Rupture process and strong ground motions of the 2007 Niigataken Chuetsu-Oki earthquake -Directivity pulses striking the Kashiwazaki-Kariwa Nuclear Power Plant -

Summary

The Niigataken Chuetsu-Oki earthquake occurred on July 16, 2007, northwest-off Kashiwazaki in Niigata Prefecture, Japan, causing severe damages of ten people dead, about 1300 injured, about 1000 collapsed houses and major lifelines suspended. In particular, strong ground motions from the earthquake struck the Kashiwazaki-Kariwa nuclear power plant (hereafter KKNPP), triggering a fire at an electric transformer and other problems such as leakage of water containing radioactive materials into air and the sea, although the radioactivity levels of the releases are as low as those of the radiation which normal citizens would receive from the natural environment in a year.

The source mechanism of this earthquake is a reverse fault, but whether it is the NE-SW strike and NW dip or the SW-NE strike and SE dip are still controversial from the aftershock distribution and geological surveys near the source. Results of the rupture processes inverted by using the GPS and SAR data, tsunami data and teleseismic data so far did not succeed in determining which fault planes moved.

Strong ground motions were recorded at about 390 stations by the K-NET of NIED including the stations very close to the source area. There was the KKNPP which is probably one of buildings and facilities closest to the source area. They have their own strong motion network with 22 three-components' accelerographs locating at ground-surface, underground, buildings and basements of reactors.

The PGA attenuation-distance relationships made setting the fault plane estimated from the GPS data generally follow the empirical relations in Japan, for example, Fukushima and Tanaka (1990) and Si and Midorikawa (1999), even if either fault plane, SE dip or NW dip, is assumed. However, the strong ground motions in the site of the KKNPP had very large accelerations and velocities more than those expected from the empirical relations. The surface motions there had the PGA of more than 1200 gals and even underground motions at the basements of the reactors locating five stories below the ground had the PGA of 680 gals.

We simulated ground motions using the characterized source model (Kamae and Irikura, 1998) with three asperities and the empirical Green's function method (Irikura, 1986). Then, we found that the source model should be a reverse fault with the NE-SW strike and NW dip to explain the strong motion records obtained near the source area. In particular, strong ground motions in the site of the KKNPP had three significant pulses which are generated as directivity pulses in forward direction of rupture propagation. This is the reason why the strong ground motions in the site of the KKNPP had very large accelerations and velocities. The source model is also verified comparing the observed records at the KKNPP with the numerical simulations by the discrete wavenumber method (Bouchon, 1981).

1. How strong are ground motions from this earthquake ? -Comparison between observation and empirical attenuation relationships of PGA and response spectra-

High seismic intensity of 6-upper in the JMA scale were measured intensively in an area along the coast line south of the epicenter of this earthquake (Fig.1). The KKNPP is located inside the high intensity area. Strong ground motions on surface observed at K-NET stations are shown in Fig.2 and those on surface and in underground at the KKNPP in Fig.3. The records at NIG018 and NIG019 and KKNPP have two or three distinct pulses. Especially, at the surface station near Unit 5 of KKNPP, maximum acceleration over 1200gal was recorded. The relationship between observed peak horizontal accelerations at K-NET and shortest distances to the source fault is shown in Fig. 4. The source faults are here assumed, determined by the Geographical Survey Institute using the GPS data. The PGA attenuation-distance relationships generally follow the empirical relations in Japan, obtained by Fukushima and Tanaka (1990) and Si and Midorikawa (1999), even if either fault plane, SE dip or NW dip, is assumed. However, the strong ground motions in the site of the KKNPP had markedly large accelerations more than those expected from the empirical relations.

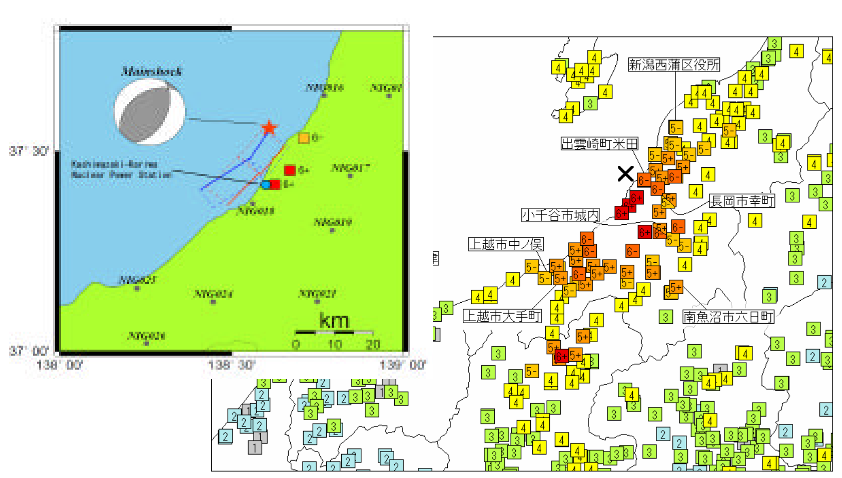


Fig.1. The focal mechanism (determined by NIED) and distribution of seismic intensity from the 2007 Niigata-ken Chuetsu-Oki earthquake.

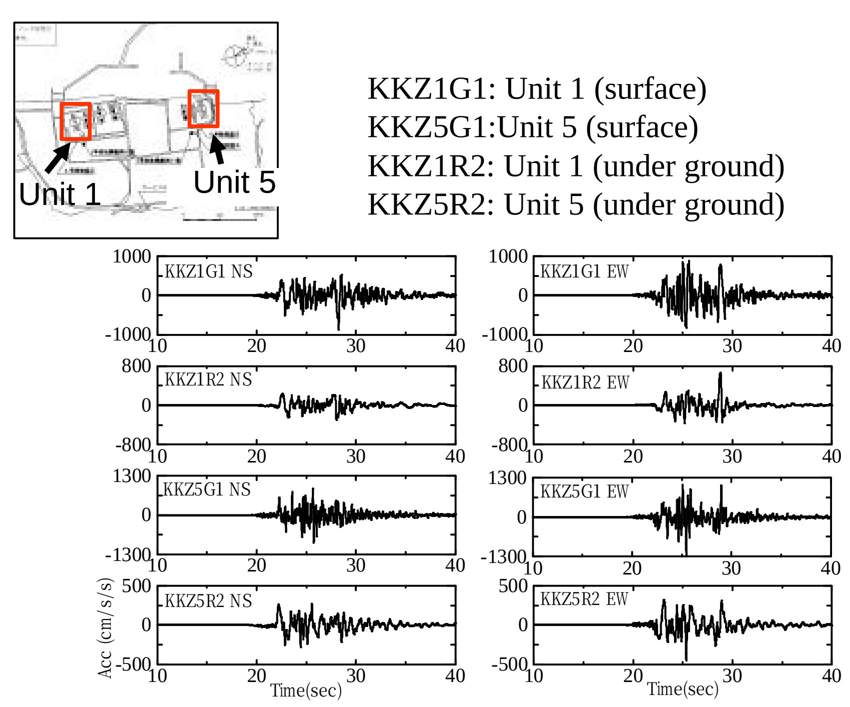


Fig.2. Example of horizontal acceleration waveforms at Units 1 and 5 of the KSWAPP.

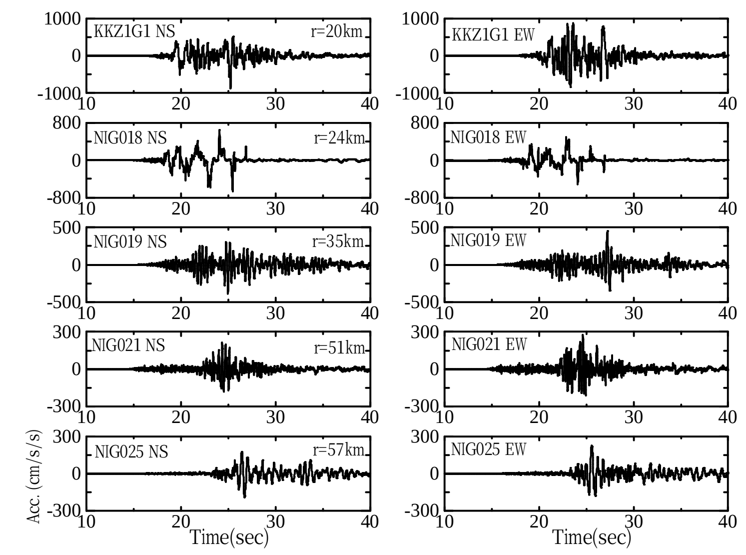


Fig.3. Examples of horizontal acceleration waveforms in near-source region.

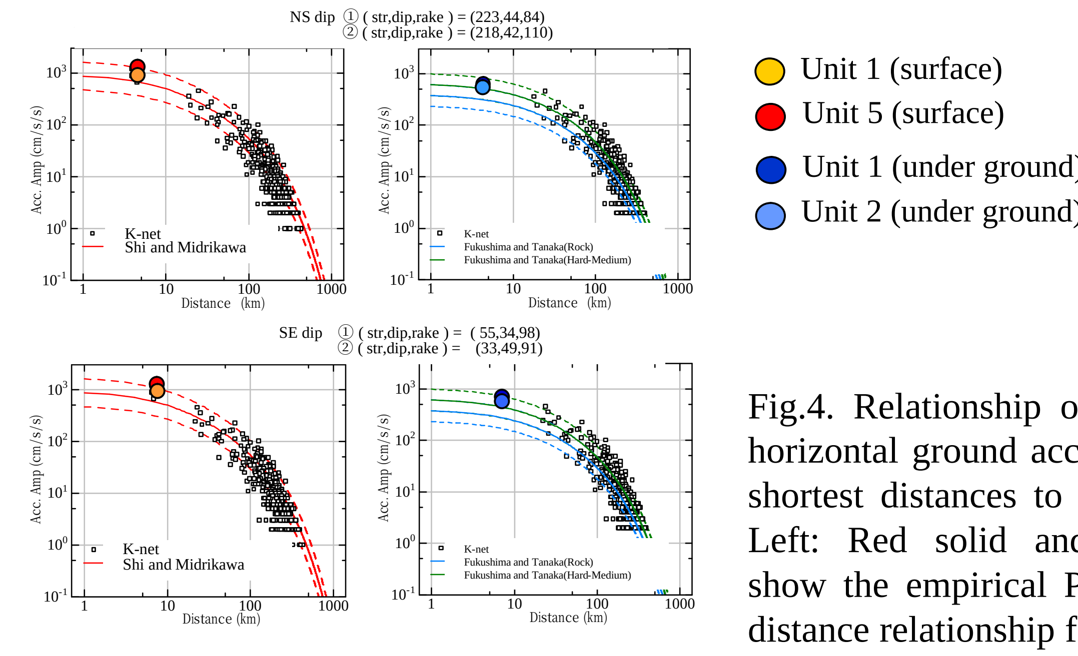
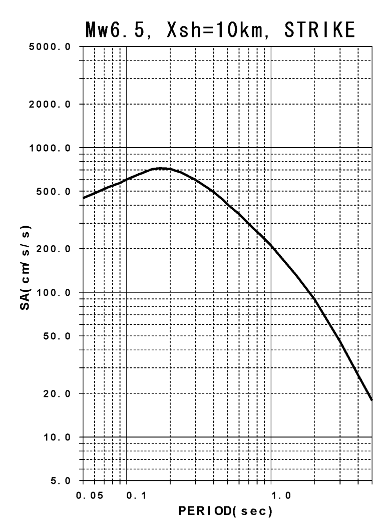


Fig.4. Relationship of observed peak horizontal ground accelerations versus shortest distances to the source fault. Left: Red solid and dotted curves show the empirical PGA attenuation-distance relationship for surface data (no site classification) by Si and Midorikawa (1999) and its standard deviation. Right: Green and blue curves show that for the average of medium and hard soil surface data and that for rock surface data.

Event factors of observed ground motions are studied for two different dip models (NW dip and SE dip). The event factors are estimated as average spectral ratio of observed response spectra to empirical spectra proposed by Abrahamson and Silva(1997) shown in Fig.5. The results are shown in Fig.6. The top and bottom panels indicate the event terms due to assumed NW-dip (model A) and SE-dip (model B) faults. The data whose shortest distances are within 30 km are used for the estimation. The result suggests that the earthquake is not a particular but almost a normal one.



Attenuation relationship

$$\ln S_a(f) = f_1(M, r_{rup})$$

$$+F \cdot f_3(M)$$

Effect of hanging wall

$$+HW \cdot f_4(M, r_{rup})$$

$$+S \cdot f_5(pga_{rock})$$

Ground response (non-linear)

Fig.5. Spectral attenuation relationship by Abrahamson and Silva (1997).

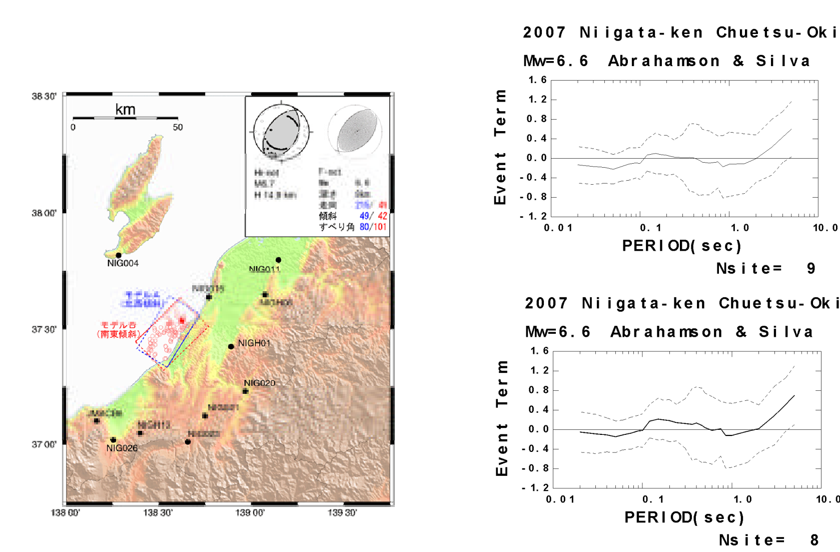


Fig.6. Map showing two fault planes with the SE and NW dips, respectively, by NIED (left) and estimated event terms due to the fault planes (right).

2. Source model estimated using the empirical Green's function method

We estimate the source model of the Niigata-ken Chuetsu-Oki earthquake using the empirical Green's function method. The strike and dip of the source model are estimated from the aftershock distribution determined by ERI of University of Tokyo as shown in Fig.7. Referring the slip distribution estimated with the waveform inversion using the empirical Green's functions by Nozu (2007) as shown in Fig. 8, we set an initial model consisting of three asperities and obtained the best-fit model by forward modeling to minimize the residuals between the observed and synthesized. Strong motion data at 16 stations in Fig 9 are used in this analysis.

The best-fit source model is shown in Fig10 and the source parameters are summarized in Table 3. The first asperity (ASP 1) is located near the hypocenter of the mainshock, the second (Asp 2) in the deeper part of south-west direction of the hypocenter; and the third (Asp 3) in the shallow part of south-east direction of Asp 2. Asp 3 is largest among the three asperities. As examples, the synthesized motions at NIG018, NIG019, NIG021, KKZ1R2 and KKZ5R2 are compared with the observed ones in Fig 11. The synthesized waveforms agree with the observed ones fairly well. In particular, three pulses in synthesized velocity and displacement waveforms are well produced at KKZ1R2 and KKZ5R2 located at B5F in underground of Unit 1 and Unit 5, respectively. The rupture on Asperity 3 propagates from sea side to land side, making significant directivity pulse as the third pulse of the waveforms of KKZ1R2 and KKZ5R2.

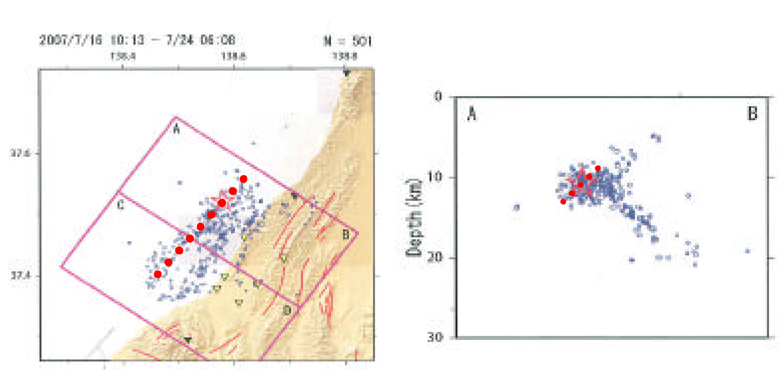


Fig.7. Aftershock distributions in the horizanntal plane and cross section perpendicular to the strike within 8 hours after the occurrence of the mainshock determined by ERI of University of Tokyo. We determined the strike and dip of the fault plane of this earthquake from this aftershock distribution.

Kojiro Irikura(1), Takao Kagawa(2), Ken Miyakoshi(2) and Susumu Kurahashi(1)
(1) Aichi Institute of Technology, Japan, (2) Geo-Research Institute

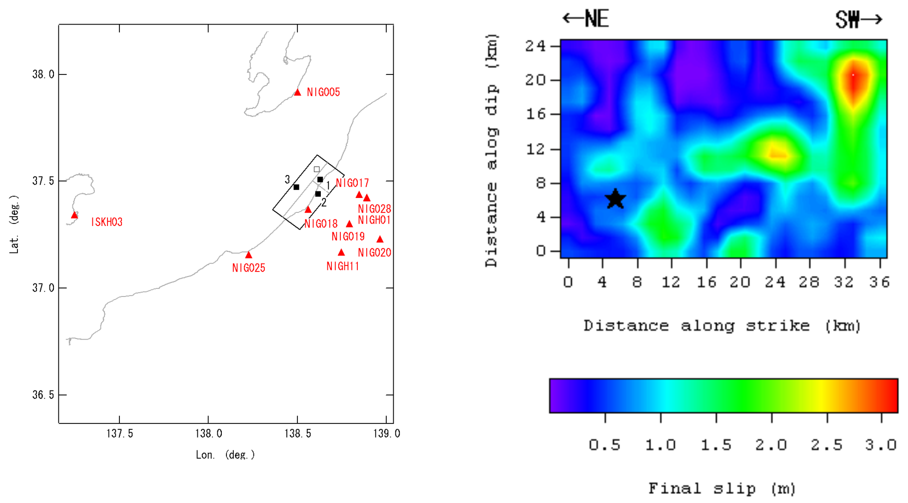


Fig.8. Slip model of this earthquake estimated with the wave inversion using the empirical Green's functions by Nozu (2007) (right). The epicenters of aftershocks and locations of K-NET stations used in the analysis are shown in the left.

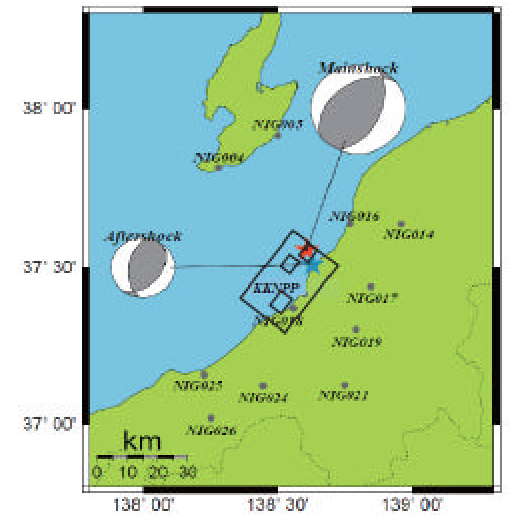


Fig.9. Map showing the locations of K-NET stations and KKNPP (circle) and the epicenters of the mainshock (red star) and an aftershock (blue star).

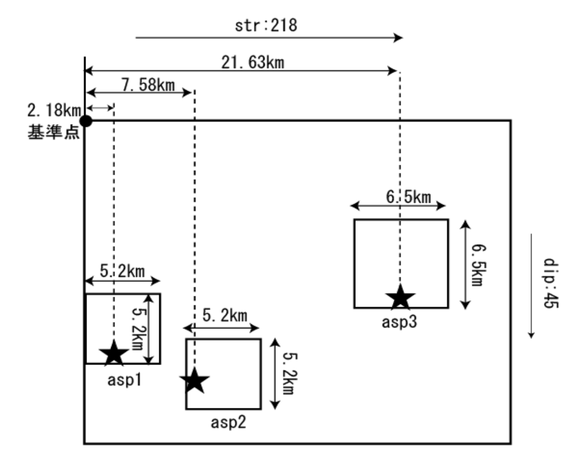


Fig.10. Source model consisting of three asperities estimated by forward modeling.

Table 1. The information of the mainshock and an aftershock used as the empirical Green's function.

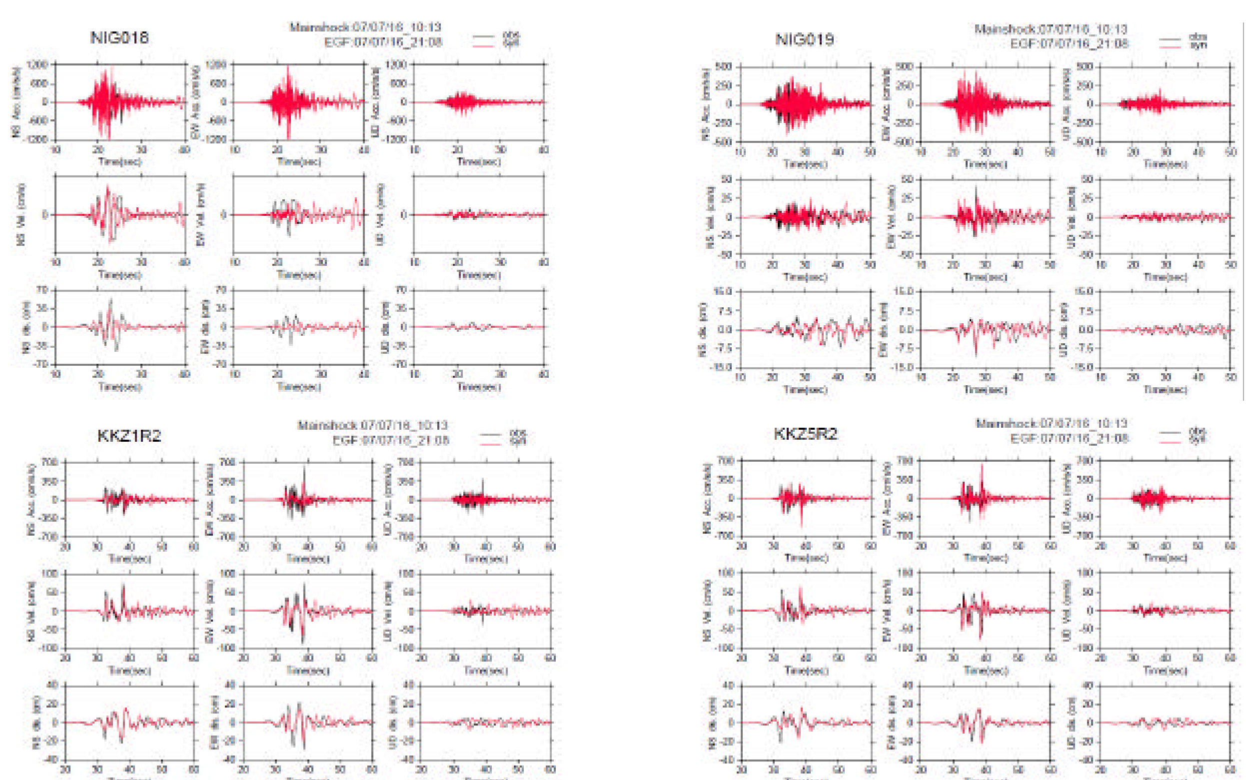
	Main shock	After shock
Origin time	07/07/16 10：13	07/07/16 21:08
Hypocentral	37.557, 138.609	37.509, 138.630
Depth	12km	20.4km
Mw	6.6	4.4
Mo（F-net）	8.37E+18Nm	5.21E+15Nm
（str,dip,rake）（F-net）	25/223 51/42 72/111	187/39 54/41 70/115

Table 2. The fault plane of the mainshock. We determined the strike and dip using the aftershock distribution.

Straike	Dip	rake	Latitude	Longitude	depth
218	45	90	37.5045	138.7301	0km

Table 3. The source parameters for each asperity.

	Rupture start point	depth	Mo(Nm)
Asp1	(2, 4)	12.0km	8.7×10^{17}
Asp2	(1, 3)	13.4km	9.0×10^{17}
Asp3	(3, 5)	9.2km	1.5×10^{18}
	L(km)×W(km)	⊿σ(MPa)	Risetime (second)
Asp1	5.2×5.2 (N: 4×4)	15.1	0.5
Asp2	5.2×5.2 (N: 4×4)	15.6	0.6
Asp3	6.5×6.5 (N: 5×5)	13.3	0.6



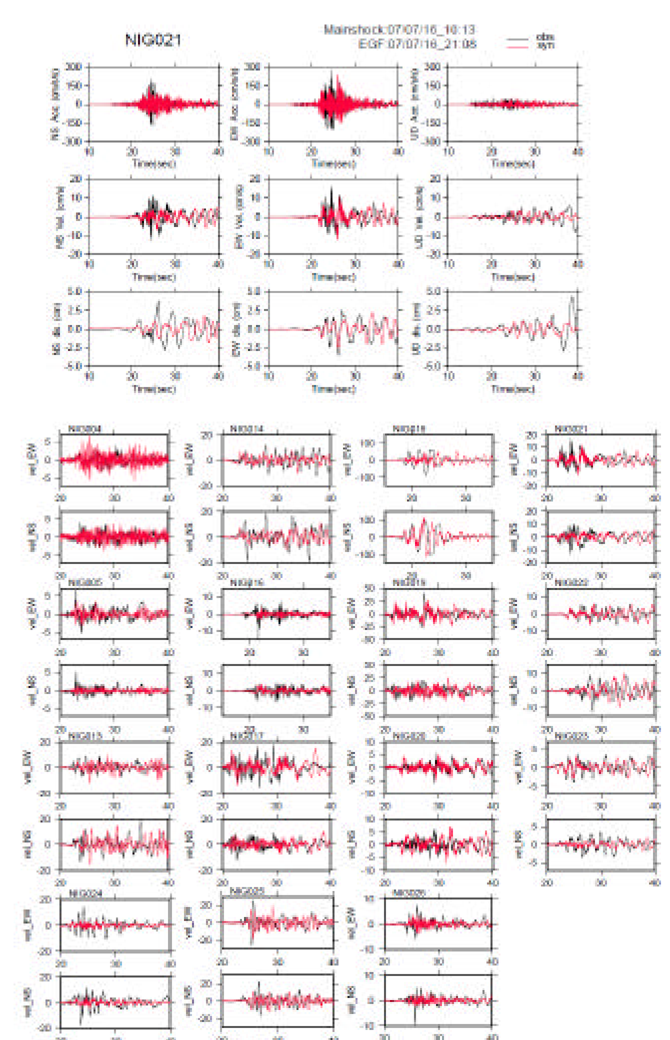


Fig.11. Comparison between the observed records (black) and synthesized motions (red). Acceleration (top), velocity (middle), and displacement (bottom) are shown at NIG018,NIG019,NIG021,KKZ1R2 and KKZ5R2.

Left figure shows comparison of velocity waveform between observed and synthesized motions of NS and EW components at 16 stations.

3. Improvement of the source model by comparing observation with theoretical simulation

Referring to the initial source model (Model 1) estimated by empirical Green's function method, next we revised source model (Model 2) using theoretical Green's function method. The discrete wavenumber method (Bouchon, 1981) associated with the reflection transmission propagator matrix method (Kennett and Kerry, 1979) was used to calculate theoretical Green's functions. Fig.12 shows S-wave velocity structure at KKZ1R2 and KKZ5R2. Theoretical velocity waveforms, which were calculated from Model 1, are overestimated at NIG018 (K-NET). Fig. 13 shows Model 2. Fig.14 shows theoretical velocity waveforms calculated from Model 2 at KKZ1R2 and KKZ5R2. The calculated waveforms agree well with the observed waveforms. Fig.15 shows the comparison of theoretical waveforms at KKZ1R2 calculated from the rupture process having multi-hypocenters (1) and circular front (2). The directivity pulses at KKZ1R2 are recognized in theoretical waveforms calculated from the rupture process having multi-hypocenters. Strong ground motions in the site of the KKNPP plant, which had three large pulses, are generated as directivity pulses in forward direction of rupture propagation from three asperities. To explain such directivity pulses, the source model should be a reverse fault with the NE-SW strike and NW dip.

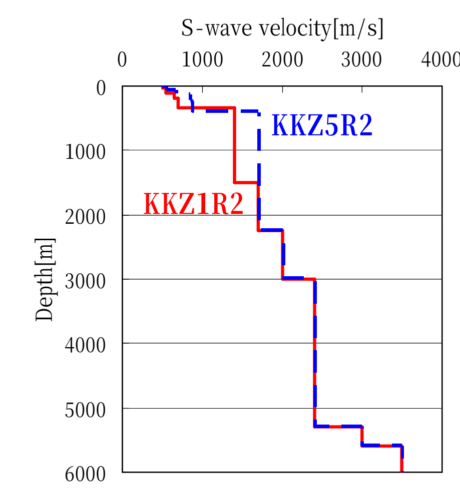


Fig.12. S-wave velocity structure at KKZ1R2 and KKZ5R2 (Kamae and Kawabe, 2007).

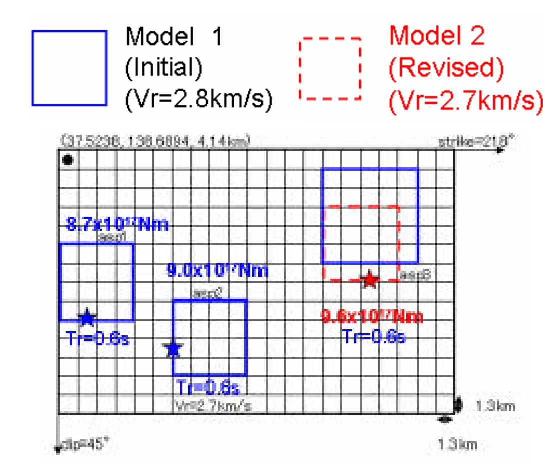


Fig.13. Initial source model (Model 1) and revised source model (Model 2).

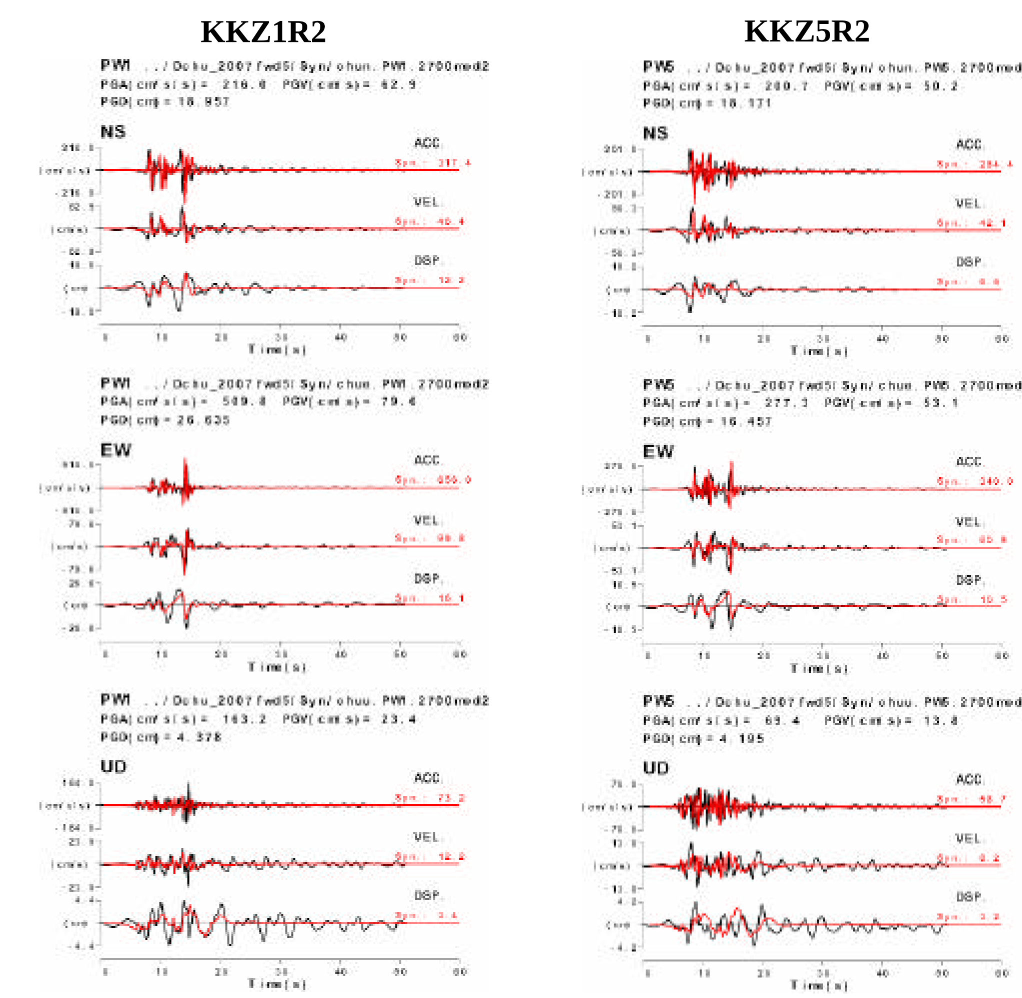


Fig.14. Theoretical velocity waveforms (red) calculated from Model 2, comparing with the observed waveforms (black) at KKZ1R2 (left) and KKZ5R2 (right).

(1) multi-hypocenters (2) circular front

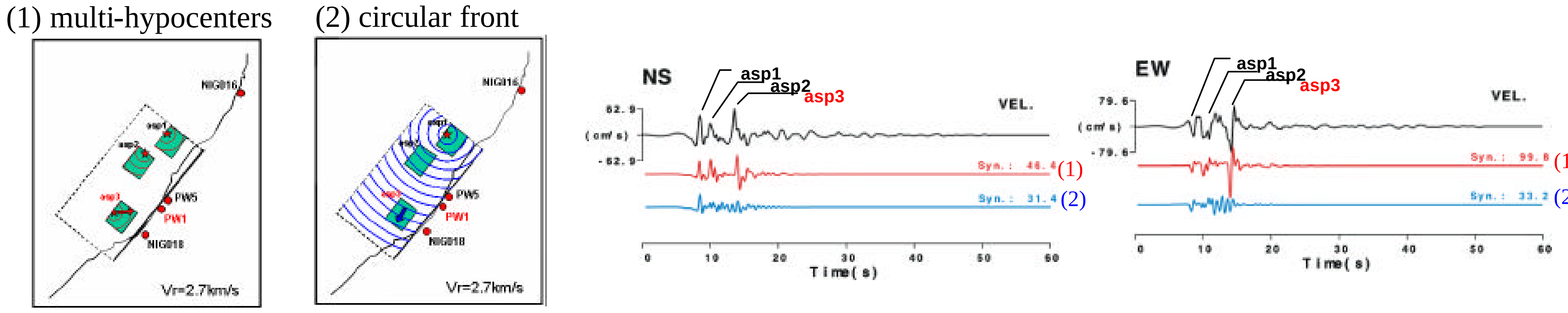


Fig.15. Comparison of theoretical waveforms at KKZ1R2 calculated from the rupture process having multi-hypocenters (1) and circular front (2).

Acknowledgements

We appreciate National Research Institute for Earth Science and Disaster Prevention (NIED) for providing the K-NET, KiK-net and F-net data. We also thank to Tokyo Electric Power Company (TEPCO) for providing strong ground motion data at the Kashiwazaki-Kariwa nuclear power plant.