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Modeling 3D Velocity Structure in the Fault Region of the 2007 Niigataken Chuetu-Oki Earthquake with Folding Structure

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ABSTRACT

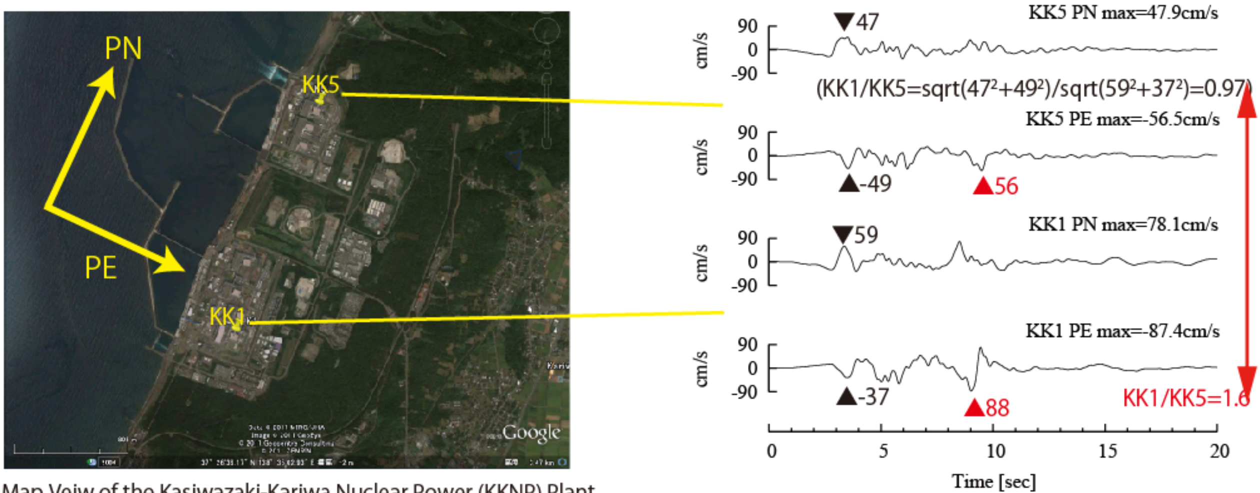
The 2007 Niigataken Chuetsu-Oki Earthquake (M6.8) produced large ground motions for the sites close to the fault plane including the Kashiwazaki-Kariwa nuclear power plant (KKNPP). For this plant, the spatial variations of ground motion have been observed (e.g., Hijikata et al., 2010). Some studies reported that the folding structure near the KKNPP cause this variations (Tokumitsu et al., 2009). In order to explain this ground motion variations, we have constructed the velocity model including the folding structure near the KKNPP where the large ground motions have been recorded. We also changed the S-wave velocity of the second layer of folding structure based on the results of R/V ratio of observed ground motions on the KKNPP. We could reproduce the general features of ground motion on the KKNPP by the simulation of finite difference method with variable grid (Pitarka, 1999) for moderate sized events which occurred on the fault area of main shock (Chuetsu-Oki earthquake) and the aftershock of the 2004 Chuetsu earthquake. Finally we have simulated the observed records for main shock of 2007 Chuetsu-Oki Earthquake to investigate the effects of folding structure on ground motion features at the KKNPP.

INTRODUCTION

The 2007 Niigataken Chuetsu-Oki Earthquake (M 6.8) produced large ground motions on many sites, including the Kashiwazaki-Kariwa nuclear power (KKNP) plant locating very close to the source despite of its size. The observed waveforms from this event constitute three distinct pulses at many sites. This means that three asperities that radiate more energy than their surroundings exist in the source area (Miyake *et al.,* 2010). We show the observed waveforms of the man shock at two sites inside the KKNPP in Fig. 1. As already mentioned, three distinct pulses for each waveform could be recognized (second pulse was not so clear to distinguish it, though). We compared the maximum values of the first pulse in Fig. 1 and recognized that the maximum amplitudes for the first, corresponding to the black triangles, and second pulses were similar. On the other hand, even both sites are located within 2 km distance, the maximum amplitudes of third pulse corresponding the red triangles in the waveforms of Fig. 1 that look coming from the third asperity are different for two sites. The peak ground velocity on the south side of the KKNPP (KK1) is much larger than that on the north side (KK5). The reason for making this difference is still in debate (Hijikata *et al.,* 2010). Uetake *et al.* (2011) and Tokumitsu *et al* (2011) pointed out that this difference would come from the folding structure below the KKNPP. Watanabe *et al.* (2011) examined the amplification factors based on the two dimensional models with folding structures for these two sites and succeeded to reproduce the larger amplification factors of KK1 than those of KK5.

In this study, we have tried to estimate the effects of folding structures below the KKNPP on ground motions. We first incorporated the folding structure into the three-dimensional velocity model surrounding the KKNPP by the combination of two different velocity models and constructed the three-dimensional velocity model. The results of ground motion simulations for the moderate sized event shows that this model worked well for the simulations for the events that occurred around the source region of Chuetsu-Oki earthquake.

Finally, we simulated the main shock of Chuetsu-Oki earthquake by using the constructed velocity model including folding structure and the source model (Shiba *et al.*, 2011). We compared how the waves are propagated from first and third asperity that produced ground motion variations between KK1 and KK5 site. The results of simulation indicate that the constructed velocity model worked well and that the folding structure beneath the KKNPP played an important role during the main shock of Chuetsu-Oki earthquake.



(a) Map Veiw of the Kasiwazaki-Kariwa Nuclear Power (KKNP) Plant

(b) Observed waveform (0.1-4.0 Hz) from main shock of the 2007 Niigataken Chuetsu-Oki earthquake on the KKNPP (KK1 and KK5 site)

Fig. 1 Observed seismograms at the KKNPP from the main shock of the 2007 Niigataken Chuetu-Oki Earthquake (PN: Plant- North Component, PE: Plant-East Component)

CONSTRUCTION OF THE THREE-DIMENSIONAL VELOCITY MODEL

The velocity model used in this study is made by the combination of two models. First one is the three-dimensional velocity model built by the Japan Nuclear Energy Safety Organization (JNES), which covers broad area including Chuetsu area (JNES, 2008). We call this model 'Broad model', hear after. This model has 7 geological layers, such as Uonuma+Haizume, Nishiyama, Shiiya, Upper-Teradomari, Lower-Teradomari, Nanaya+Green Tuff and Basement. Each layer us subdivide into some small layers based on the material parameters shown in Table 1. JNES (2008) confirmed that this model generally worked well for the ground motion simulation, however, the folding structure below the KKNPP is no included.

The other model includes the folding structure. This model is based on the modification of two-dimensional model established by Tokumitsu *et al.* (2009). They precisely modeled the folding structures below the KKNPP based on the results of geophysical surveys. They got seven two-dimensional sections, S1 to S7 in Fig. 2. We interpolate between them and construct three dimensional models on the squares shown in Fig. 2. As for the outside of this model, we expanded the most outer section (S1 and S7) to the lines of S1' and S7', respectively. We call this model 'Local Folding model' hear after.

Before we combine these two models, we tuned the S-wave velocity of local folding model. We have tried to match the predominant periods of theoretical R/V ratio or H/V ratio with those of the observed records for some sites on the KKNPP. We picked KK1 site as the southern part of the plant and KK5 site as the northern part of the plant based on Uetake (2010). The observed H/V ratios are calculated by using the records of the Off-Ibaragi earthquake (M_j 7.0) on May 8 2008. In order to match the predominant frequencies of the observed records, we changed the S-wave velocity of the Shiiya layer to 1.2 km/s from 1.0 km/s shown as the Table 1(b). We show the comparison of H/V ratio based on the observed records with the theoretical ones in Fig. 3. Modified models (Vs 1.2 km/s for the Shiiya layer) show good agreement of the predominant frequencies around 0.3 Hz. After we made the local folding model based on the procedure mentioned above, we substituted the area surrounding the KKNPP of the broad model above the lower-Teradomari layer into the local folding model. The lower-Teradomari layer in broad model is located deeper than that in local folding model around the KKNPP. This holds the folding structure on the upper surface of the lower-Teradomari and above layers of local folding model.

Table 1: Material parameters of the velocity model

(a) Material parameters for broad model

No.	Geological Layer	Vs [km/s]	Vp [km/s]	ρ [g/cm^3]
1	Uonuma+Haizume 1	0.70	1.7	1.86
2	Uonuma+Haizume 2	0.98	2.0	1.98
3	Uonuma+Haizume 3	1.08	2.5	2.13
4	Nishiyama 1	0.70	1.7	1.86
5	Nishiyama 2	0.98	2.0	1.98
6	Nishiyama 3	1.08	2.5	2.13
7	Shiiya 1	0.84	1.9	1.94
8	Shiiya 2	0.98	2.5	2.13
9	Shiiya 3	1.68	3.3	2.30
10	Upper-Teradomari	1.87	3.7	2.30
11	Lower-Teradomari	2.20	4.1	2.40
12	Nanaya+Green Tuff	2.64	4.7	2.50
13	Basement	3.15	5.5	2.65

(b) Material parameters for local folding model

Geological Layer	Vs [km/s]	Vp [km/s]	ρ [g/cm^3]
Nishiyama	0.7	1.9	1.7
Shiiya	1 -> 1.2	2.2	2.1
Upper-Teradomari	1.7	3.3	2.3
Lower-Teradomari	2	4.2	2.4
Nanaya	2	4.6	2.5
Green Tuff	2.6	4.6	2.5
Basement	3.1	5.2	2.6

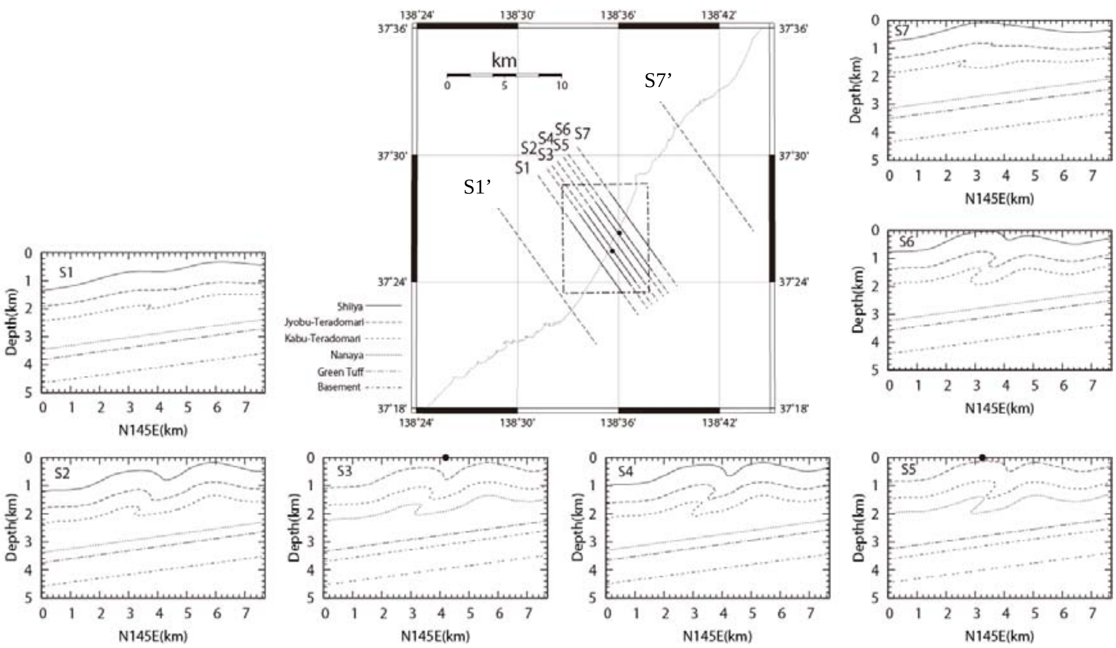


Fig. 2 Cross section of the two-dimensional folding structures developed by Tokumitsu et al. (2009)

S1' and S7' correspond to the cross section that we expanded the model of S1 and S7, respectively.

However, just substituting local folding model above the upper-Teradomari of broad model produce the gaps of velocity structure on the vertical boundaries of the connected area. Thus, we modified the velocity structure on the boundary area of broad model connecting to the area of local folding model in order to reduce the artificial refracted waves that are generated around the boundary area. We show the cross section of the velocity model passing through KK1 with smoothing the boundary between broad model and local folding model assuming 4 km width for the boundary area in Fig. 4 (KK1 is approximately located 20 (EW direction) and 30 (NS direction). In Fig. 5, we show the comparison of the snap shots of the propagating wave front of EW component after 6 sec of the origin time without (1) and with (2) modification of the boundary area. As seen around the circled area in the figures, the reduction of the refracted waves from the boundary area could be seen based on the modification of boundary area between two models.

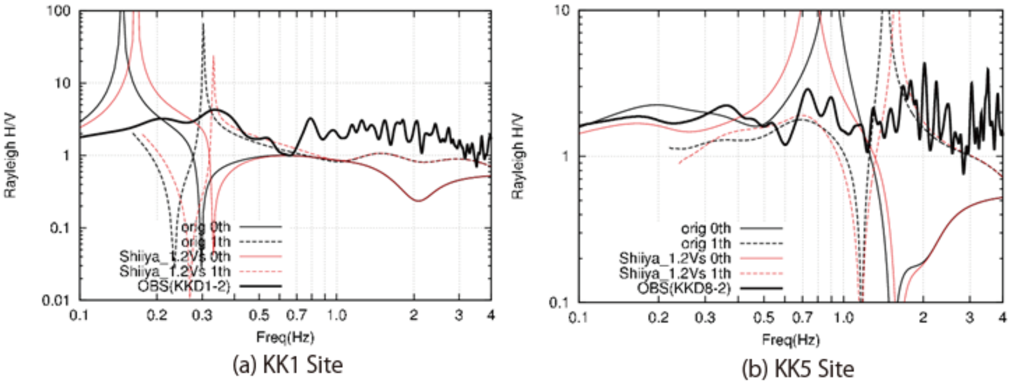


Fig. 3 Comparison of H/V ratio by the observed records with by the theoretical ones based on the 1D strucure

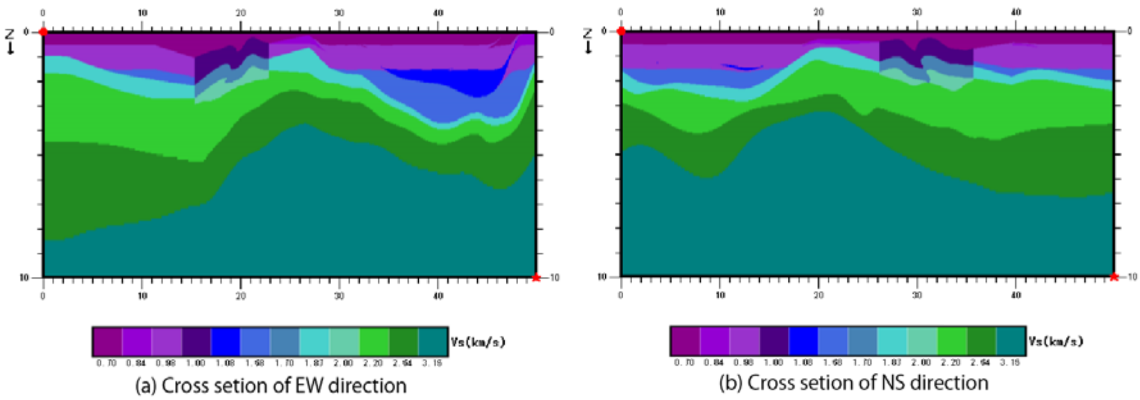


Fig. 4 Cross section of the velocity model on the KK1 with smoothing the boundary between broad model and local folding model (Every number is in km)

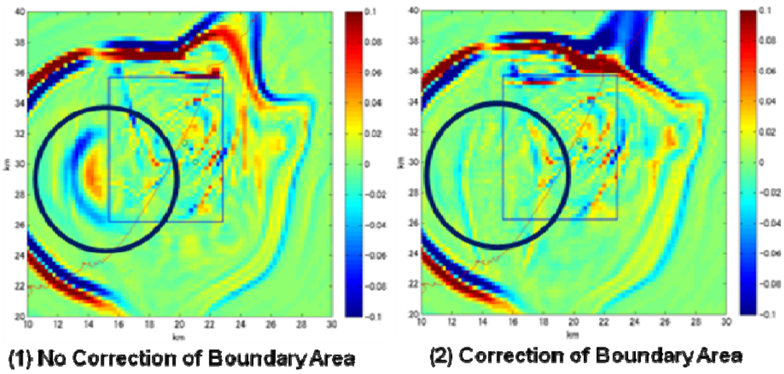


Fig. 5 Comparison of the snapshots without (1) and with (2) the modification of the boundary area between two velocity models

VERIFICATION OF THE MODEL AND GROUND MOTION SIMULATION

Ground Motion Simulation of Moderate Sized Event

In order to validate the velocity model, we simulated the observed records at the KKNPP for three moderate sized events. Two are occurred on the asperity 1 and 3 determined by Shiba (2008), respectively. First one is occurred on the asperity 1(northern side of the asperity) at 21:08 of July 16, 2007. We call this event as Aft 1. Second one is occurred on the asperity 3 (southern side of the asperity) at 17:42 of July 16, 2007. This event is called as Aft 2. Last is one of the large aftershocks of the 2004 Chuetsu-earthquake occurring at 19:46 of Oct 23, 2004. We name this event as Land. We used the finite difference method developed by Pitarka (1999) with variable grid spacing for the simulation. The target period is 10 sec through 0.25 sec, leading to the minimum size of the grid 25m. The total area of modeling is 50 km (EW) x 50 km (NS) x 20 km (depth).

We modeled each event as the point source. We first model them based on the 1D structure to check whether the observed amplitude ratio of two horizontal components at the KKNPP and other adjacent sites, such as K-NET Kashiwazaki could be reproduced. Based on these moldings, we set the focal depth 7 km for Aft2 instead of 5 km determined by JMA. The focal depths by JMA are used for other events (Aft1, Land). We used the focal mechanism and seismic moment determined by the Broadband Seismograph Network (F-net) (Fukuyama *et al.*, 1998). The locations of epicenter are same as those of JMA locations. The shape of source time functions is assumed to be the isosceles. The rise time for each event is set based on the width of S-wave pulse of the observed waveforms at rock sites of F-net stations adjacent to the source. The values of rise time are 0.7 s for Aft1, 0.4 s for Aft2, and 1.44 s for Land, respectively. The source parameters for the simulation are shown in Table 2. We show the location of epicenter and focal mechanism for each event in Fig. 6. The dashed -rectangle areas in Figure 6 correspond to the area of asperities determined by Shiba (2008).

Table 2: Source parameters of each event used for the simulation

Event	Occurrence Date	Epicenter	Depth [km]	Mechanism			Seismic Moment [Nm]	Mechanism	Rise Time [sec]
				Strike	Dip	Rake			
Aft1	2007/7/16 (21:08)	(138.630,37.509)	13.6	187	54	70	5.21E+15	F-net	0.70
Aft2	2007/7/16 (17:42)	(138.557,37.415)	7.0	309	78	37	2.09E+14	F-net	0.40
Land	2004/10/23 (19:46)	(138.875,37.295)	12.0	16	52	73	1.17E+17	F-net	1.44

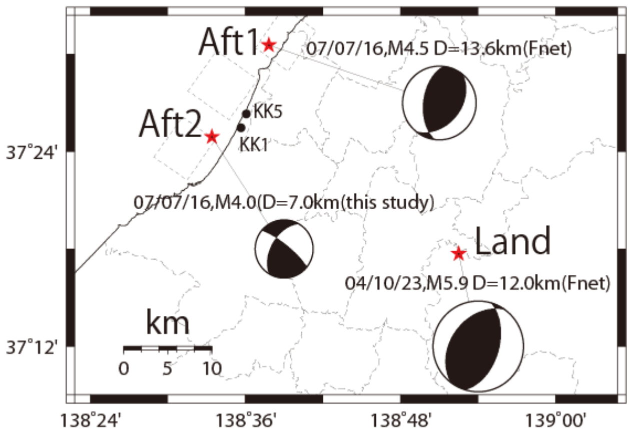


Fig. 6 Locations of the epicenter for simulated moderate sized event and its mechanism

In Fig. 7, we show the results of simulations for each event. We rotated all waveforms to PE and PN component and band-pass filtered between 0.1 Hz – 4 Hz for all of them. Because we tried to compare the records on the base mat for the site, the effects of surface geology above it have been removed from the observed record. As shown in Fig. 7 (1), the synthetic motions for Aft1 agree well with the observed records of body waves for both KK1 and KK5. This trend is the same as for Land shown in Fig. 7 (3). Except that the reproductions for the observed records of PN components and following surface waves are insufficient, general features of observed records for Aft2 could be reproduced shown in Fig. 7(2). We also show the comparison of ground motions between KK1 and KK5 for Aft1 and Aft2 of the observations as well as the synthetic motions in Fig. 8. The comparison of wave field at KK1 and KK5 for Aft1 shows that the observed wave fields for those sites are very similar and these are reproduce in the synthetic motions, represented by the maximum values. On the contrary, the wave field for Aft2 that occurred around the asperity 3 shows that the observation that amplitudes of KK1 site are almost doubled to those of KK5 site and this relation could be reproduced in theoretical calculations. These results mean that the constructed three-dimensional velocity model worked well for the ground motion simulations for these moderate sized events.

Hayakawa *et al.* (2011) showed that the large amplitude of KK1 site comes from the folding structure where KK1 is located on the synclinal axis. They also showed that the wave field from Aft1 whose epicenter is located close to the asperity 1 produced similar ground motions, because the seismic wave fields are propagated around the region that is not affected by the folding structure. This indicates that the folding structures can be very important role for ground motion features if the wave field is propagated through that region.

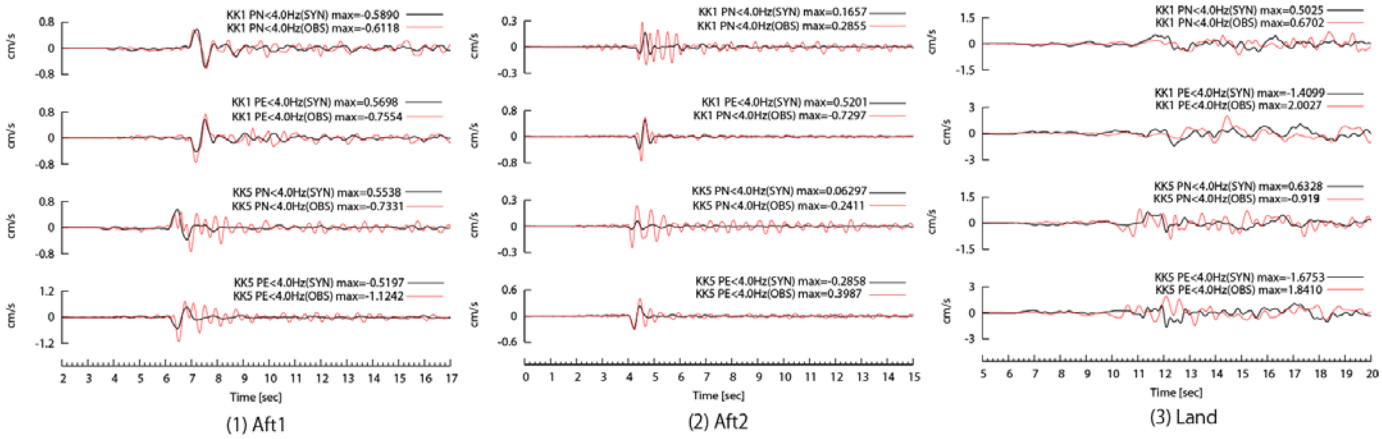


Fig.7 Comparison of the observed waveform at KK1 and KK5 sites for simulated moderate sized events

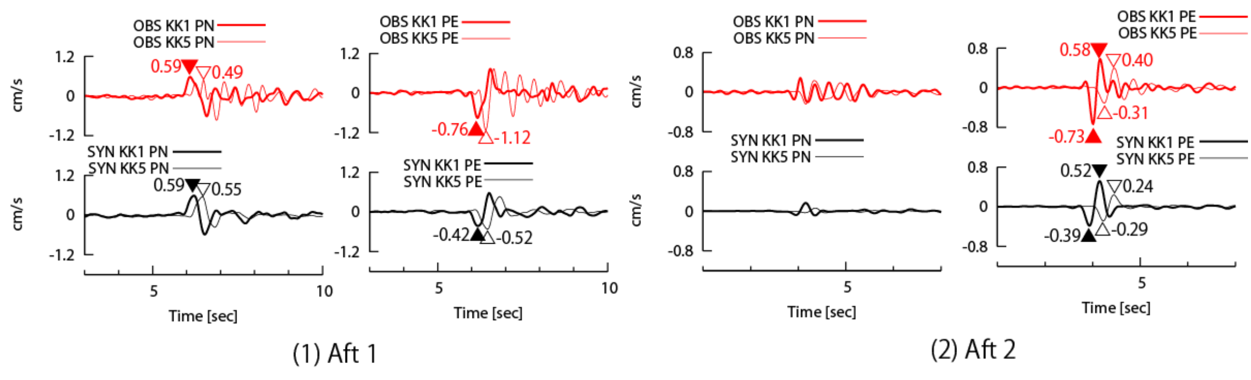


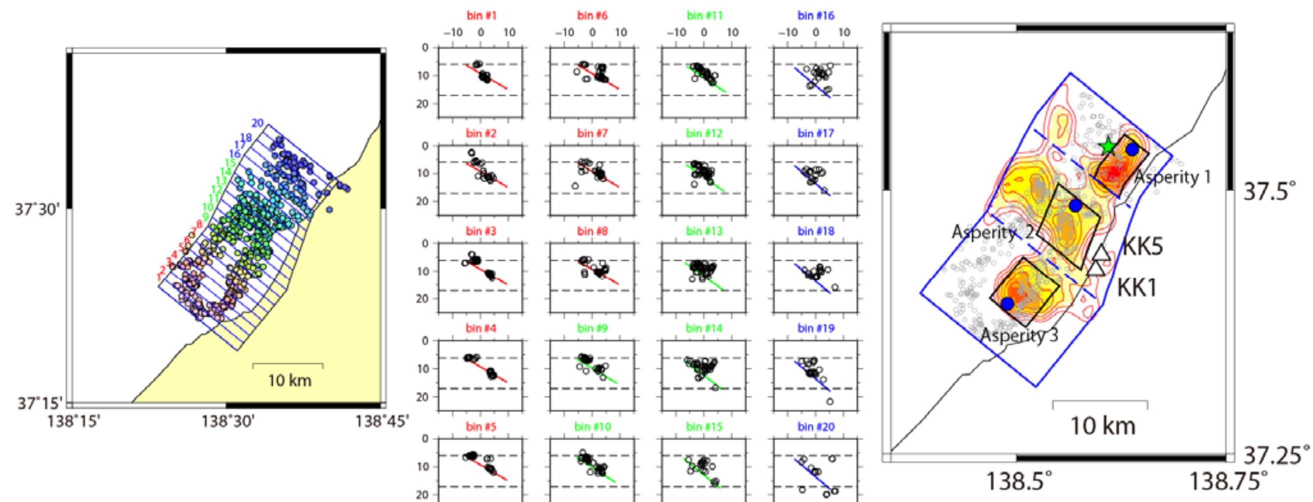
Fig. 8 Comparison of the wave field at KK1 and KK5 sites for Aft1and Aft2

<u>Ground motion simulations of main shock of the 2007 Chuetsu-Oki earthquake</u>

Finally, we tried to simulate the observed records of main shock of the 2007 Chuetsu-Oki earthquake to investigate the effects of folding structures on ground motions seen as the ground motion simulations for moderate sized events. We have used the characterized source model by Shiba *et al.* (2011). Shiba *et al.* (2011) recently updated the model determined from their previous model (Shiba, 2008) by using the empirical green's functions based on the aftershock distributions newly determined by Shinohara *et al.* (2008). As shown in Fig. 9(a), the distribution changes along the strike direction (39°) leading to modeling different dip angle dependent on the asperity. After they estimated the slip distribution shown the area by surrounded by the blue lines in Fig. 9(b), three asperities were extracted from the slip distribution to construct the characterized source model. The locations of each asperity are represented by the area with black lines in Fig. 9(b) and source parameters for each asperity is shown in Table 3. We used that characterized model. Compared to the previous model (Shiba, 2008), the surface of the asperity and effective stress have been changed only for the asperity 1. This model also changes the dip angle for each asperity unless the strike angle is same as all asperities. The dip angles are 40° for asperity 1 and 30° for asperity 3, respectively. For asperity2, we divided the area into some small rectangular ones with different depth of the top and dip angles linearly changing from 40° (north side, asperity 1) to 30° (south side, asperity 3). This model assumes the multi-hypocenter for each asperity (Blue circles in Fig. 9(b)). As for the slip velocity functions, we used the model proposed by Nakamura and Miyatake (2000) based on the dynamic modeling for our simulation. The results are filtered between 0.1 to 4.0 Hz same as of the simulations for moderate sized events. In Fig. 10, we compare the results of ground motion simulations for the main shock of the 2007 Chuetsu-Oki earthquake. The source model (Shiba *et al.*, 2011) did not specify the nucleation times for each asperity. Then we set the time shifts for each asperity when we combined the calculated waveforms for each asperity (top three waveforms of each graph in Fig. 10) to achieve the better fitting to the observed data (red lines) shown in the bottom of each graph in Fig.10. Even the amplitudes from asperity 1 are insufficient and there are little differences of amplitudes (peak values) between KK1 and KK5 from asperity 3, the general features of observed data could be reproduced.

Table 3: Source Parameters for each asperity determined by Shiba *et al.* (2011)

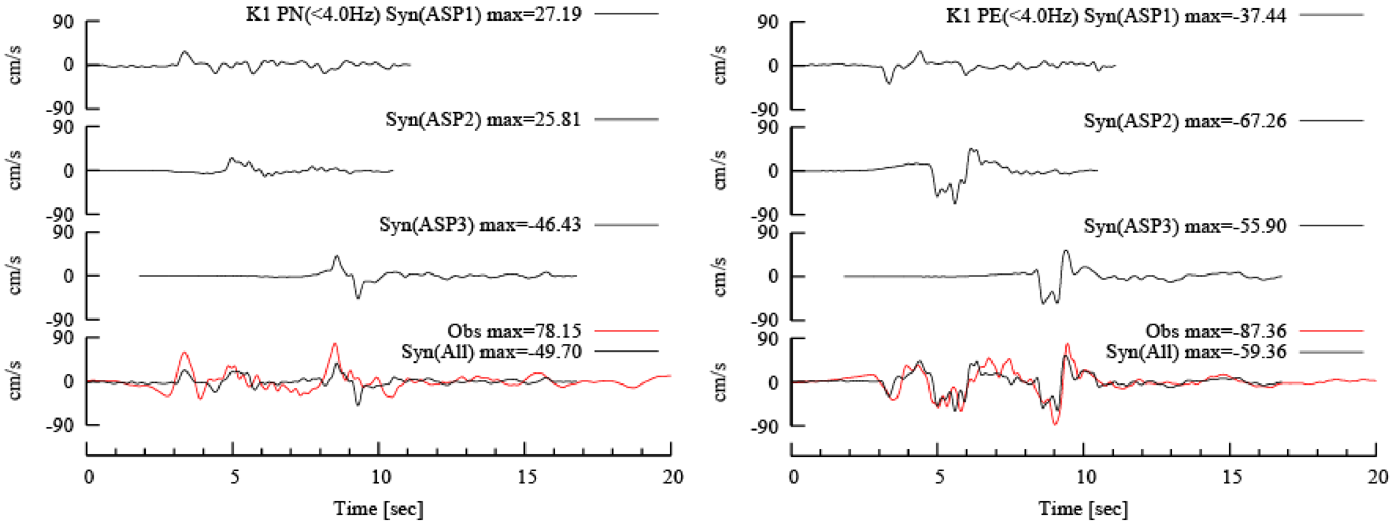
	Asperity 1	Asperity 2	Asperity 3
Depth of the Top [km]	14.0	9.7–10.6	9.5
Length [km]	5.6	5.6	5.6
Width [km]	4.2	7	5.6
Rake Angle [°]	90	90	90
Effective Stress [Mpa]	23.15	20.84	19.91
Seismic Moment [10^19 Nm]	1.09	2.11	1.43
Rise Time [s]	0.4	0.4	0.4
Rupture Velocity [km/s]	3	2.8	3



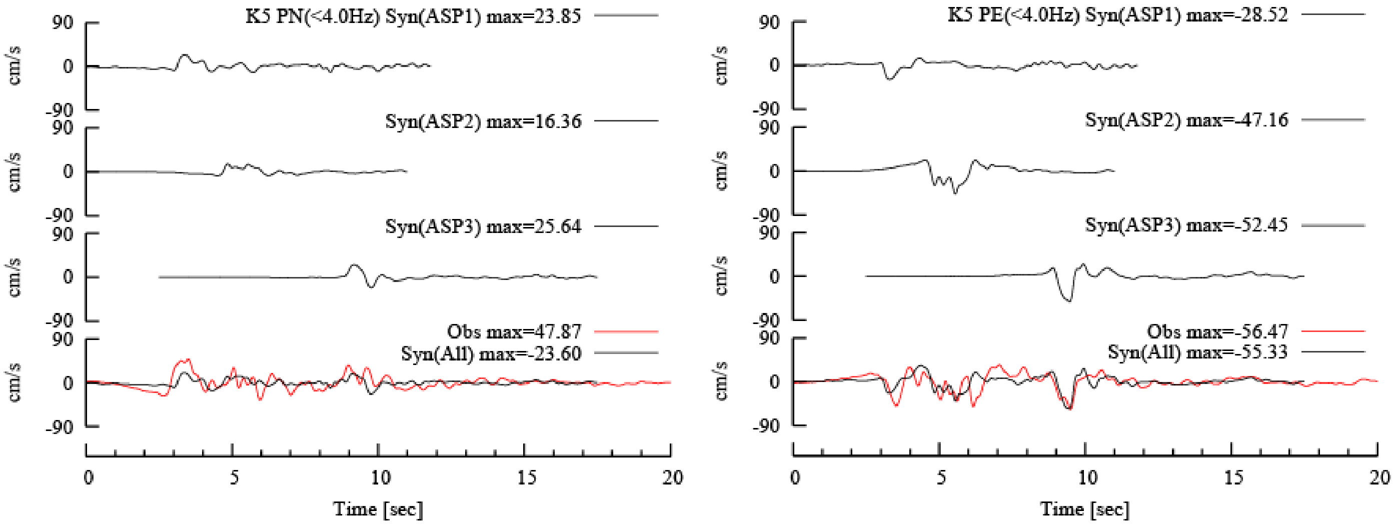
(b) Source model derived by Shiba etal.(2011)

(a) Aftershock distribution determined by Shinohara etal. (2008) and initial fault plane by Shiba et al. (2011)

Fig. 9 Distribution of aftershock (a), location and shape of each asperity by Shiba et al. (2011) (b) (Modified after Shiba etal., 2011)



(1) Results of ground motion simulation for the KK1 site



(2) Results of ground motion simulation for the KK5 site

Fig. 10 Results of Ground motion simulations for the main shock of 2007 Chuetsu-Oki Earthquake

DISCUSSION: MECHANISM OF WAVEPROPAGATION THROUGH THE FOLDING STRUCTURE

The better agreement of the observed data with the simulated ground motions indicates that the source model as well as the constructed velocity model worked well. In order to get the better understands of the mechanism of wave propagation through folding structure, that might produce large ground motions from the asperity 3, we compared the snapshots of wave propagation from asperity 1 with those from asperity 3. The locations of the cross section for each asperity with folding structure are shown as the red lines in Fig. 10 (a) and Fig. 11 (a), respectively.

The snapshots of how waves are propagated from asperity1 are shown in Fig. 11 with one second interval. We plotted the snapshot as the plan view (b), (e) and the cross section connecting from center of asperity 1 and KK1 ((c), (f)) and for KK5 ((d), (g)), respectively. The snapshots show that the waves propagate relatively smooth i.e., the wave field seen on the cross section of KK5 could be seen on the next snapshots of KK1 cross section and the diffraction or focusing caused by the folding structure have not been seen toward to

KK1. This feature agrees with what have seen in the ground motion simulation for Aft1 in moderate sized events. This indicates that the folding structure is not important for the wave propagation from northern side of the KKNPP.

For the wave trains from asperity 3, we show the snapshots in Fig. 11 with one second interval as the plan view (b), (e) and the cross section connecting from center of aspeirty3 and KK1 ((c), (f)) and for KK5 ((d), (g)), respectively. The first snapshots show that the wave fields look similar for KK1 and KK5. On the other hand, the wave fields on the send snapshot produced different features for KK1 and KK5. Especially to the area with large amplitude corresponds to the line of the synclinal axis (Tokumitsu *et al.*, 2009) showing inside the squared area and may cause the focusing because of this folding structure. This feature agrees with what have seen in the ground motion simulation for Aft2 in moderate sized events. The wave trains showing that features come from the asperity 3 and this may cause the reason that produced the difference of peak amplitude between KK1 and KK5 during the main shock of 2007 Chuetsu-Oki earthquake (Fig. 1). This indicates that the folding structures below the KKNPP plays important roles for the wave propagated from western side of the KKNPP.

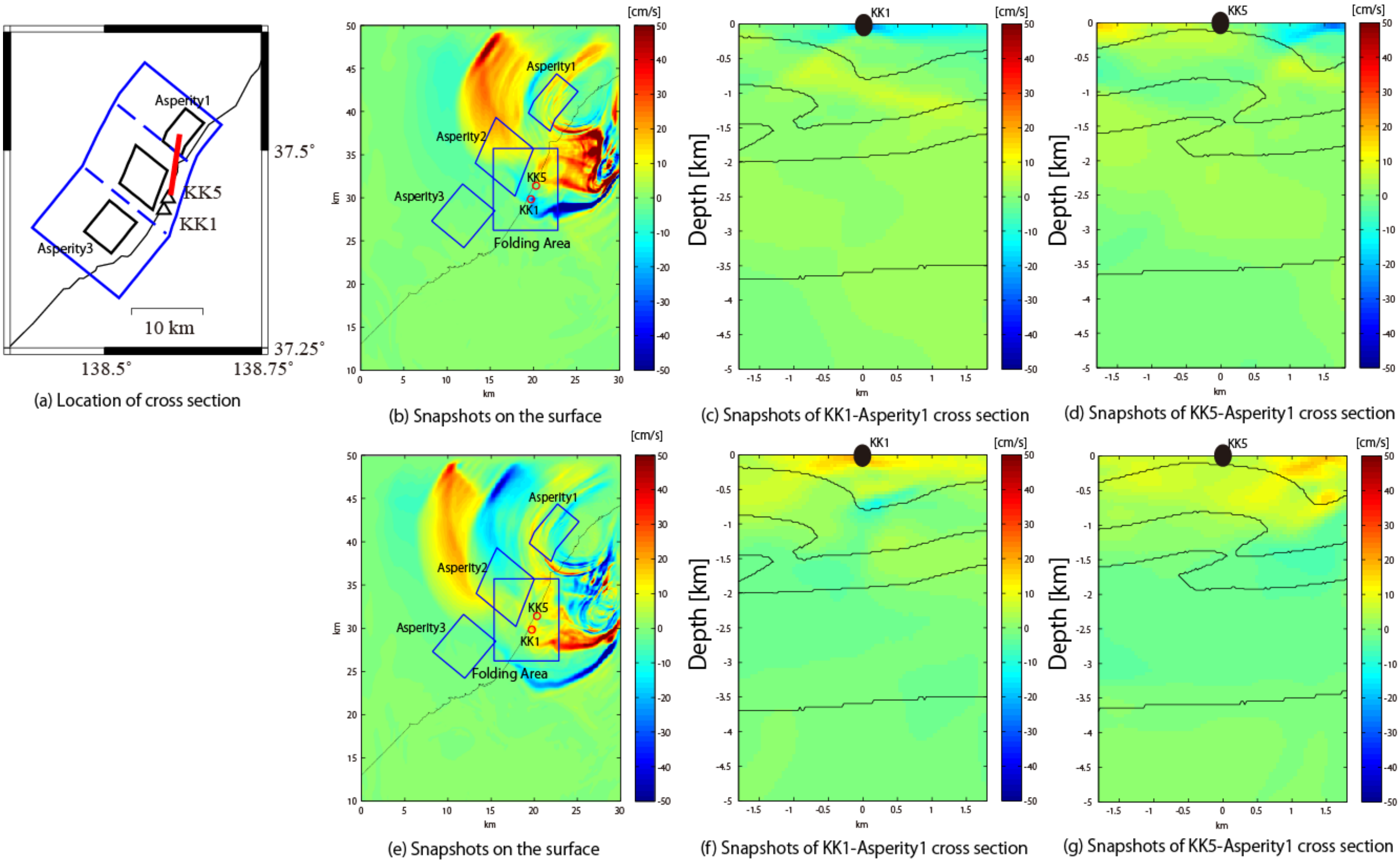


Fig. 11 Snapshots of the EW-component wave field coming from the asperity 1
(Left hand side corresponds to the source area on cross section)

SUMMARY

We have constructed the three-dimensional velocity model that incorporates the precise folding structures around the Kashiwazaki-Kariwa nuclear power plant, where the large ground motions have been observed during the 2007 Chuetsu-Oki earthquake. The constructed model is combined two models, the model including precise folding structures adjacent to the KKNPP and the model constructed for the more broad area. We connected these models smoothly to reduce the artificial diffracted waves generating around the connected area. During the construction of this model, we tuned the S-wave velocity of one layer in the models with folding structure based on the fitting of the H/V ratio based on observed records to the theoretical ones.

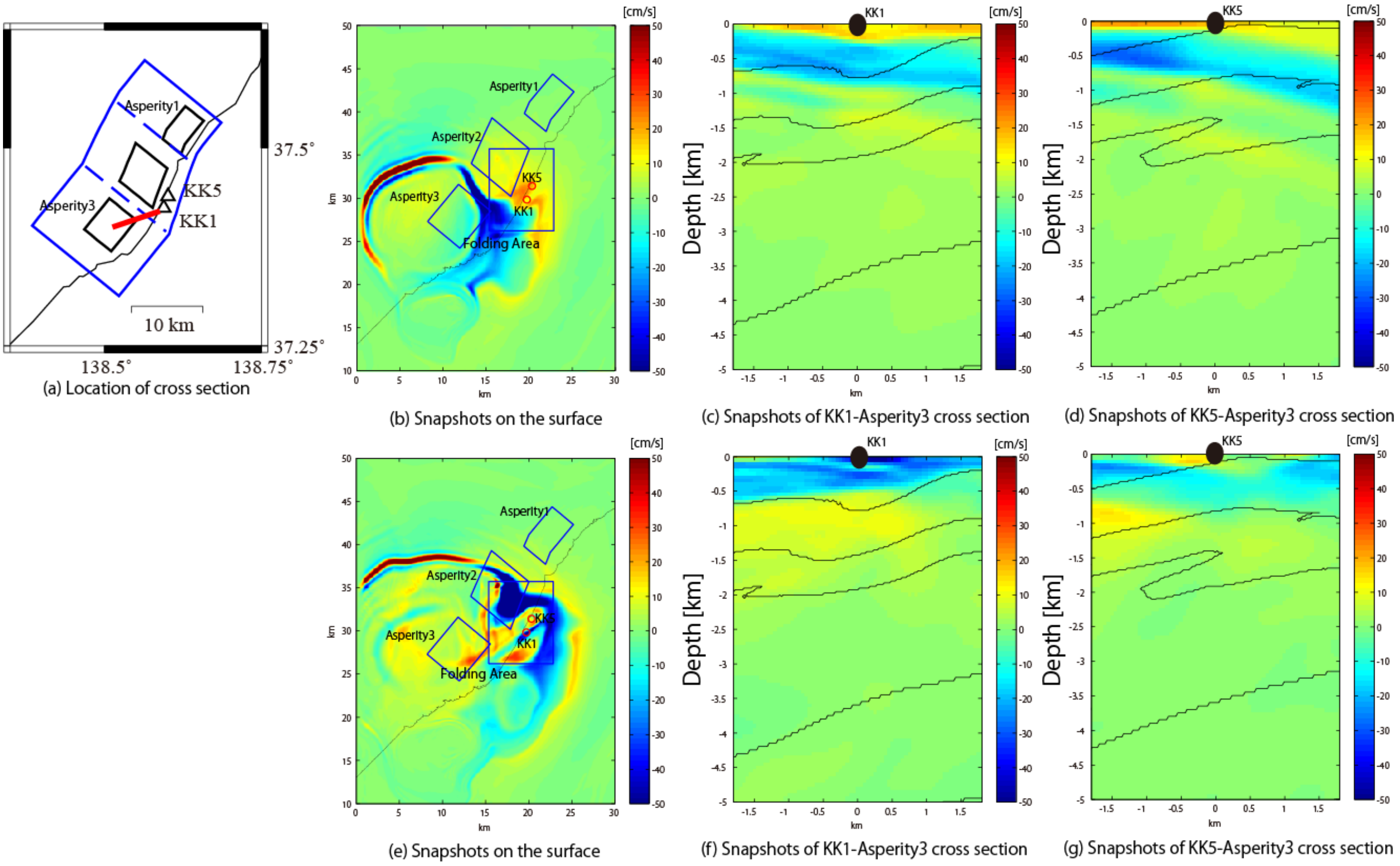


Fig.12 Snapshots of the EW-component wave field coming from the asperity 3
(Left hand side corresponds to the source area on cross section)

In order to validate this velocity model, we have simulated ground motions for moderate sized events that occurred around the fault area of Chuetsu-Oki earthquake. The synthetic calculations could reproduce some distinct observed ground motion features; the ground motions at KK1 site produced large ground motions for Aft that occurred around asperity 3 are larger than that at KK5 site like main shock of Chuetsu-Oki earthquake and the ratio of peak values between KK1 and KK5 for aft1. This indicates that the observed ground motion variations at KKNPP might cause the folding structures adjacent to the KKNPP.

Finally we did the ground motion simulation for the main shock of the 2007 Chuetsu-Oki earthquake. We used the source model by Shiba *et al.* (2011) with assuming non-planar fault planes. We combined the synthetic waveforms for each asperity with delay of nucleation time to get better fitting of the observed data. We could reproduce the general features of observed data from the main shock of 2007 Chuetsu-Oki earthquake. Snapshots of how the waves are propagated indicate that the waves from northern side (asperity 1) are not affected by the folding structure so much, i.e., ground motions features look same as KK1 with KK5. On the other hand, the folding structures below KKNPP have very important roles for the wave propagation from southern side (asperity 3). The results of simulation show that the folding structure might cause the ground motion variations during the main shock of the 2007 Chuetsu-Oki earthquake.

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