

Finite difference simulations of seismic wave propagation for the 2007 Mw 6.6 Niigata-ken Chuetsu-Oki earthquake: Validity of models and reliable input ground motion in the near field

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Hideo Aochi, Ariane Ducellier, Fabrice Dupros, Mickael Delatre, Thomas Ulrich, et al.. Finite difference simulations of seismic wave propagation for the 2007 Mw 6.6 Niigata-ken Chuetsu-Oki earthquake: Validity of models and reliable input ground motion in the near field. Pure and Applied Geophysics, 2013, 170 (1-2), pp.43-64. 10.1007/s00024-011-0429-5 . hal-00980238

HAL Id: hal-00980238 https://brgm.hal.science/hal-00980238

Submitted on 17 Apr 2014 $\,$

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Submitted to special issue of PAGEOPH (Jan 2011), revision on July 2011, accepted on Sept

19 Abstract

20 Finite difference simulations of seismic wave propagation are performed in the Niigata area, 21 Japan, for the 2007 Mw 6.6 Niigata-ken Chuetsu-Oki earthquake at low frequencies. We test 22 three 3D structural models built independently in various studies. First aftershock simulations 23 are carried out. The model based on 3D tomography yields correct body waves in the near 24 field, but later phases are imperfectly reproduced due to the lack of shallow sediment layers; 25 other models based on various 1D/2D profiles and geological interpretation provide good site 26 responses but generate seismic phases that may be shifted from those actually observed. Next, 27 for the mainshock simulations, we adopt two different finite source models that differ in the near-field ground motion, especially above the fault plane (but under the sea) and then along 28 29 the coastline. Each model is found to be calibrated differently for the given stations. For 30 engineering purposes, the variations observed in simulated ground motion are significant, but 31 for seismological purposes, additional parameter calibrations would be possible for such a 32 complex 3D case.

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34

36 **1. Introduction**

37 The 2007 Mw 6.6 Niigata-ken Chuetsu-oki earthquake occurred on 16 July slightly off 38 of the northwest coastline of the Japanese mainland (Figure 1). The hypocentral depth is 39 about 10 km and the fault mechanism is reverse, causing no significant surface rupture. 40 Although modern structures incurred little significant damage, the event did shut down the 41 Kashiwazaki-Kariwa nuclear power plant located above the inferred fault plane, which 42 induced changes in the seismic hazard evaluation criteria applied to nuclear power plants. 43 This earthquake's mechanism is quite complex and remains uncertain despite the dense 44 observation network in operation (cf. Aoi et al., 2008). The main reason for this is that the 45 subsurface structure is so complex that commonly used algorithms based on a 1D structure 46 model are unable to accurately determine aftershock locations (Kato et al., 2008, 2009; 47 Shinohara et al., 2008). Immediately after the mainshock, high acceleration levels measured 48 on seismic records along the coast tended to indicate that the fault orientation was northwest 49 dipping, despite the fact that the geological structure would indicate a southeast dipping fault. 50 However on the basis of aftershock observations obtained from arrays deployed for one 51 month after the mainshock, the interpretation that predominantly emerges is that the major 52 part of faulting is southeast dipping (Kato et al., 2009). Multisegment models are inferred 53 from the InSAR observations (Aoki et al., 2008; Nishimura et al., 2008), and the possibility 54 of rupture transfer between multisegment models is also dynamically simulated (Aochi & 55 Kato, 2010). Thus understanding this earthquake is a seismologically challenging problem, 56 and it is worth ascertaining how well we can reproduce the ground motion using the known 57 seismological information for this earthquake.

58 The basic concept behind the seismic hazard evaluation is to be able to predict ground 59 motion under a given situation (cf. Douglas & Aochi, 2008). As the time series analyses are 60 increasingly called on in studying nonlinear soil-structure interaction in engineering

61 seismology, the need is ever greater to provide the (input) ground motion quantitatively from 62 seismological observations. Recent progress in numerical simulation and computational 63 resources enables us to theoretically simulate ground motions at high frequencies up to 64 several Hz by taking into account a complex source description and heterogeneous material 65 parameters. However the frequency limit still stands at around 0.5 - 1 Hz when comparing 66 with the observed data. Well-known, successful examples can be cited for the 1995 Hyogo-67 ken Nanbu (Kobe), Japan, earthquake or the 2004 Parkfield, California, earthquake (cf. 68 Pitarka et al., 1998; Sasetyan, 2007). Both examples feature very shallow strike-slip faulting, relatively better studied than the fault mechanism for the 2007 Chuetsu-Oki earthquake we 69 70 are dealing with in this paper. In any case, we believe it important to demonstrate how 71 seismological insights serve to reproduce the ground motions in such difficult and complex 72 cases.

In this paper, to study the validity of 3D subsurface structure models, we begin with simulations of the aftershocks, considered as point sources. We thence move on to the mainshock simulation using different finite source models provided by some seismological inversion studies. We compare the simulated ground motions with the records obtained on the permanent networks in terms of the waveforms and response spectra. In this paper, our aim is not to tune up the parameters to obtain the best model, but rather to analyze each model in detail and discuss how we can procure reliable input ground motion in the near field.

80

81 2. Numerical Simulation Methodology

All the simulations in this paper are carried out using the finite difference method based on the staggered grid with 4th order in space and 2nd order in time (Aochi & Madariaga, 2003, Dupros *et al.*, 2008, references therein). The finite fault is approximated by a series of point sources in space (Olsen, 1994; Graves, 1996) and an arbitrary source time function can be considered at each point. How material heterogeneity dealt with is considered a crucial
issue in the finite difference scheme (cf. Moczo *et al.*, 2002; 2007). In this study, we follow
Graves (1996) by averaging the material parameters, since the material interface is not always
precisely defined at the FD grids we used.

90 We define our physical model volume as 110 km (EW) x 120 km (NS) x 30 km 91 (depth). We use a grid spacing of $\Delta s = 200$ m and a time step of $\Delta t = 0.01$ sec for most of the 92 simulations; in some cases, we calculate with $\Delta s = 100$ m and $\Delta t = 0.005$ sec, and $\Delta s = 75$ m 93 and $\Delta t = 0.0035$ sec are used to check the convergence of simulations. For all cases, ten finite 94 difference grids are added at each edge as a Perfectly Matched Layer absorbing boundary 95 (Collino & Tsogka, 2001; Komatitsch & Martin, 2007). Thus, the numerical dimension is 570 96 x 620 x 160 = 56 million grids for $\Delta s = 200$ m, 1120 x 1220 x 310 = 423 million for $\Delta s = 100$ 97 m and 1356 x 1716 x 429 = 1 billion for $\Delta s = 75$ m. The calculation duration is 60 seconds. The upper frequency limit in the simulations is usually estimated as $f_{\text{max}} = V_{\text{min}} / (5\Delta s)$, where 98 V_{\min} denotes the minimum wave velocity in the structural model being used (Levander, 1988). 99 100 Based on several tests using different grid spacings and filter frequency ranges, we find it 101 empirically to be a quite useful parameter.

102 Our simulation procedure is illustrated schematically in Figure 2. The input files both 103 for the structure and the source need to be handled with care. For the structure, we read the 104 original files provided by different studies and assign the material property at each grid in our 105 simulation program. For the source models, however, we format the source files prior to the 106 simulations after carefully ascertaining how the inversions have been achieved. Since the 107 synthetic near-field ground motion is quite sensitive to the source description in time and 108 space, in order to reproduce the ground motions using the source models inverted from the 109 observations, we must understand exactly how they are solved in terms of the Green's 110 function being used and detailed source time description (cf. Aochi et al., 2011).

The numerical dimension is not overly large, compared to some advanced simulations 111 112 of wave propagation using finite difference methods (cf. Olsen et al., 2009; Furumura & Saito, 113 2009). In order to be able to repeat several simulations for verification and calibration 114 purposes, we improved time performance through a hybrid implementation using MPI 115 (Message Passing Interface) and threads by OpenMP (Open Multi-Processing) (Aochi & 116 Dupros, 2011). It takes 40-minute and an 8-hour runs for coarse and medium-sized grids 117 respectively, on the 128 processors (16 nodes x 8 cores) on JADE at CINES, the French 118 national computing centre. It takes about 18 hours for the finer grid on the 256 processors (32 119 nodes x 8 cores, namely 32 MPI sub-domains x 8 OpenMP threads).

120

121 **3. 3D Structural Models**

122 Geological Features

123 In this section, we will be explaining three 3D structure models we use in this study. 124 Their key features are summarized in Table 1, and the cross-sections of each model are shown 125 on Figure 3. The flat part of this region and the folded hills in between, as well, are composed 126 of thick sedimentary layers. Conversely, the surrounding mountains to the south and east are 127 characterized by rocks. The complex lateral variations in basement structure along the NE-SE 128 fault striking are ascribed to Miocene rifting during the opening stage of the Sea of Japan and 129 the subsequent shortening of the crust (Okamura et al., 1995; Kato et al., 2009). Because the 130 Mw 6.6 Chuetsu earthquake in 2004 occurred 30 km southeast of the area ruptured in 2007, 131 this region is recognized as an active fracture zone or strain concentration zone, which had 132 been identified through structural geology (Okamura et al., 1995) and GPS observations 133 (Sagiya et al., 2000). Because this area exhibits complex 3D structures, the velocity structure 134 must be correctly reproduced if we are to generate sound synthetic ground motions.

136 **The ERI Model**

The first model (hereinafter referred to as the "ERI" model) is built by P- and S-wave travel time Double-Difference tomography from aftershock observations on land and at the sea bottom (Kato *et al.*, 2008; Shinohara *et al.*, 2009; Kato *et al.*, 2009). A relocated aftershock distribution is provided as well, based on the ERI model. The minimum grid interval is 3 km (N125°E) x 5 km (N35°E) x 3 km (vertical). The minimum S-wave velocity (Vs) obtained is 866 m/s.

143

144 **The NIED Model**

The second model (hereinafter referred to as the "NIED" model) is taken from 145 146 Fujiwara et al. (2009) and is available on the J-SHIS website (Japan Seismic Hazard 147 Information Station: http://www.j-shis.bosai.go.jp). The area of interest is largely the same as 148 Hikima et al. (2007), also based on Fujiwara et al. (2006). Hikima et al. (2007) associate the 149 preliminary structural model with the seismic reflection results, calibrate the structure (layer 150 depths) beneath each station by means of the observed H/V spectrum (1D tuning) and also 151 tune up the structure along cross-sections between source and receiver, particularly for the 152 aftershocks of the 2004 Chuetsu earthquake (2D tuning). The file (J-SHIS) provided is 153 described in terms of depth to the layer boundaries at mesh nodes of 45" in longitude and 30" in latitude (the 3rd mesh for land planning in Japan), namely about a 1 km x 1 km mesh. It 154 155 contains 32 layers between the surface and the basement characterized by an S-wave velocity 156 (Vs) of 3300 m/s, but many of these are not present in the region of concern. The minimum 157 Vs is set at 350 m/s.

158

159 The GSJ Model

160 The third model, referred to in this paper as the "GSJ" model, is presented in 161 Sekiguchi et al. (2009). They improved the earlier NIED model (Fujiwara et al., 2006) for the 162 Niigata area by carefully calibrating layer depths and rock parameters based on seismological 163 observations and taking into account the regional dependency of material parameters. The file 164 (appended CD-ROM of Sekiguchi et al., 2009) provides the depth of layer boundaries at mesh 165 nodes of 0.00625 degrees longitude and 0.004167 degrees latitude, i.e., about a 0.5 x 0.5 km 166 mesh. Model 2 designated in their CD-ROM contains 50 layers above the Moho. Because the 167 parameters beneath the basement (Vs = 3300 m/s) are not supplied, we have used those from 168 their previous study in other regions, the central part of Japan (Sekiguchi & Yoshimi, 2010).

169

170 **Comparison**

171 The original features of each model are provided in the corresponding references. 172 Figure 3 shows the cross-sections for these three models derived from the numerical 173 simulations. We note that while there are many layers in the NIED and GSJ models, all of 174 them are not always present at the finite difference grid point. We then interpolate the 175 material parameters by averaging (Graves, 1996) instead of estimating precisely the interface plane between the finite difference grids (Moczo et al., 2002). While uncertainties linked to 176 177 the numerical processing remain on the scale of a calculation grid, the models used do 178 adequately represent characteristic features in Figure 3. The three models are visually similar 179 in terms of the shape of the basin structure. Although the tomography study (the ERI model) 180 is carried out independently, it does detect the basin structure (low velocity zone) well. As the 181 ERI model is inverted from dense observation data mainly above the aftershock area, the 182 resolution toward the north (Y=20 km) is not good enough to be comparable with the other 183 two models. The NIED and GSJ models are similar, but the bedrock depth seems different: 184 the NIED model is generally deeper.

186 4. Aftershock simulations

187 Model settings

188 In order to examine the structural models in detail, we begin by simulating some small 189 earthquakes. We chose two aftershocks of the 2007 Niigata-ken Chuetsu-oki earthquake that 190 were well located by Kato et al. (2008) and Shinohara et al. (2008) and also have mechanisms 191 obtained by the F-net broadband seismograph network (http://www.fnet.bosai.go.jp). Table 2 192 summarizes the source parameters. The hypocental depths given by the two catalogues differ 193 by a few kilometres, although the epicenters are relatively well determined. The seismicity 194 distribution in this area is often shallower than that routinely obtained (cf., the progress report 195 of the Japanese national project on the observation along the strained zone, MEXT, 2010). 196 We impose a smooth bell-shaped source time function (cubic B-spline function) of a 0.5second duration at the hypocenter (Figure 4), which is reasonable for events of Mw 4.4. We 197 198 simulate these sources for each of the three geological models.

Before discussing the simulation results, a question may be raised concerning the quality of finite difference simulations. In Appendix, we have provided our synthetic comparisons between the finite difference and spectral element methods using the ERI model for the first aftershock. It is thus found that the numerical simulations are reliable enough to provide the ground motion under the given model and conditions.

204

205 Near-Field Ground Motion

Figure 4 shows the comparison at station KZK (F-net) using the three structural models, all of which are simulated with $\Delta s = 100$ m. This station is located at a depth of 60 m on terrain characterized as rocky, not only locally but also regionally to a certain extent. In the simulations, the event origin times are set at 0. We align the observations for the origin time 210 reported by the relocated earthquake catalogue (Table 2). The seismograms are not filtered at 211 this station. First we observe that the P-wave arrives simultaneously for all the cases (UD 212 component), but the S-wave arrival does differ somewhat. The ERI model, for which the 213 earthquakes are relocated, yields the best arrival time, whereas the other two models, NIED 214 and GSJ, display a delay of a few seconds (EW and NS components). Then, the two models 215 predict much longer and stronger ground shaking than observations in the later phases. This 216 would tend to indicate that their S-wave structure might need to be better tuned up, supposing 217 that the relocated earthquake parameters are correct here. For this KZK station, the ERI model 218 appears to be better constrained, presumably thanks to their 3D tomography coverage from 219 the source area to the station. However, we find that the EW component of the first aftershock 220 (07/16) displays a clear discrepancy between the synthetics and the observation, even with 221 ERI model, as the later phases are those that become dominant in terms of amplitude. This 222 issue is not perfectly resolved and represents a common tendency for this aftershock along the 223 coastline (NIG018 and KK as well). The synthetics do not properly account for the later 224 phases, possibly due to the more complex layer that is shallower than the given resolution (3 225 km in depth, see Table 1).

226

227 The Regional Wave Field

Figures 5 and 6 show the comparison at different stations for different structural models for Aftershocks 1 and 2 respectively. Each seismogram is aligned as was described above. The seismograms are filtered with a 0.1 -0.5 Hz band-pass filter and only the EW component is shown; the response spectra for 5 % damping are also compared. There are still difficulties in reproducing both arrivals and later phases in a satisfactory manner, since they must exhibit a correct velocity profile on the direct path (first arrivals) as well as in a larger surrounding volume for the later phases. In this sense, it is not possible to determine whether 235 one model is better than another at this stage insofar as none of them are perfect for a236 particular study.

However, some remarks can be made, also briefly summarized in Table 3. First, some 237 238 models are seen to generate later phases that are too large at some stations, for example, the 239 GSJ model at NIGH12. The first phase, on the other hand, is fairly accurately rendered by 240 some models at most stations because the source and structure parameters are relatively well 241 established. We note some time shift in phase among the simulations and/or with respect to 242 the observation, at NIG004 and NIG025 among others, for example. This indicates that 243 further improvement may be achieved both in source and structural parameters, but this is not 244 this study's objective. Generally in the near field (cf., NIG018, NIGH11, NIG019, NIG017, 245 NIG016, counter-clockwise), where the propagation path is relatively simple, the 246 reproduction is quite good (especially Figure 6 for Aftershock 2). The response spectra 247 indicate the validity of the average response around the given stations. The simulation of 248 Aftershock 2 is found to be more consistent with the observation than that of Aftershock 1, 249 for which the simulations underestimate the long-period potion of the spectra at the nearest 250 station along the coast. This once again indicates that Aftershock 1 could afford further 251 calibration, probably of the focal depth and/or local structure around the source. In the 252 Kashiwazaki area in the simulation of Aftershock 2, station KZK (a rock site) is well 253 reproduced by the ERI model, while NIG018 (a soil site) is rendered best by the GSJ model, 254 reflecting local geological conditions.

255

256 Discussion

As already stated, the simulations are sometimes not as satisfactory for Aftershock 1. Reasons for this could be that the source parameters are not well constrained or the local structure for this earthquake is not precise enough. As the arrival times of the main phases are

260 fairly good in different directions, the earthquake location appears reliable. Our next step, 261 then, was to invert Aftershock 1's focal mechanism using the ERI model and apply the 262 neighbourhood algorithm so as to generate a wide range of parameters without prior 263 information. After several trials using different stations and different components of the 264 seismograms, we always obtain a focal mechanism of approximately (strike, dip, rake) = 265 $(181^{\circ}, 65^{\circ}, 84^{\circ})$, which differs from the reference solution only by 10 degrees. We may 266 accordingly conclude that the focal mechanism obtained is stable. The remaining open 267 question is: how is it possible to have only one component that does not fit well?

268

269 **5. Mainshock simulations**

Finite source models and simulations in 1D layered models

271 In this section, we chose two finite source models, both involving a southeast dipping 272 reverse fault. Figure 7 shows the projection of the fault plane and the final slip obtained and 273 Table 4 summarizes their characteristics. We used model B (southeast dipping) drawn from 274 Aoi et al. (2008). The model initially obtained by Hikima and Koketsu (2007) was recently 275 integrated into the work of Miyake et al. (2010). We found hypocental locations only about 1 276 km apart; however, due to differences in strike and dip, the disrepancy between the two fault 277 planes is greater. Both models are analysed using available near-field strong ground motion. 278 The only significant difference is that Hikima and Koketsu (2007) used the nearest station 279 data (KK) at the Kashiwazaki-Kariwa nuclear power plant, while Aoi et al. (2008) do not. 280 Note that the data at NIG018 seems to have been distorted by the strong liquefaction at the 281 site, and the record at KZK is saturated for the mainshock. In Figure 8, we show the source 282 time function for each model, which is not retrieved directly from their provided file but 283 rather is based on our input file after changing the file format to make it compatible with our code (e.g. Figure 2). This is important so as to verify our simulations and also for oursubsequent discussion of how the strong ground motion is radiated.

286 We first entered these input files in the simple 1D structure and verified that the source 287 model was properly taken into account. Aoi et al. (2008) introduced the moving source effect 288 when calculating their Green's functions semi-theoretically. We approximated this effect 289 numerically by means of 5 x 5 sub-sub-point sources distributed on each sub-fault in our 290 finite difference simulation, as we already demonstrated in other earthquakes (e.g. Aochi et al., 291 2010). For this earthquake, we observe that the moving source effect is also visible at NIG004. 292 Table 5 gives the 1D velocity structure models derived from the inversions. These are 293 representative of their reference velocity models to a certain extent, but it should be borne in 294 mind that the two inversions adopt different 1D velocity models independently calibrated at 295 every station, that is, the wave field we simulate here does not simultaneously represent all 296 the stations. We chose NIG004 and NIG016 for, as seen on Figure 9, the 1D structure from 297 Aoi et al. corresponds better to NIG004 and that from Hikima & Koketsu to NIG016. The 298 compared ground motions were filtered between 0.1 and 0.5 Hz and calculated with $\Delta s = 200$ 299 m. The origin time is set at 10:13:22.16 (JST) for the observation, and the simulations start at 300 t=0. Our synthetic ground motion for the Aoi et al. model is consistent with the observation at 301 NIG004. Note that their inversion uses only 14 seconds, consisting mainly of the S-wave. 302 This confirms our implementation of the finite source models. At NIG016, the synthetic 303 motion from Hikima & Koketsu reproduces the characteristic waveforms, especially for the 304 vertical component, with time shift of a few seconds. Such a time shift is common in 305 inversions, as the location of the hypocenter and the origin time are not always the same. 306 These verifications not only confirm our numerical implementations but also reflect some of 307 the inversion procedures.

We first carried out simulations in 1D layered models. The reason for this is that most seismological and seismic hazard applications still call on this simple structure except for a few well-known areas in the world, such as southern California, southeastern Japan and Taiwan. In practice, the two source models that were adopted are deduced using this approximation. It accordingly is worthwhile to observe the effects of a 3D structure with respect to the 1D layered models.

314

315 Simulations in 3D structure models

It is not at all evident that the combination of any 3D structure model with any finite source model obtained within a 1D layer model can coherently reproduce the observation, although this procedure is recommended to predict the ground motion for scenario earthquakes intended for use in quantitative seismic hazard studies. It is thus useful now to seek to obtain the characteristic ground motions at different stations and discuss the capability and limitations of the given models.

Figures 10 and 11 show the comparison of a number of synthetic ground motions and the observations at each station for both source models, bearing in mind the fact that the duration of the source process is approximately 15 seconds (Figure 8). The ground motions correspond to the EW component alone and are filtered between 0.1 and 0.5 Hz, because the comparison using this component is enough representative. The ERI model is simulated with $\Delta s = 200$ m and the others with $\Delta s = 100$ m.

Let us examine the stations in the near field (NIG018, NIGH11, NIG019, NIG017, NIG016, counter-clockwise). The source model from Aoi *et al.* properly reproduces the waveforms for the first main phases (about 15 seconds) at NIG016 and NIG019, and the one from Hikima & Koketsu is well suited to NIG017. This coincidence implies that the 1D structural model used in their inversions may be briefly consistent along the concerned cross333 section. Looking at later phases, we also note that goodness of fit is influenced more by the 334 structure than by the source. Both source models reproduce the later phases properly at 335 NIGH11, NIG019, and NIG017 with the NIED and GSJ structures but not with the ERI 336 structure. For NIG018, the three characteristic main pulses are clearly visible, especially in 337 the combination of the NIED structure and the Hikima & Koketsu source model, though the 338 amplitude is much smaller in the synthetics. An additional study of nonlinear soil dynamics 339 could be conducted for this station using the synthetic seismograms as input ground motion, 340 but this is beyond the scope of our study.

341 Now let us look at the stations at moderate distance (NIG025, NIG024, NIGH12, NIGH09, NIGH07, NIG011, NIG010, and NIG004). The ERI structure, for example, 342 343 produces much larger later phases at NIG004, NIG025 and NIGH07, not noticeable in earlier 344 comparisons of aftershocks (Figures 5 and 6), implying that the validity of structure should be 345 evaluated taking into account the frequency content of the source time function. Furthermore, 346 it is noted that the observed motion is much larger (spectra over all the frequency range) than 347 any synthetics at NIG010 and NIG011, and this discrepancy is more obvious for the 348 mainshock than for the aftershock. This indicates that the mainshock generates much larger 349 surface waves than the aftershock.

In this section, we combine different source and structure models to simulate the ground motions. For the same reason already cited in the previous section for the aftershock simulations, it is impossible to determine whether one model is better than the others, for this depends on which aspect one is looking at, since no combination is currently perfect.

354

355 **6. Discussion**

The numerical simulations reflect the current level of seismological knowledge concerning this earthquake. For practical reasons, it is thus important to study the variations in

358 the calculated result from the standpoint of seismic hazard studies. It was predictable that the 359 simulations for the mainshock would not fit the data well in terms of waveforms because the 360 fault models are derived supposing some 1D structures: this may be the limit of our 361 seismological knowledge. However, for engineering purposes, the variation of the simulated 362 ground motions is meaningful. Figures 12 and 13 show the PGV (Peak Ground Velocity) map 363 (different frequency ranges up to 0.5 Hz) for the three structural and two source models. Each 364 source model is also calculated with the reference 1D velocity models (Table 5). As observed 365 in the seismograms (Figures 10 and 11), the source model from Hikima & Koketsu yields 366 stronger ground motion near the coastline rather than offshore; furthermore, the PGV 367 generated from the model by Aoi et al. is centred along the blind fault trace. This latter feature 368 is common for thrust fault earthquakes due to the geometry. In other words, it is confirmed 369 that the model from Hikima & Koketsu integrates some complexity in the rupture process that 370 is acquired particularly from the very near-source records such as the station at the 371 Kashiwazaki-Kariwa nuclear power plant. On the other hand, different 3D structure models 372 briefly give the similar characteristic. The expansion of the green area is consistent with the 373 existence of low-velocity sediments beneath the Sea of Japan between Sado Island and the 374 mainland as well as in the Niigata plain (see topographical map in Figure 3), which cannot be 375 seen in 1D structure modelling. The amplification under the sea is stronger for the ERI 376 structural model, which is the only model constrained from the OBS stations, although the 377 shallow sediment layer under the sea is difficult to evaluate. Cirella et al. (2008) also obtained 378 the finite source model by the joint inversion of strong motion and GPS data and show their 379 forward modelling result in the 1D structure. Concerning the ground motion pattern above the 380 fault plane, the model by Cirella et al. (2008) is closer to the one by Hikima & Koketsu used 381 here. Kawabe and Kamae (2010) simulate the wave propagation in a 3D structure model 382 provided by JNES (Japan Nuclear Energy Safety Organization, internal report, 2005) focusing on the Kashiwazaki-Kariwa nuclear plant. They used a characterized, simple source model
with three asperities and obtained the comparable synthetic ground motions (frequency range
0.05 – 1.6 Hz), strongly affected by these asperities as well as by their local 3D structure. The
JNES model may be more precise around this point of interest but remain essentially local in
scope. Thus for the purposes of a regional discussion as provided in this paper, this model
should be further compiled with other models.

389 We are also interested in other engineering parameters which characterize the ground 390 motion. Figure 14 shows the comparison of PGV values (up to 0.5 Hz) at K-net and KiK-net 391 stations. In terms of PGV (one of the most simple engineering parameters), we can confirm 392 that the simulations are globally consistent with observations within this frequency range 393 except for NIG018, and probably for other stations where later phases are not well modelled 394 (e.g. NIG010 in the ERI structure). This is because the PGV is less sensitive to the details of 395 the rupture process, being mainly affected by macroscopic parameters like fault location, fault 396 geometry, rupture directivity, rupture velocity, and final magnitude. In this sense, both source 397 models are suitable for simulating regional ground motion around the fault.

398 As already seen, this earthquake is an example in which it is difficult to quantitatively 399 reproduce the waveforms. One possible reason is that the complex 3D structure masks the real 400 features of this earthquake. Many kinematic inversions adopt the southeast dipping fault 401 geometry, but this orientation is not the only one sustainable. Aochi and Kato (2010) 402 demonstrate the possibility of a dynamic rupture transfer from a northwest dipping sub-fault 403 to another southeast dipping sub-fault. The two models we used in this study differ in fault 404 orientation, in the position of asperities and in rupture timing, and actually do not fit the same 405 stations. Our study reported in this paper does not aim to calibrate the parameters, but the 406 computing performance we have achieved will allow us to investigate further the source 407 parameters in a 3D structure as well as to refine the structural models. We see that even the 408 subsurface structure obtained through fine tomography might not be sufficient to reproduce 409 observed strong motions, nor those created through the use of both geologic and geophysical 410 data. For some stations suffered from the strong ground motion (c.f. NIG018), it will be 411 necessary to study by coupling with the nonlinear site effects at local level. We may conclude 412 that a combination of tomography and data compiling in velocity structure modelling are 413 called for.

414

415 **7. Conclusion**

416 Finite difference simulations of seismic wave propagation are carried out in the Niigata area, 417 Japan, for the 2007 Mw 6.6 Niigata-ken Chuetsu-Oki earthquake at low frequencies. Some of 418 the calculations are extended up to 1 Hz considering the minimum velocity in the medium of 419 350 m/s. However we limit our discussion to 0.5 Hz throughout this study because of lack of 420 precision in the model. We test three 3D structure models, all of which are built differently in 421 various studies. From the aftershock simulations, it is seen that none of the models are 422 uniform in their resolution and precision in this region, as the later phases are poorly 423 reproduced in some more distant stations. The model based on 3D tomography (ERI model) is 424 good enough for the near field in terms of body waves (arrival time), but its precision for 425 shallow sediment layers is insufficient to reproduce the later phases properly, while the other 426 models (NIED and GSJ models), based on various 1D/2D profiles and geological 427 interpretation, work well for the site response, but do sometimes cause a time shift in phases. 428 For the mainshock simulations, we adopt two different finite source models (Aoi et al., 2008; 429 Hikima and Koketsu, 2008), which differ in the near-field ground motion, especially above 430 the fault plane (but under the sea) and also along the coastline. It is found that each model is 431 calibrated differently for the given stations. For engineering purposes, the variation observed 432 in simulated ground motion is significant, but for seismological purposes, further parameter

433 calibration is desirable and possible for such a complex 3D case using current high

434 performance computing.

435

436 Acknowledgments

437 This work is carried out mainly in the framework of the French national ANR DEBATE 438 project (DEvelopment of Broadband Accleration Timeseries for Engineers; 2009-2012). We 439 thank all the colleagues for making available their numerical results: Drs. A. Kato, S. Aoi, H. 440 Sekiguchi, K. Hikima and K. Koketsu. Many fruitful discussions were held with Profs. Raul 441 Madariaga, Dr. Fabian Bonilla and Prof. Hiroshi Kawase, and Dr. Ken'ichi Tsuda from the 442 DEBATE project. We thank Prof. Peter Moczo and Dr. Eiichi Fukuyama for improving the 443 manuscript. We also express our appreciation for the data provided by K-net, KiK-net, and F-444 net of the National Research Institute for Earth Science and Disaster Prevention. HA thanks 445 NIED for his invitation to Japan in October 2010. MY thanks AIST-GSJ for funding his visit 446 to BRGM in 2009-2010. Part of the simulations were carried out at the super computing 447 center (CINES) in France.

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572 Appendix: Comparison between finite difference and spectral element

573 methods

574 Finite difference simulations are widely used for practical applications, but their 575 quality is sometimes debated especially in the framework of synthetic benchmark tests (e.g. 576 Day et al., 2001; Chaljub et al., 2010). As pointed out by many researchers, the finite 577 difference scheme does not represent any interface correctly (free surface, faulting and 578 material interface) but always gives an approximate solution. In this study, we do not deal 579 explicitly with the interface plane in the numerical simulations even though the models 580 initially supplied (the NIED and GSJ models) are defined by layers. As none of the three 581 models are defined at the finite difference grids of calculation, estimating the material 582 interfaces at given points requires further assumptions.

583 In this appendix, we are describing a comparative test using the finite difference as 584 well as the spectral element methods (De Martin, 2011). We adopt the first example, namely 585 the ERI structure model for the first aftershock. In the spectral element scheme, the material 586 properties are interpolated at each of the GLL (Gauss-Lobatto-Legendre) points. The entire 587 domain is uniformly meshed with hexahedra, constrained by the lowest S-wave velocity. The 588 mesh is composed of 208,936 geometrical nodes, 196,425 hexahedra 1200 m in size in all 589 directions and 16,757 quadrangles for absorbing boundaries by paraxial approximation 590 different from our finite difference simulation. The polynomial order of the basic functions is N = 4, and the total number of degrees of freedom is 46 million (including the redundant GLL 591 592 at the interfaces between the CPUs). Also, the finite difference simulation here is carried out 593 with a grid spacing of 200 m.

594	Figure A1 shows the comparison of the seismograms at NIG004 filtered in the
595	frequency range between 0.1 and 0.5 Hz using the ERI model for Aftershock 1. Despite the
596	completely different numerical procedures, the overall waveforms are well enough
597	reproduced to allow the characteristics of the ground motion to be discussed. Figure A2
598	shows the goodness-of-fit (GOF; Kristekova et al., 2009) for the surrounding K-net stations
599	as a function of epicentral distance. This criterion provides a succinct evaluation of how
600	similar two signals are by a score assigned on a scale of 0 (poor) to 10 (excellent), and ranges
601	higher than 6.5 and 8.5 are considered as good and excellent, respectively. It is observed that
602	the GOD is better at closer distance because of the reduced influence of numerical dispersion
603	and of little impact from absorbing conditions. In fact, the worst station, NIG002, which is
604	qualified as fair (range 4.5 to 6.5), is very close to the model edge. Otherwise, it is confirmed
605	that the simulations are fair enough both in amplitude and phase for the purpose of our
606	discussions.

607 Tables

	ERI model	NIED model	GSJ model
Area covered	Around the area of the 2004	All of Japan	Niigata area
	and 2007 earthquakes		measuring about 200
			km x 200 km
Principal data	P- and S-wave tomography	Seismic reflection,	NIED model,
included	of the aftershock	geological	geological
		interpretation, 1D	interpretation,
		tuning, 2D tuning	geophysical borehole
			data, 1D tuning
Given	3 km (N35°E) x 5 km	45" in longitude and	0.00625 degrees in
resolution	(N125°E) x 3 km at least	30" in latitude	longitude and
			0.004167 degrees in
			latitude
Vs minimum	866 m/s	350 m/s	400 m/s
Given	Vp, Vs by point	Vp, Vs, ρ by layer	Vp, Vs, ρ by layer
property			

Table 1: Characteristics of the three different structural models. See the references in the text.

609

- Table 2: Source parameters of the aftershocks used in the simulations. The relocated
 hypocentral parameters are based on Kato *et al.* (2008) and Shinohara *et al.* (2008). The focal
 mechanisms are obtained routinely by F-net of NIED.

	Aftershock 1	Aftershock 2
Origin Time (JST)	2007/07/16 21:08:1.86	2007/07/18 16:53:5.01
Relocated	37.4983°N, 138.6147°E, 15.413	37.4327°N, 138.5943°E, 16.880
hypocenter	km	km
Routinely obtained	38.5088°N, 138.6297°E, 11 km	37.4418°N, 138.6153°E, 20 km
hypocenter		
Mw	4.4	4.4
Focal mechanism	187°/54°/70°; 39°/41°/115°	39°/62°/95°; 208°/29°/80°
(strike/dip/rake)		

- Table 3: Brief summary of characteristics of the three 3D structural models from the
- 618 aftershock simulations.

Model	Positive characteristics	Aspects to be improved
ERI	Synthetics at near-field rock site, especially in the south	Finer shallow structure, larger area
NIED	Synthetics at near-field soil site, good site response generally	Parameters in shallower soft layers, deep structure
GSJ	Synthetics at near-field soil site, good site response generally, similar to NIED	Same as above

- 620 Table 4: Characteristics of the finite fault models used in this study. Some parameters were
- 621 not specified by Hikima and Koketsu (2007), but we have supplied an estimated condition
- 622 indicated in the blank.

Model	Aoi et al.	Hikima & Koketsu
Reference	Model B from Aoi <i>et al.</i> (2008)	Hikima & Koketsu (2007)
Hypocentral location	37.54°N, 138.61°E	37.54014°, 138.62653°E
Focal depth	8.9 km	10 km
Fault geometry	Strike N49°E, dip 42°	Strike N38°E, dip 34°
Total seismic moment	$1.62 \times 10^{19} \text{ N.m}$	Not specified $(1.02 \times 10^{19} \text{ N.m})$
Sub-fault number	15 (strike) x 12 (dip)	15 (strike) x 9 (dip)
Sub-fault size	2 km x 2 km	2 km x 2 km
Source time discretization	6 multi-windows	7 multi-windows
Rake	Free in each window	Free in each window
Source time function	A smoothed ramp function	Unknown (Ramp function)
Moving rupture effect	Yes	Unknown (No)

Table 5: 1D structure models used for the simulations of this study. (a) For Aoi's model, (b)for Hikima & Koketsu's model.

627 (a)

628

Depth of the top	Vp [m/s]	Vs [m/s]	Density [kg/m ³]	Q (attenuation)
of the layer [km]				
0.0	4600	3090	2600	300
1.383	5900	3300	2700	300
13.632	6700	3800	2900	500
27.533	7700	4300	3250	500
(b)				
Depth of the top	Vp [m/s]	Vs [m/s]	Density [kg/m ³]	Q (attenuation)
of the layer [km]				
0.0	2286.806	1020.620	2057.361	100
0.5	2570.792	1238.071	2114.158	100
1.0	2933.326	1517.943	2186.665	100
1.5	3091.167	1639.359	2218.233	100
2.0	3259.370	2094.144	2251.874	100
3.0	3682.388	2330.547	2336.478	100
4.0	4031.846	2490.645	2406.369	100
5.0	4308.815	2753.608	2461.763	100
6.0	4557.710	2891.243	2511.542	100
7.0	4763.741	3107.153	2552.748	100
8.0	5001.851	3403.074	2600.370	100
9.0	5375.374	3767.530	2675.075	100

10.0	5887.317	3403.074	2777.464	250
14.0	6517.827	3767.530	2903.565	250
20.0	6903.343	3990.372	2980.669	250
33.0	7587.204	4262.474	3113.777	250

632 Figure captions

634	Figure 1: Map of the area surrounding the 2007 Niigata Chuetsu Oki earthquake. The star
635	represents the hypocentral location defined by Aoi et al. (2008). The black rectangle indicates
636	the projection of the fault plane according to Aoi et al. (2008). The grey rectangle indicates
637	the projection of the fault plane according to Hikima & Koketsu (2008). The pink dots
638	represent the aftershocks relocated by Kato et al. (2008) and Shinohara et al. (2008) recorded
639	over the space of one month immediately after the mainshock. The triangles and names are
640	the seismograph stations from K-net, Kik-net, F-net and the Kashiwazaki-Kariwa nuclear
641	power plant operated by TEPCO (KK).
642	
643	Figure 2: Schematic representation of the simulation procedure.
644	
645	Figure 3: Cross-sections of different 3D structure models in the numerical simulations. See
646	the text for the details of each model, ERI, NIED and GSJ.
647	
648	Figure 4: Comparison of synthetic and observed ground motion for the selected aftershocks
649	(Table 2) at station KZK using three different structural models. All the seismograms are not
650	filtered. The earthquake location and the given moment release function are shown at the top.
651	Response spectra are calculated at the bottom for the waveforms up to 0.5 Hz.
652	
653	Figure 5: Comparison of synthetic and observed ground motion for the first aftershock (Table
654	2) at different stations for each structure model. The ground motion is calculated over 60
655	seconds, then filtered between 0.1 and 0.5 seconds. The response spectra are also shown.
656	

Figure 6: Figure 5: Comparison of synthetic and observed ground motion for the secondaftershock (Table 2) at different stations for each structure model.

659

Figure 7: The two finite source models used in this study. Also see Table 4 for theircharacteristics.

662

Figure 8: Source time function prepared as the input file for the numerical simulations. Each panel is shown every 2 km, as are their inversions. Red lines indicate the dip component (rake 90°) and blue ones represent the strike component (rake 0°) at each point.

666

667 Figure 9: Synthetic ground motions at NIG004 and NIG016 for the source models from Aoi *et*

668 *al.* and Hikima & Koketsu, simulated in 1D structure models, respectively. The seismograms

are filtered between 0.1 and 0.5 Hz.

670

671 Figure 10: Comparison of the synthetic ground motions at different stations for the Aoi source

model of the mainshock using the three different 3D structure models. The component is

East-West. The waveforms are filtered between 0.1 and 0.5 Hz.

674

Figure 11: Comparison of the synthetic ground motions at different stations for the Hikima &

676 Koketsu source model of the mainshock using the three different 3D structure models. The

677 component is East-West. The waveforms are filtered between 0.1 and 0.5 Hz.

678

679 Figure 12: Map of peak ground velocity (PGV) for each component (x: east-west, y: north-

680 south, z: up-down) and the source model from *Aoi et al*. The seismograms are filtered up to

681 0.5 Hz.

683 Figure 13: PGV map for the source model from Hikima & Koketsu.

684

685 Figure 14: Comparison of horizontal (geometric mean) PGV for six simulations (see also

686 Figures 11 and 12). X symbols represent the observed values.

687

688 Figure A1: Comparison of synthetic seismograms at NIG004 calculated using the finite

689 difference and spectral element methods. The structure is the ERI model and the source is

690 Aftershock 1. The signals are filtered between 0.1 and 0.5 Hz.

691

692 Figure A2: The goodness-of-fit between the two simulations at the surrounding K-net stations.

693 The seismograms are filtered between 0.1 and 0.5 Hz, and the scores for both amplitude (left)

and phase (right) are shown for each component. The stations are aligned versus epicentral

695 distance. The reference for the score is taken for the spectral element method. The coherence

between two signals is excellent for a range of 8.5-10, good for 6.5-8.5 and fair for 4.5-6.5.

697 Figure 1 :



700 Figure 2:



Figure 3:



Figure 4 : (revised)



713 Figure 5:



717 Figure 6:



719 Figure 7:







726 Figure 9 :









Figure 12 : (revised)



737 Figure 13 :













