Numerical simulation of the Mw 6.6 Niigata, Japan, earthqhake: Reliable input ground motion for engineering purpose

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ABSTRACT:
The 2007 Niigata, Japan, earthquake (Mw6.6) caused some damages in the Niigata Prefecture, especially around Kashiwazaki. We carry out numerical simulations of seismic wave propagation to understand the strong ground motion which has affected the Kashiwazaki area. We adopt a finite difference method with a 4^{th} order in space staggered grid. We use a 3D geological structure model, obtained by seismic tomography of aftershocks observations. Preliminary tests of this structure model confirm a good agreement of waveforms comparing to the recorded data set. We then test two finite source models, obtained by seismic kinematic inversion for the mainshock. The simulated synthetic seismograms around the Kashiwazaki area seem to be still small in amplitude with respect to the recorded data, although the data should be influenced strongly by the non-linear soil behaviour. The geological and seismological models should be refined further and additional non-linear soil analysis should be carried out.

Keywords: finite difference, wave propagation, 2007 Niigata-ken Chuetsu-Oki earthquake, input ground motion

1. INTRODUCTION

For the study of the soil and structure behaviour under earthquake ground motion excitation, the most basic question is how to characterize the input ground motion. The Mw6.6 2007 Niigata-ken Chuetsu-Oki, Japan, earthquake is remembered not only for the regional damages (15 killed people, about 2000 injured people, and about 1000 damaged houses and buildings) but also the significant impact on the nearby nuclear power plant, which was shut down during the earthquake and is still partially stopped due to the reevaluation and enhancement of the seismic resistances. We have recently launched a French national project DEBATE (DEvelopment of Broadband Acceleration Time histories for Engineers, 2009-2011) among four French partners through collaboration with some Japanese institutes. This project aims to model a reliable input ground motion by hybrid simulations and then study non-linear soil behaviour. The 2007 Niigata Chuetsu-Oki earthquake is one of our test cases because of the abundance of recorded data and the complexity in the observed phenomena. In this paper, we report the part about low frequency wave propagation simulations.

As already pointed out by different seismologists, the near wave field of the 2007 Niigata Chuetsu-Oki earthquake was complexly generated such that the effect radiated from the finite source area, namely the seismological asperities, is non-negligible (see Special issue of "Earth Planets Space", vol. 60, no. 11, 2008). Thanks to the dense observation network in Japan, many data are available. However, for the mainshock, some stations show strong non-linear effect in the soil behaviour, such as the K-net station NIG018 (see also Figure 1). Even in the nearby station in the nuclear plant, non-linearity is inferred. Another nearby station of F-net, KZK, has a record saturating its measuring capacity. Thus those data could not be compared directly with our simulations, but it is our objective to provide a reliable input ground motion for such stations. In this paper, we use the existing information obtained by different researchers and compile them to simulate the ground motions. We first briefly explain our numerical methods and the data used in this paper. Then we begin with testing some aftershocks, whose source processes are much easier than the mainshock. At last we simulate the mainshock. We will discuss the reliability of such simulations to estimate the near field ground motion.

2. METHOD AND DATA

First of all, Figure 1 shows geographical setting of the mainshock epicentre, aftershocks distribution, the used fault planes projections and the surrounding seismological stations recorded during the 2007 Niigata Chuetsu-oki earthquake. For simplicity, we take our simulation origin (X, Y) = (0, 0) at the indicated epicentre (full star), and hereafter we will use this notation to simplify our explanations. The station coverage is rather good for this earthquake, but the ruptured area is under the sea at a depth of about 10 km. This makes difficult to get a better image of the earthquake source. The 3D structure model which we use in this study is shown along two cross-sections EW and NS in Figure 1. This is based on Kato et al. (2009) in which the tomography resolution is better at the centre around the aftershocks and poorer at a distance according to their observations locations. In the centre, the result is obtained every 3 km (5 km in the NS direction) at minimum. At the end of model, result spacing becomes 10-20 km in both horizontal and vertical directions. We then linearly interpolate this result inside and extrapolate it as a 1D structure horizontally outside. The earthquake occurred in an active folding and thrusting zone along the coast and this forms a 6 km thick basin structure (Sato, 1994) as shown by the tomography along the cross sections (Figure 1, results after Kato et al., 2009). Only limited places are characterized by relatively "rock" site, for example, at KZK (F-net) station (see cross section BB' at around Y=-25 km) or the very narrow coast area (see cross section AA' at about X=6 km). Unfortunately the tomography result does not cover the Sadogashima Island in the north (Y >= 20 km in the cross section BB'). Therefore we will have to discuss only the stations located in the south and east.

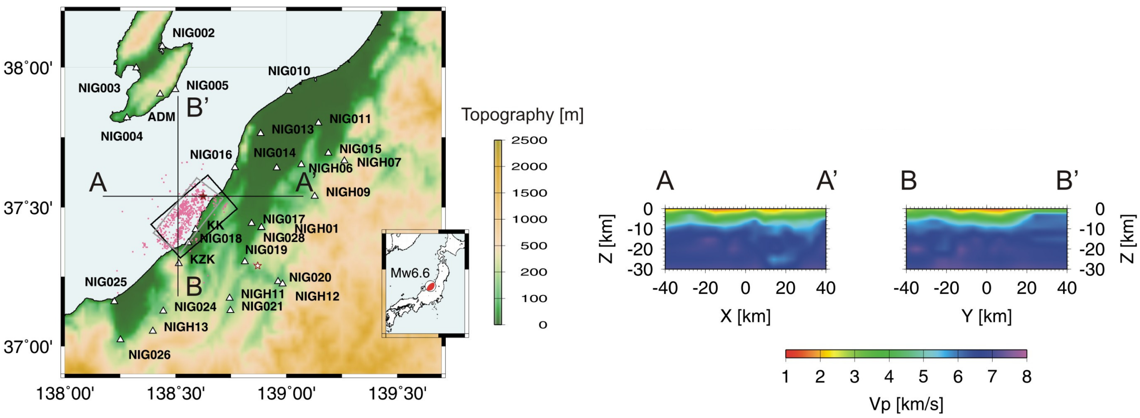

Figure 1. Map of the sources and stations of the 2007 Niigata Chuetsu-Oki earthquake. The full star represents the epicentre of the mainshock, represented by (X, Y) = (0, 0). Two rectangles, in black and in grey, show the finite source model, south-eastern dipping, of the mainshock (Mw6.6) obtained by Aoi et al. (2008) and Hikima and Koketsu (2008), respectively. The small circles in pink show the aftershock distribution during about the first 30 days (Kato et al., 2008; Shinohara et al., 2008). The stations (K-net, Kik-net, F-net, TEPCO) are represented by triangles. For information, the epicentre of the 2004 Niigata Chuetsu-Oki earthquake is plotted by an open star. The cross sections of the 3D geological structure are shown along AA' and BB' (Kato et al., 2009).

For the main shock, we adopt two models, both of which are dipping in the south-east, obtained by Aoi et al. (2008) and Hikima and Koketsu (2008), respectively. They use the regional data, particularly the acceleration data from K-net and Kik-net. However their choices of stations are slightly different. Hikima and Koketsu (2008) tried to tune up the model using the station KK, located at the nuclear power plant. The two fault planes are superposed in Figure 1. However their hypocentre depths are 8 and 10 km, respectively, according to the relocated catalogue they use. Thus the two fault planes are systematically shifted by about two kilometres. This should be taken into account when watching the simulation results. The detail will be discussed later.

Figure 1 also plots the aftershock distribution during 1 month just after the mainshock (Kato et al., 2008; Shinohara et al., 2008). For the simulations carried out to test the geological model, we select a few earthquakes, whose mechanisms are well determined by the analysis of F-net. The epicentre locations are consistent with each other in these two database.

Based on all the above information, we simulate the wave propagation in this region using a finite difference method (Dupros et al., 2008). The method uses the standard staggered grid in the 4th order in space and kinematic sources are introduced in terms of double-couple forces regardless of a point source or a finite source (Aochi and Madariaga, 2003; reference herein). In most cases, we use a grid spacing of 200 m for a dimension of 110 km x 120 km x 30 km, and a time step of 0.01 seconds for a duration of 40 seconds. Theoretically, the upper frequency limit we can treat is then f_{max} = 0.866 Hz, as the lowest wave velocity is given at 866 m/s in Kato et al. (2009). We tested a twice finer grid, but we do not see any significant difference in the synthetic seismograms around the frequency of 0.5 – 1 Hz, which should be the physical resolution given by the structure and the source model we use in this study.

3. SIMULATION OF AFTERSHOCKS

The 3D velocity structure model used in this study was obtained from the aftershocks observations, using the arrivals of P- and S-waves and the aftershock hypocentres are also relocated (Kato et al., 2008; Shinohara et al., 2009; Kato et al., 2009). Before simulating the main shock, we test this 3D structure model for some aftershocks. According to the aftershocks observations (16th July – 29th August) of the 2007 Niigata-ken Chuetsu-Oki earthquake, we choose two earthquakes whose focal mechanisms and magnitudes are obtained from Japanese broadband network F-net (16th July 21:08 Mw4.4 and 18th July 16:53 Mw4.3) with relatively good qualities. The aftershocks are given by a point source with a bell-shape source time function with a duration of 0.5 seconds.

Figures 2-3 show the comparison between synthetic (red) and observed (blue) velocity waveforms at selected K-net and Kik-net stations for each aftershock. The time 0 of the observation data is aligned exactly at the origin time indicated by the relocated catalogue so that we can compare them with synthetics in the absolute time axe (not only relative waveforms but also arrival time of waves). All the waveforms are filtered between 0.1 and 0.5 Hz.

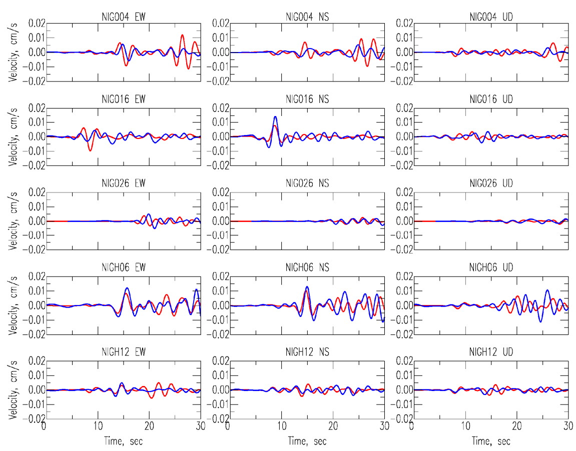

Figure 2. Synthetic (red) and observed (blue) seismograms in velocity for three components at five stations for the first aftershock (16th July, Mw4.4).

We first observe that the direct P- and S-waves arrive consistently in the area where the tomography is covered. As the figures are filtered, it is difficult to distinguish the waves, but we can see the good fit of the waveform arriving first. Unfortunately, there are systematic time shifts at stations NIG004 and NIG005 in Sado Island in the north, as the tomography coverage is not enough. We then observe that it is still difficult to fit the later phases. This is due to the resolution limit of the tomography. The good agreement of the main phases is also observed in the very near field, at station KZK (not shown due to the page limit), while the later phases in observation continue larger and longer than the simulation. We think that the 3D geological model is sufficient for the frequency range we watch in this study (up to 0.5 Hz). For higher frequencies, the model should be refined further through full waveform tomography, for example.

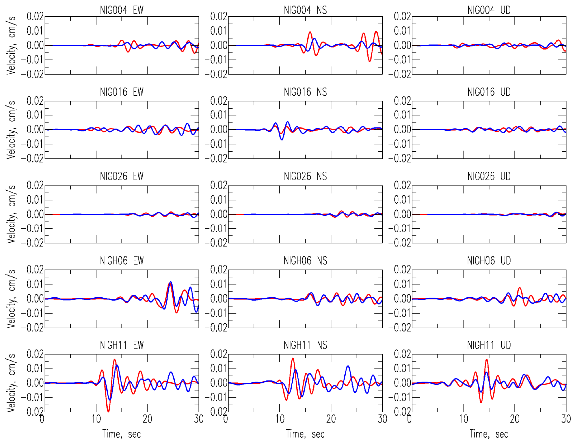

Figure 3. Synthetic (red) and observed (blue) seismograms in velocity for three components at five stations for the second aftershock (18th July, Mw4.3).

4. FINITE SOURCE MODELS OF THE MAIN SHOCK

The fault mechanism of the 2007 Niigata-ken Chuetsu-Oki earthquake is not yet well resolved. According to the currently more popular interpretation (e.g. Miyake et al., 2010), we adopt a fault plane dipping in the south-eastern direction. This orientation is demanded principally from the aftershocks relocations (Kato et al., 2008; Shinohara et al., 2008) but is not necessarily favourable to explain the strong ground motion observed above the fault plane (e.g. Aoi et al., 2008). We use two finite fault models, Aoi et al. (2008) and Hikima and Koketsu (2008). Figure 4 shows the spatial slip distributions obtained by the two inversions. The epicentre locations do not change (< a few hundreds metres = 1 or 2 finite difference grids), but the hypocentre depth has a difference of 2 km. Both fault planes are overlapped well on the horizontal plane as shown in Figure 1. We also find at least two asperities well identified. One is a few kilometres from the epicentre in the south-south-west, very close to the coast line. Another is about 10 km from the epicentre in the back direction of the fault strike. Therefore, both models are qualitatively consistent for low frequencies.

Nowadays, one thing to which the engineers should pay attention is that the seismologists often use different 1D stratified structure models varying station by station, calibrated from the aftershocks recordings. In their inversion procedures, the time windows are usually very narrow (equivalent to the rupture duration) to principally use the main phase of S-wave. In the framework of this usage, the calibrated 1D structure may be reasonable. However this may be not evident when we aim to reproduce the waveforms at whole scale in the realistic 3D geological model.

Let us see some preliminary tests for verifying our simulation procedures. We suppose at this step two typical 1D structure models as summarized in Table 1. Model 1 is the one assumed in Aoi et al. (2008) at the source area. As they needed the information only at the seismogenic depth of this earthquake, the shallow is not detailed but this model corresponds to “very hard” rock sites. In their inversion, 1D structure model used at NIG004 (Sado Island) is similar to Model 1. We prepare another Model 2, which has a relatively soft layer at a few kilometres from the ground surface, which is similar to the ones used in Hikima and Koketsu (2008) inversion analysis. Figure 5 shows the synthetic seismograms at NIG004 using Model 1 with the source model of Aoi et al. (2008). As we do not know exactly the time marker in the observation data for the mainshock, we shift manually the time axis so as to be compatible with the simulation, while time 0 is always the origin time for the simulation. Therefore we show two seismograms separately. Aoi et al. (2008) use a time window of 14 s beginning from 1 s before the estimated S-wave arrivals, namely briefly corresponds 12 – 26 seconds in Figure 5. In this period, we find that the simulation reproduces well the characteristic waveforms in observation, as shown on the paper of Aoi et al. (2008). This assures that we have correctly introduced their finite source model in the finite difference code. This “hard rock” model seems valid only at NIG004 among the stations they and we use. The other stations have a slower layer at shallow depth.

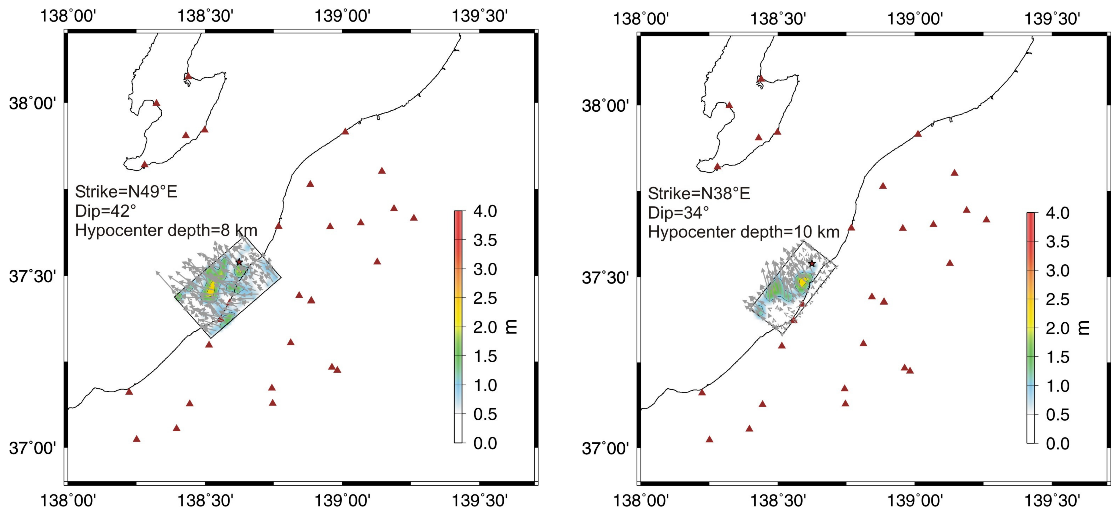

Figure 4. Fault slip distribution obtained from the inversions, projected on the horizontal plane. The color shows the amount of slip and the vector shows the rake direction at each subfault of the models. Left panel shows the model B of Aoi et al. (2008) and right represents the one of Hikima and Koketsu (2008).

Table 1. 1D stratified structure models used for validating source model. Roof layer depth is given in km, P-waves and S-waves velocity V_P and V_S are given in km.s^{-1} and density ρ is given in kg.dm^{-3}.

Model 1				Model 2			
Depth	V_P	V_S	ρ	Depth	V_P	V_S	ρ
0	4.6	3.09	2.6	0	3	1.5	2.6
1.383	5.9	3.3	2.7	1	4.2	2	2.6
13.632	6.7	3.8	2.9	3	5.4	3.1	2.6
27.533	7.7	4.3	3.25	6	5.9	3.3	2.7
				13	6.7	3.9	2.9

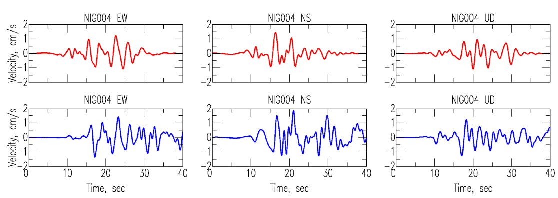

Figure 5. Synthetic and observed seismograms in velocity for three components for the Aoi et al. (2008) source model with the 1D structure Model 1. The above (red) shows the synthetic, the bottom (blue) the observation. All the waveforms are filtered between 0.1 and 1 Hz.

We are able to carry out the same discussion using Hikima and Koketsu (2008) source model. Figures 6 and 7 show the synthetic seismograms at station NIG024 and NIG026 in the southern part. For comparison, we use two 1D structure models. As shown clearly, Model 2 fits well the observation and

Model 2 is actually closer to the one used in their analyses. The introduction of soft layer at shallow depth amplifies the waveforms and generates the later phases.

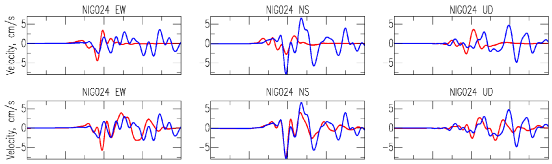

Figure 6. Synthetic (red) and observed (blue) seismograms in velocity for three components using the Hikima and Koketsu (2008) source model and two different 1D structures for station NIG024. Models 1 and 2 correspond to top and bottom rows, respectively. All the seismograms are filtered between 0.1 and 0.5 Hz.

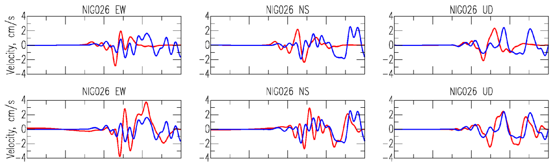

Figure 7. Synthetic (red) and observed (blue) seismograms in velocity for three components using the Hikima and Koketsu (2008) source model and two different 1D structures for station NIG026. Models 1 and 2 correspond to top and bottom rows, respectively. All the seismograms are filtered between 0.1 and 0.5 Hz.

5. SIMULATION OF MAIN SHOCK IN 3D GEOLOGICAL STRUCTURE

In the previous sections, we have shown how the 3D structure model and the finite source models are. Now we try to compile all the elements in order to carry out the simulations of the main shock in 3D complex geological structure. As the northern stations such as NIG004 are not well calibrated in the used 3D structure, we discuss mainly with the stations in the south and east on the main land of Japan. Figures 8 and 9 show the simulation results at several stations for the two finite source models. It is not exactly expected that the synthetic seismograms fit the observation in terms of phase, as the source models are obtained for 1D structures. We do not aim to fit the data in this study.

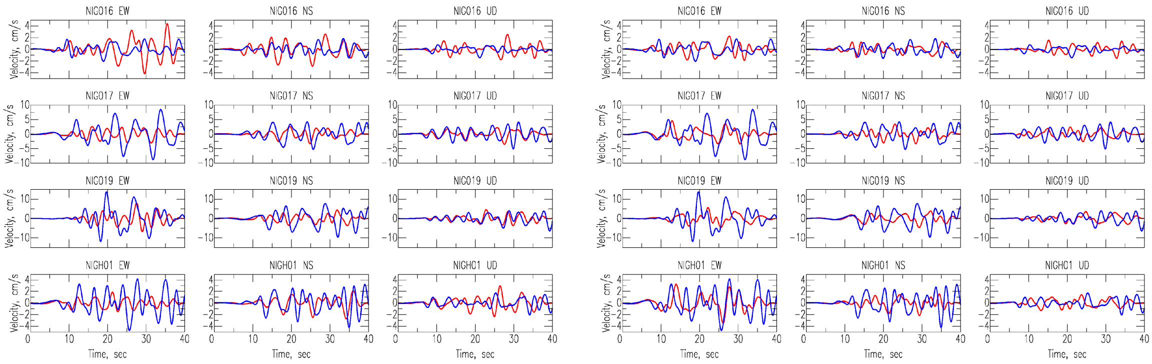

Figure 8. Synthetic (red) and observed (blue) seismograms in velocity using the 3D structure model and Aoi et al. (2008) source model (left) and Hikima and Koketsu (2008) source model (right). The selected stations are in the eastern direction of the ruptured area (NIG016, NIG017, NIG019 and NIGH01). All the seismograms are filtered between 0.1 and 0.5 Hz. See also Figure 9.

In the observations, the largest amplitudes are sometimes brought by the later phases due to the complex wave propagation in a 3D medium. However in the forward direction of the rupture propagation, namely in the south-western direction such as NIG024, NIG025 and NIG026, the simulation provides some characteristic waveforms, especially with the model of Hikima and Koketsu (2008). The initial phases seem to be comparable. This infers that the propagation path of the direct waves in the 3D structure model is relatively simple and briefly consistent with the 1D structure used in their inversion. As the later phases are difficult to reproduce even for aftershocks, it is not surprising to see the discrepancy in phase.

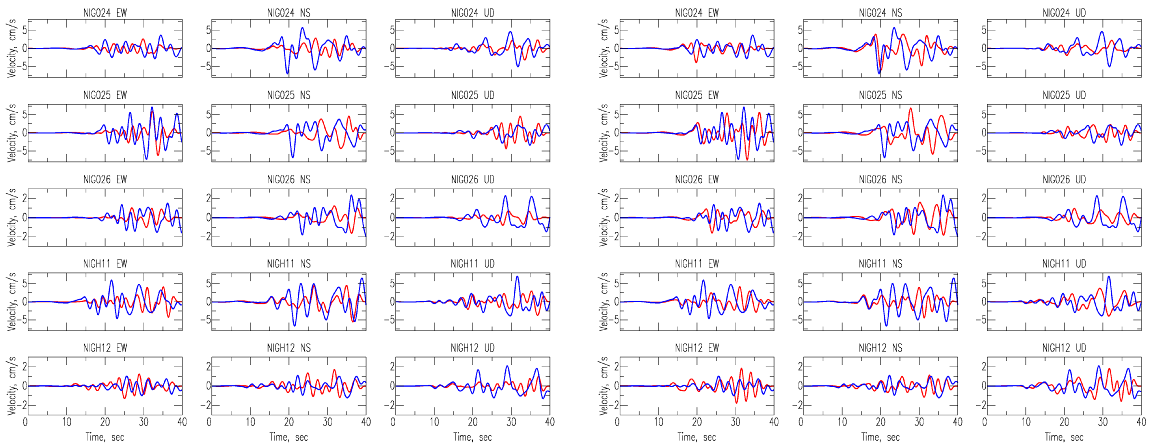

Figure 9. Synthetic (red) and observed (blue) seismograms in velocity using the 3D structure model and finite source models: Aoi et al. (2008) at left and Hikima and Koketsu (2008) at right. The selected stations are located in the south (NIG024, NIG025, NIG026, NIGH11 and NIGH12). See also Figure 8.

6. VERY-NEAR-FIELD GROUND MOTION AND DISCUSSION

The purpose of this paper is to obtain reliable input ground motions in the very-near-field around Kashiwazaki area. As we have no observation at really "linear" rock sites except for the borehole recording at the nuclear power plant, our study can be validated only if we carry out dynamic non-linear soil analyses using our simulation results and compare with the observed accelerations in this area. This will be another task in our on-going project. In this paper, we show how the estimated ground motions are. We discuss at two points: at the centre of Kashiwazaki city (station NIG018, located on the soil surface), suffering from severe liquefaction, and at the nuclear plant site (named station KK, here). For the station on the nuclear plant site, as the linearity is not assured due to the strong motion, the simulation may be comparable only with the observation at the deepest seismograph in the Service Hall of Kashiwazaki-Kariwa nuclear plant (KSH SG4, 250 m depth). Figure 10 shows the seismograms at these two points with the two simulations using the fault models of Aoi et al.(2008) and Hikima and Koketsu (2008) in the 3D geological model. At NIG018, the amplitude in observation is much larger than the synthetic one by a factor of 5-10. This is a future task to wonder whether the non-linear soil behaviour at this area can explain this significant amplification or whether input ground motion model should be further improved. At KK station, the synthetic seismograms seem to underestimate the observations, particularly in the EW component, although the data are not shown in Figure 10. A further tuning of the models would be necessary.

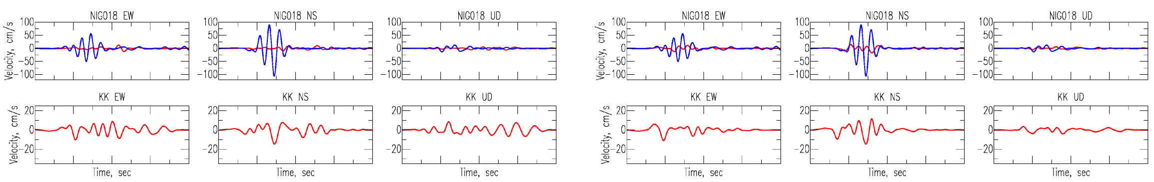

Figure 10. Synthetic (red) and observed (blue) seismograms in velocity at station NIG018 (top) and at Kashiwazaki-Karima nuclear plant station (bottom). The two simulations using the fault models of Aoi et al.

(2008) and Hikima and Koketsu (2008) correspond to the left and right panels, respectively. All the seismograms are filtered between 0.1 and 0.5 Hz.

We have discussed in this study the frequencies up to 0.5 Hz. This is not the numerical limit but the physical model limit we use in this study. Through the simulations of aftershocks, we estimate that the sustainable resolution is generally around 0.5 Hz, although some stations, such as KZK, may allow us to discuss up to 1 Hz according to the given tomography resolution. Then the finite source models are often tuned up for the frequency up to 0.5-1 Hz. In other words, it is important to improve both the structure and the source for a better imaging of the earthquake.

6. SUMMARY

The wave propagation during the M_w 6.6 2007 Niigata-ken Chuetsu-Oki earthquake was modelled through finite difference simulations at low frequencies (up to 0.5 Hz). The 3D geological model we use in this study was validated through the simulations of the aftershocks in the area where the tomography study was held. For a larger area of this region and a higher frequency, however, a further study will be required. By compiling the 3D structure model and finite source models obtained from the seismological inversion, the simulations of main shock allowed us to estimate the ground motion in the near field. The estimated input ground motion at Kashiwazaki town is significantly small in its velocity amplitude. Non-linear analyses of soil in that area will be required to validate the obtained simulation results.

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