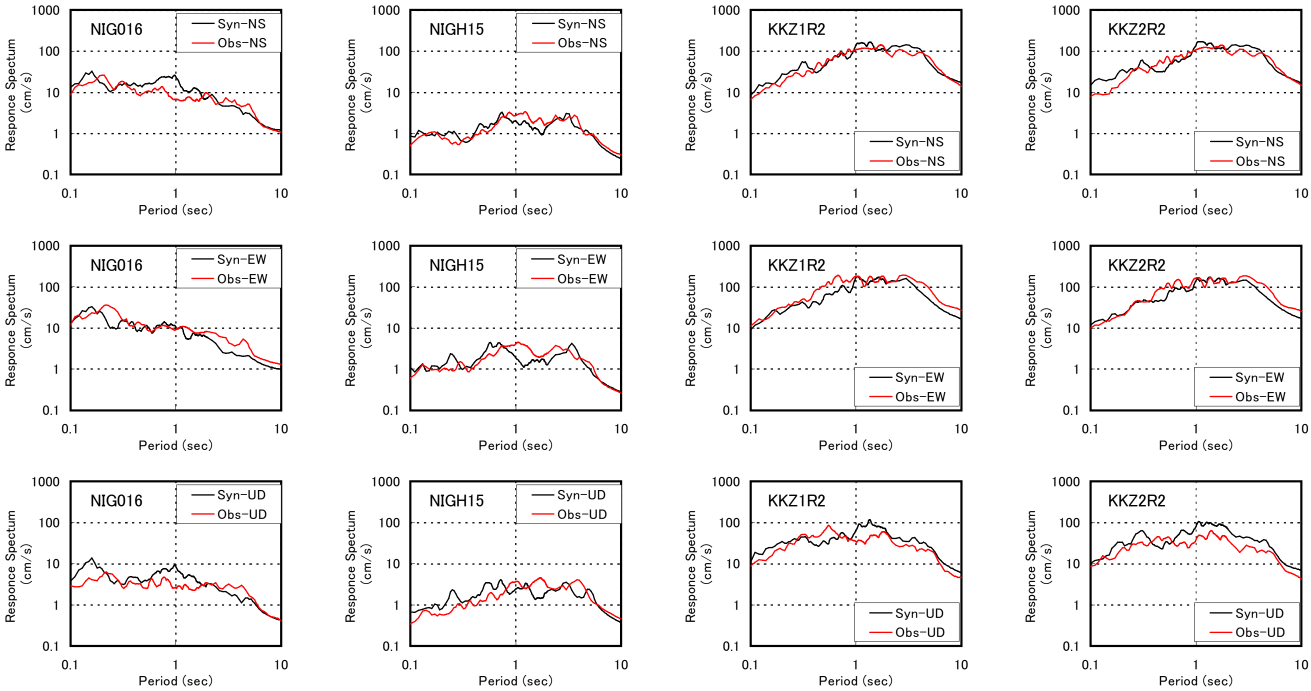

Figure 4 Comparison of the pseudo-velocity response spectra (PVRS) with damping factor of 0.05 of the synthesized motions and those of the observed motions at four sites. Black line shows the PVRS of the synthesized motions. Red line shows the PVRS of the observed motions.

3. 3-D SIMULATION AND DISCUSSION

Ground motion simulations were performed using 3-D finite-difference procedure proposed by Pitarka (1999) to verify the validity of the proposed source model and to investigate why the destructive pulsive waveforms from Asp-3 were generated at KKZ1R2 and KKZ5R2 in KK-site. This simulation algorithm is accurate to fourth order in space and second order in time, and with a non-uniform spacing staggered-grid formulation. We set an absorbing region outside the finite computation region shown in Fig. 5 and applied the non-reflecting boundary condition of Cerjan *et al*. (1985) and the A1 absorbing boundary condition of Clayton and Engquist (1977). The implementation of the attenuation into the method is based on the technique by Graves (1996), which considers Q to be identical and frequency dependent for both P and S waves (Kawabe and Kamae, 2008). The 3D velocity structure used for this region (44.4km×60.0km) is from Japan Nuclear Energy Safety Organization (2005) (2005). This model is composed of several layers with different velocity on basement rock. The depths of each sedimentary layer and basement rock surface are shown in Fig. 6. The parameters of these layers are summarized in Table 4. Fig. 7 illustrates the simulated peak ground velocity (PGV) distribution in a horizontal component (EW). Fig. 8 shows the comparison between the synthesized velocity waveforms and the observed ones in frequency range of 0.05-1.6 Hz at KKZ1R2 and KKZ5R2. Here, you should notice that the synthetics are amplified 1.5 times of the original ones. You can see that the waveforms are simulated fairly well at both stations although the amplitudes are underestimated about 1.5 times comparing with the observed ones because of not including lower velocity layers in the current 3D model. Furthermore, the conspicuous different ground motion amplification from Asp-3 between KZK1R2 and KZK5R2 is not completely reproduced because of the same reason. However, we concluded from Fig. 7 representing the PGV distribution in vertical cross section that this is due to a focusing of seismic wave depending on the folded underground structure in this region. Next, we attempted to investigate quantitatively the 3 dimensional effect at KZK1R2 from the comparison with the one dimensional computation using the discrete wavenumber method (Bouchon, 1981). Fig. 9 shows the comparison of PGV distributions between a couple of the techniques in EW direction passing through KZK1R2. The synthesized PGV at KZK1R2 is amplified about 1.5 times by the 3 dimensional effect. These results suggest the validation of the proposed source model composed of three asperities and the importance of considering a detailed underground structure in strong ground motion predictions.

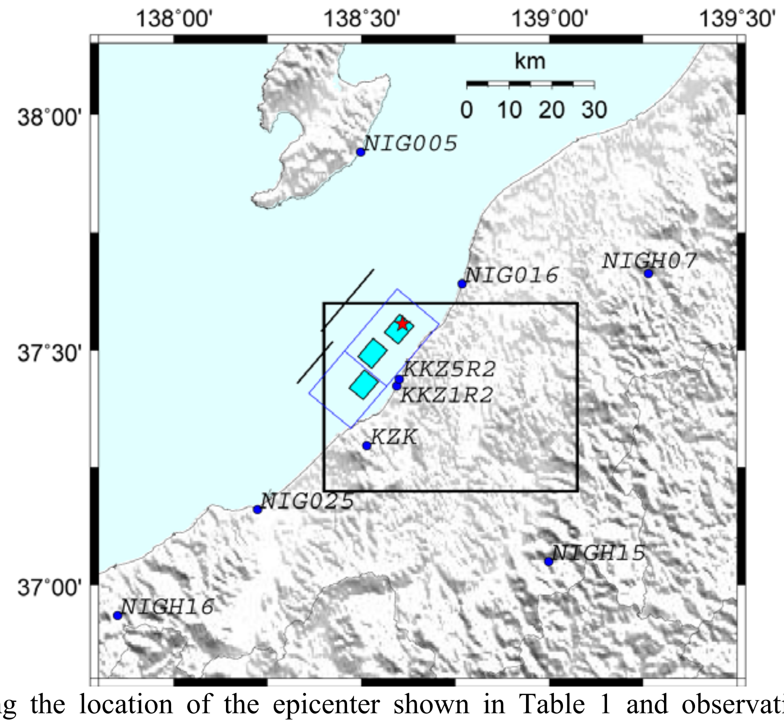

Figure 5 Map showing the location of the epicenter shown in Table 1 and observation stations. The thick rectangular box depicts the region for the 3D finite difference simulation.

Table 4 Parameters of the velocity structure model

Layer No.	density (g/cm^3)	Vs (km/s)	Vp (km/s)
Layer 1	2.05	0.80	2.20
Layer 2	2.20	1.30	2.90
Layer 3	2.25	1.40	3.10
Layer 4	2.35	1.70	3.70
Layer 5	2.40	2.00	4.10
Layer 6	2.50	2.40	4.70
Layer 7	2.65	3.00	5.50
Layer 8	2.70	3.50	5.80

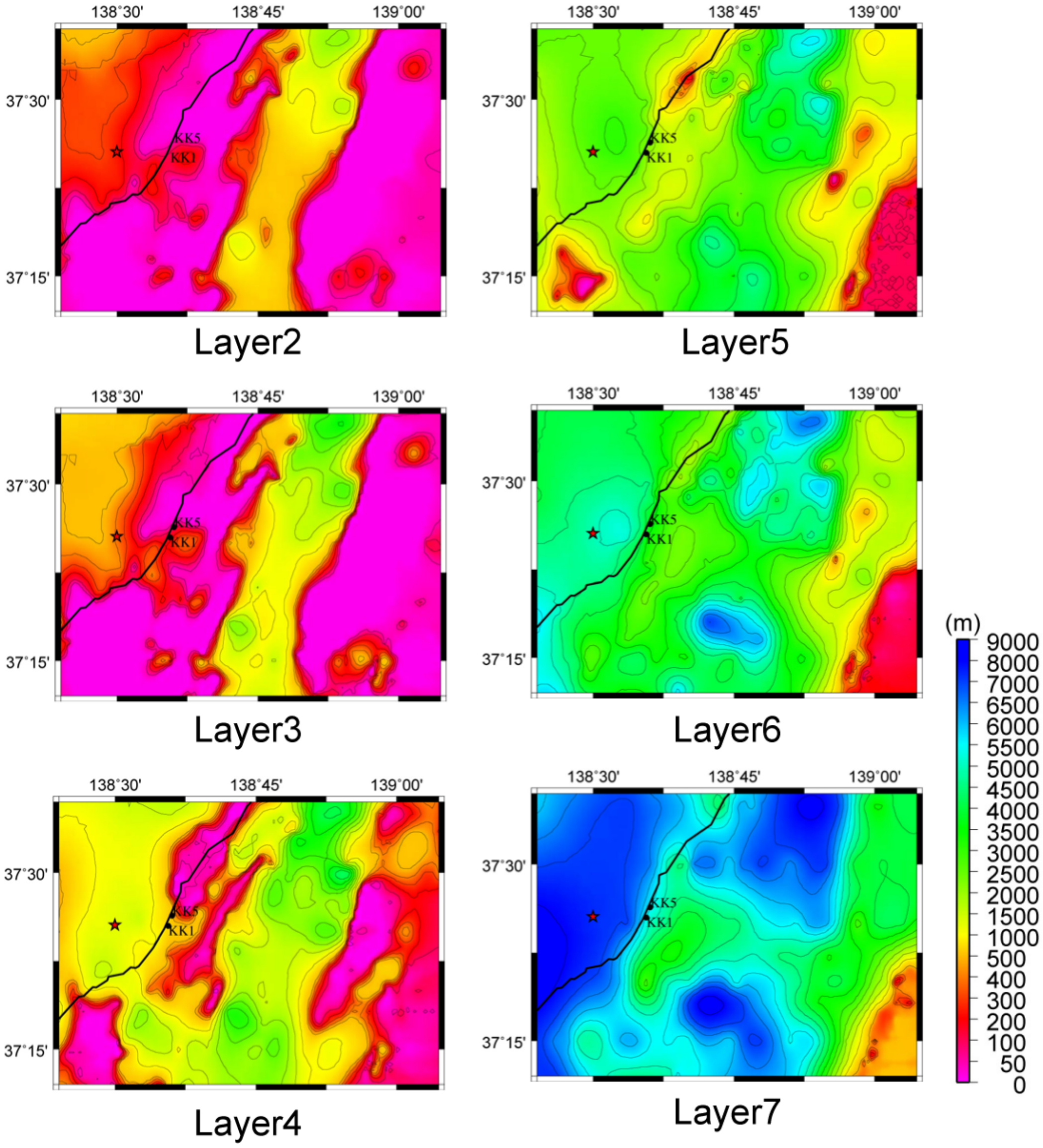

Figure 6 Topography of the bedrock surface and the boundaries between sedimentary layers of the velocity structure model.

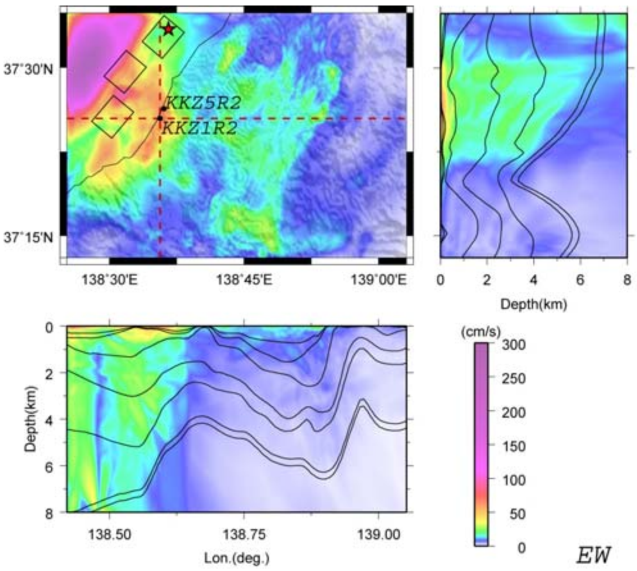

Figure 7 The simulated peak ground velocity (PGV) distribution on surface and in two cross-sections passing through KZK1R2.

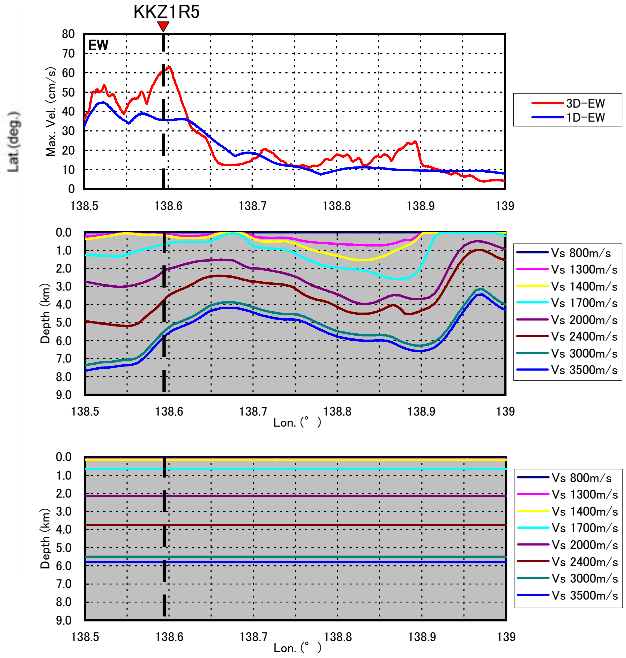

Figure 9 The comparison of PGV distributions between a couple of the techniques in EW direction passing through KZK1R2.

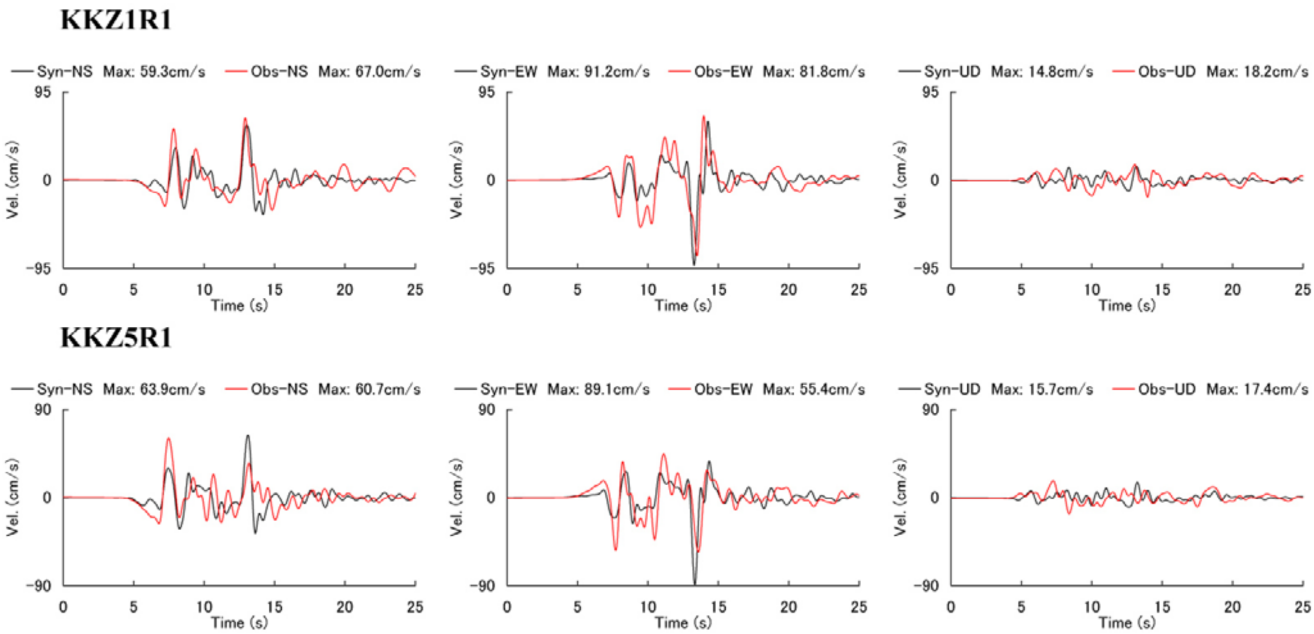

Figure 8 The comparison between the synthesized velocity waveforms and the observed ones in frequency range of 0.05-1.6 Hz.

4. CONCLUSIONS

To investigate why the destructive ground motions were observed at KK-site during the Niigataken Chuetsu-oki earthquake, Japan, we firstly proposed the source model consisting of three asperities on the reverse fault plane with SE dipping by the forward modeling using the empirical Green's function method, secondly verified the validation of the model through some theoretical simulations (3-D and 1-D simulations). We found that the large amplitude ground motion from Asp-3 lying south-west direction of the KK-site was amplified by the focusing of the seismic wave due to the folded underground structure. A more detailed investigation is needed in simulations using the continuous geological surveys at just KK-site as well as in the corresponding region.

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