Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

Simulation of strong ground motions based on pseudo point-source model – Application to crustal earthquakes

A. Nozu
Port and Airport Research Institute, Yokosuka, Japan

ABSTRACT: The pseudo point-source model is a new type of source model for strong motion simulation, in which strong ground motions are generated from a few point sources distributed on the fault. The source spectrum associated with the rupture of a subevent is assumed to follow the omega-square model. The source model consists of only six parameters for each subevent. In this study, the applicability of the model to two large crustal earthquakes in Japan, namely the 1995 Kobe earthquake (M_J7.3) and the 2007 Chuetsu-oki earthquake (M_J6.8) was investigated. The results show that, the model can well simulate strong ground motions affected by forward-directivity effects if the corner frequency is appropriately assigned.

1 INTRODUCTION

Recently strong motion simulations with considerations of the source, path and site effects have increasingly been recognized as a useful tool to determine reasonable design ground motions (e.g., Evangelista et al. 2017). In our country, the characterized source model, which is composed of rectangular subevents that generate strong ground motions, have extensively been used for the purpose of predicting strong ground motions (e.g., Kamae & Irikura 1997). Those subevents are referred to as “asperities” or “Strong Motion Generation Areas (SMGAs)” (Miyake et al. 2003). On the other hand, the author (Nozu 2012) proposed a new source model, namely, the pseudo point-source model, which could be regarded as a simplified version of the conventional characterized source model.

In the pseudo point-source model, the spatiotemporal distribution of slip within a subevent is not modeled. Instead, the source spectrum associated with the rupture of a subevent is modeled and it is assumed to follow the omega-square model (Aki 1967). The source model consists of only six parameters for each subevent, namely, the longitude, latitude, depth, rupture time, seismic moment and corner frequency of the subevent. The model involves much less model parameters than the conventional characterized source model. Once the model parameters are given, by multiplying the source spectrum with the path effect and the site amplification factor, the Fourier amplitude at the site of interest can be obtained. Then, combining it with the Fourier phase of a smaller event, the time history of strong ground motions from the subevent can be calculated. Finally, by summing up contributions from the subevents, strong ground motions from the entire rupture can be obtained.

There were two major motivations for this simplification (Nozu 2012). First, the Fourier phase of strong ground motions is determined mostly by the path and site effects; it is less important to consider the effect of rupture propagation within a subevent on the Fourier phase. Secondly, the Fourier spectra of strong ground motions recorded at rock sites during past large earthquakes tend to show relatively smooth shapes that lack significant peaks and troughs. However, synthetic Fourier spectra calculated with a conventional characterized source model tend to express artificial peaks and troughs related to the sizes of the subevents or the numbers of discretization. Therefore, it was intended to simply model the shapes of the source spectra to better reproduce the observed Fourier spectra.

If such a simplified source model can explain strong ground motions with certain accuracy, it would also be helpful in reducing costs for strong motion prediction especially when a large number of scenarios are considered. In fact, according to the results of past studies, the model could explain strong ground motions from a mega-thrust earthquake (Nozu 2012) and intra-slab earthquakes (e.g., Wakai et al. 2014), sometimes better than the conventional characterized source models.

In this study, the applicability of the model to crustal earthquakes was investigated. Two large crustal earthquakes in Japan, namely the 1995 Kobe earthquake (M_J7.3) and the 2007 Chuetsu-oki earthquake (M_J6.8) were selected. The former is a predominantly strike-slip earthquake and the latter is a predominantly dip-slip earthquake. These earthquakes were selected because strong motion simulations based on conventional source models had been conducted for these earthquakes (e.g., Nozu et al. 2006, Nozu et al. 2008) and comparisons could be made between the results of the conventional source models and the pseudo point-source models.

2 METHODS

2.1 *Strong motion simulation based on the pseudo point-source model*

The strong ground motion simulation based on the pseudo point-source model can be outlined as follows.

First, it is assumed that strong ground motions are generated by subevents distributed on the fault. Then, strong ground motions associated with the rupture of one subevent are calculated in the frequency domain as follows:

$$F(f) = |S(f)| \times |P(f)| \times |G(f)| \times O(f)/|O(f)|_p \tag{1}$$

where $F(f)$ is the Fourier transform of the strong ground motions associated with the rupture of the subevent, $|S(f)|$ is the source spectrum of the subevent, assumed to follow the ω^{-2} model (Aki 1967). More specifically, it can be expressed as follows:

$$|S(f)| = R_{\theta\varphi} \cdot FS \cdot PRTITN \cdot M_0/\left(4\pi\rho\beta^3\right) \cdot (2\pi f)^2/\left(1 + (f/f_c)^2\right) \tag{2}$$

where M_0 is the seismic moment of the subevent, f_c is the corner frequency of the subevent, and ρ and β are the density and the shear wave velocity in the source region, respectively. $R_{\theta\varphi}$ is the radiation coefficient, FS stands for the amplification due to the free surface (=2), and $PRTITN$ is a coefficient that represents the partitioning of S-wave energy into two horizontal components as defined by Boore (1983). $|P(f)|$ is the path effect, and $|G(f)|$ is the empirically-evaluated site amplification factor at the site of interest. Equation 1 implies that the Fourier amplitude spectrum of the ground motions from the subevent can be evaluated as the product of the source, path and site effects. $O(f)$ is the Fourier transform of an actual record at the site of interest and $|O(f)|_p$ is its Parzen-windowed amplitude (Nozu et al. 2009) (a band width of 0.05 Hz was used). $O(f)$ gives the Fourier phase information for the ground motions from the subevent. The time history of the ground motions from the subevent can be obtained with the inverse Fourier transform. Finally, strong ground motions from the entire rupture can be obtained by summing up the contributions of the subevents, considering the arrival times from the different subevents. The source model consists of only six parameters for each subevent: the longitude, latitude, depth, rupture time, seismic moment and corner frequency of the subevent. This source model therefore requires far fewer model parameters than do conventional models.

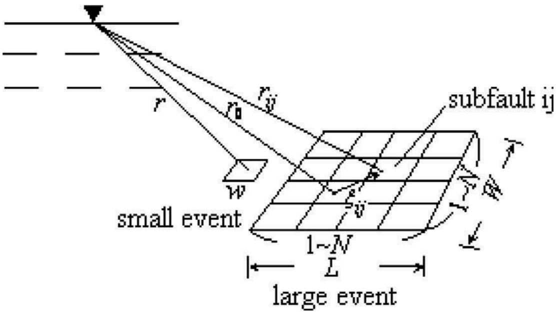

Figure 1. Superposition of Green's functions. The large rectangle shows an asperity.

2.2 *Strong motion simulation based on the characterized source model*

In this section the strong motion simulation used in the author's past studies (Nozu et al. 2006, Nozu et al. 2008) will be explained. The method was first proposed by Kowada et al. (1998) and improved by the authors (Nozu et al. 2009). The method is now widely used in the design of port and airport structures in Japan. A FORTRAN program for this method is available at https://www.pari.go.jp/bsh/jbn-kzo/jbn-bsi/taisin/sourcemodel/somodel_program.html.

First, a small event is hypothesized, whose area is equal to the area of the asperity of the target earthquake divided by N^2 and whose final slip is equal to the final slip of the asperity divided by N (Figure 1). The ground motions from the small event is called the "Green's function". The source spectrum of the small event is assumed to follow the ω^{-2} model (Aki 1967). The ground motions from the small event can be calculated based on exactly the same equations as in the pseudo point-source model, that is, Equations 1 and 2, except that the seismic moment and the corner frequency in Equation 2 should be replaced by those for the small event. The seismic moment for the small event is equal to that of the asperity divided by N^3. The corner frequency of the small event can be evaluated by the following equation (Brune 1970, 1971).

$$f_{ce} = 0.66\beta / S_{\mathrm{e}}^{0.5} \quad (3)$$

where f_{ce} and S_{e} are the corner frequency and the area of the small event, respectively.

Once the ground motions from the small event is evaluated, it can be superposed (e.g., Miyake et al. 2003) to obtain the ground motions from the entire asperity (Figure 1). Finally, strong ground motions from the entire rupture can be obtained by summing up the contributions of the asperities, considering the arrival times from the different asperities.

3 APPLICATION TO CRUSTAL EARTHQUAKES

3.1 *The 1995 Kobe, Japan, earthquake (M_J7.3)*

The methods were applied to the 1995 Kobe (Hyogo-ken Nanbu) earthquake, which was a shallow crustal earthquake and killed more than 6000 people in and around Kobe City. Strong ground motions at two CEORKA sites in Kobe, KBU and MOT, were simulated.

The conventional simulation (Nozu et al. 2008) was based on the characterized source model by Yamada et al. (1999) (Figure 2). Based on the simulation of aftershock ground motions, the seismic moments of the asperities were re-evaluated by Nozu et al. (2006) as 3.4×10^{17} Nm, 1.3×10^{18} Nm and 2.3×10^{18} Nm for the asperities 1,2 and 4, respectively. The Awaji-side asperity (Asperity 3) was neglected in the simulation because it had little effects on ground motions in Kobe. Relative rupture times were 0.0 s, 1.8 s and 6.9 s for the asperities

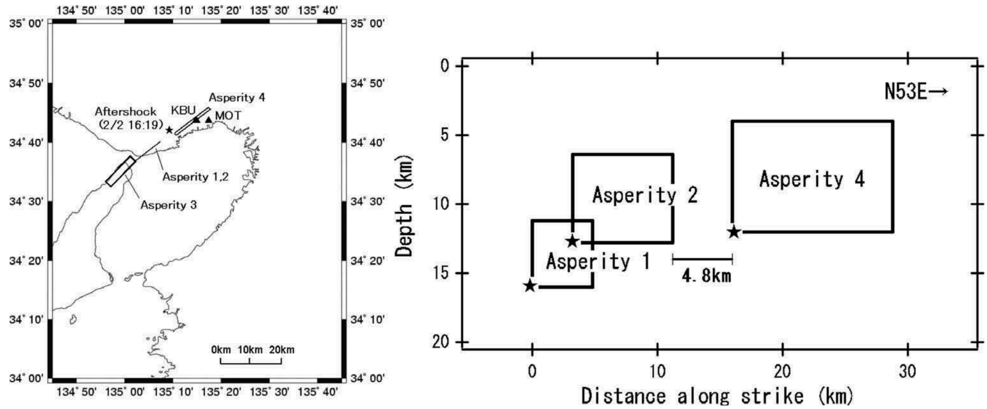

Figure 2. (left) The characterized source model by Yamada et al. (1999) for the 1995 Kobe earthquake, the epicenter of the aftershock used and the CEORKA strong motion sites KBU and MOT. (right) Its cross section for the Kobe side. The characterized source model has three asperities in the Kobe side. The stars indicate the rupture starting point for each asperity.

1,2 and 4, respectively. Rise times were 0.4 s, 0.5 s and 0.6 s for the asperities 1,2 and 4, respectively.

The pseudo point-source model for the Kobe earthquake was developed as a simplified version of the characterized source model mentioned above. Point sources were put at the centers of the asperities. Table 1 shows the model parameters for the final model. For the initial model, the seismic moments were the same as those for the characterized source model and the corner frequencies were determined based on Equation 3 using the area of the asperities (0.48, 0.32 and 0.23 Hz for the asperities 1,2 and 4, respectively). Then, those values were corrected to achieve better fit to the observation as shown in Table 1. The relative rupture times for the point sources include the effects of rupture propagation inside the asperities.

Other parameters were common to the two simulations: The density and shear wave velocity of 2.7×10^3 kg/m^3 and 3.5 km/s were used, respectively. The averaged radiation coefficient of 0.63 was used. The coefficient *PRTITN* (Boore 1983) was assumed to be 0.71. The Q value of $Q=180f^{0.7}$ (Petukhin et al. 2003) was used to represent the path effects. The site amplification factors empirically evaluated by Nozu & Nagao (2005) for the target sites were used. For the evaluation process of the site amplification factors, see also Nozu et al. (2006). The evaluated site amplification factors can be downloaded from https://www.pari.go.jp/bsh/jbn-kzo/jbn-bsi/taisin/siteamplification_jpn.html. To evaluate the phase characteristics, the records from an aftershock (February 2, 1995) was used, whose hypocenter is shown in Figure 2.

Synthetic velocity waveforms and velocity Fourier spectra are compared with the observed ones in Figures 3 & 4 for the characterized source model and in Figures 5 & 6 for the pseudo

Table 1. Parameters for the pseudo point-source model for the 1995 Kobe earthquake.

	Subevent 1	Subevent 2	Subevent 3
Longitude (deg.)	135.061	135.103	135.238
Latitude (deg.)	34.623	34.65	34.732
Depth (km)	13.6	9.6	8
Seismic moment (Nm)	3.4×10^{17}	1.0×10^{18}	3.0×10^{18}
Corner frequency (Hz)	0.48	0.48	0.18
Relative rupture time (s)	0	2.6	8.1

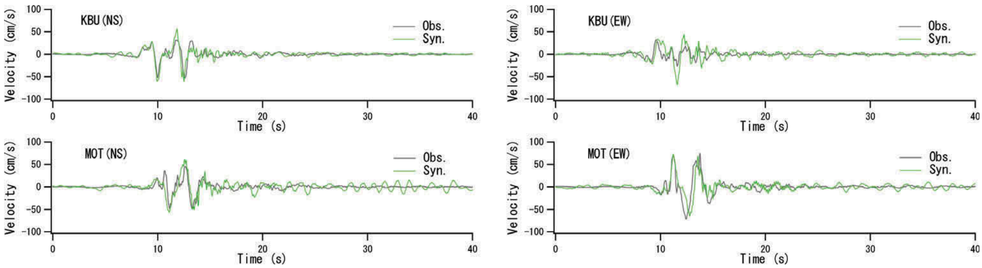

Figure 3. The recorded (black) and simulated (green) velocity waveforms at KBU and MOT for the 1995 Kobe earthquake. The simulation was based on the characterized source model.

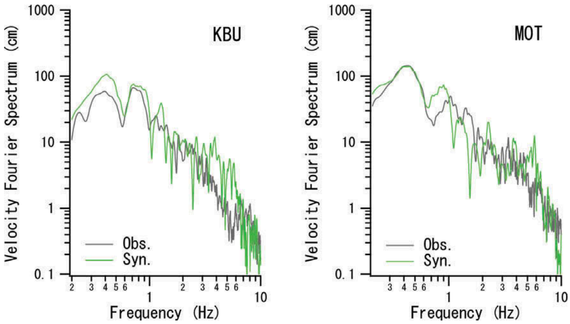

Figure 4. The recorded (black) and simulated (green) velocity Fourier spectra at KBU and MOT for the 1995 Kobe earthquake. The simulation was based on the characterized source model.

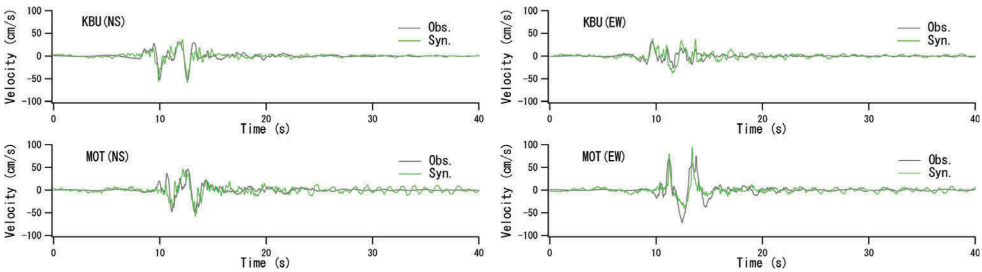

Figure 5. The recorded (black) and simulated (green) velocity waveforms at KBU and MOT for the 1995 Kobe earthquake. The simulation was based on the pseudo point-source model.

point-source model, respectively. It can be clearly seen that the damaging velocity pulses generated by the asperities were reproduced with high accuracy, not only with the characterized source model but also with the pseudo point-source model.

3.2 *The 2007 Chuetsu-oki, Japan, earthquake (M_J6.8)*

Next the method was applied to the 2007 Chuetsu-oki earthquake. Strong ground motions at three strong motion stations, namely, KKZ1R2 (TEPCO), NIG016 (K-NET) and NIG018 (K-NET) were simulated. Locations of the sites are shown in Figure 7.

Based on the final slip distribution estimated from a waveform inversion (color contours in Figure 7), the characterized source model (red rectangles) was developed (Nozu, 2008). The

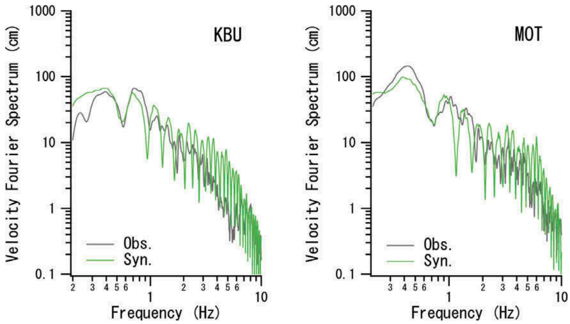

Figure 6. The recorded (black) and simulated (green) velocity Fourier spectra at KBU and MOT for the 1995 Kobe earthquake. The simulation was based on the pseudo point-source model.

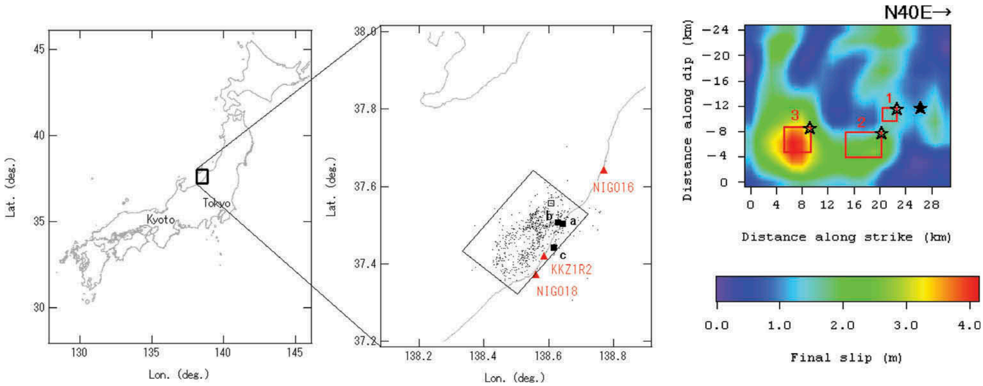

Figure 7. The 2007 Chuetsu-oki earthquake. The map in the central panel shows the location of the fault (black rectangle) with the sites (red triangles) and the aftershocks (black squares) used for the analysis. The dip angle is 36 degrees. The right panel shows the final slip distribution for the earthquake estimated from a waveform inversion (color contours) and the characterized source model based on the inversion results (red rectangles). The open stars indicate the rupture starting point for each asperity.

seismic moments of the asperities were 0.4×10^{18} Nm, 1.0×10^{18} Nm and 1.0×10^{18} Nm for the asperities 1,2 and 3, respectively. Relative rupture times were 1.3 s, 2.4 s and 6.4 s for the asperities 1,2 and 3, respectively. Rise times were 0.17 s, 0.33 s and 0.25 s for the asperities 1,2 and 3, respectively.

The pseudo point-source model for the Chuetsu-oki earthquake was developed as a simplified version of the characterized source model mentioned above. Point sources were put at the centers of the asperities. Table 2 shows the model parameters for the final model. For the initial model, the seismic moments were the same as those for the characterized source model and the corner frequencies were determined based on Equation 3 using the area of the asperities (1.16, 0.47 and 0.77 Hz for the asperities 1,2 and 3, respectively). Then, those values were corrected to achieve better fit to the observation as shown in Table 2. The relative rupture times for the point sources include the effects of rupture propagation inside the asperities.

Other parameters were common to the two simulations: The density and shear wave velocity of 2.7×10^3 kg/m^3 and 3.5 km/s were used, respectively. The averaged radiation coefficient of 0.63 was used. As for the coefficients *PRTITN* (Boore 1983), values ranging from 0.63 to 0.77 were selected so that the observations can be explained well. The Q value of $Q=166f^{0.76}$ (Satoh & Tatsumi 2002) was used to represent the path effects. The site amplification factors empirically evaluated for the target sites were used (Nozu et al. 2008). To evaluate the phase

Table 2. Parameters for the pseudo point-source model for the 2007 Chuetsu-oki earthquake.

	Subevent 1	Subevent 2	Subevent 3
Longitude (deg.)	138.579	138.6	138.505
Latitude (deg.)	37.541	37.527	37.443
Depth (km)	11.4	13.2	12.9
Seismic moment (Nm)	0.4×10^{18}	1.0×10^{18}	1.0×10^{18}
Corner frequency (Hz)	1	0.3	0.5
Relative rupture time (s)	1.3	3.4	7.4

characteristics, the records of the aftershocks a (7/16 15:37), b (7/16 21:08) and c (7/18 16:53) (Figure 7) were used for NIG016, KKZ1R2 and NIG018, respectively. At KKZ1R2 and NIG018, nonlinear behavior of the soil was considered (Nozu et al. 2008).

Synthetic velocity waveforms and acceleration Fourier spectra are compared with the observed ones in Figures 8 & 9 for the characterized source model and in Figures 10 & 11 for the pseudo point-source model, respectively. The results are quite reasonable except for the overestimation of the velocity waveforms and Fourier spectra at NIG016, located north-east of the source region, for the pseudo point-source model.

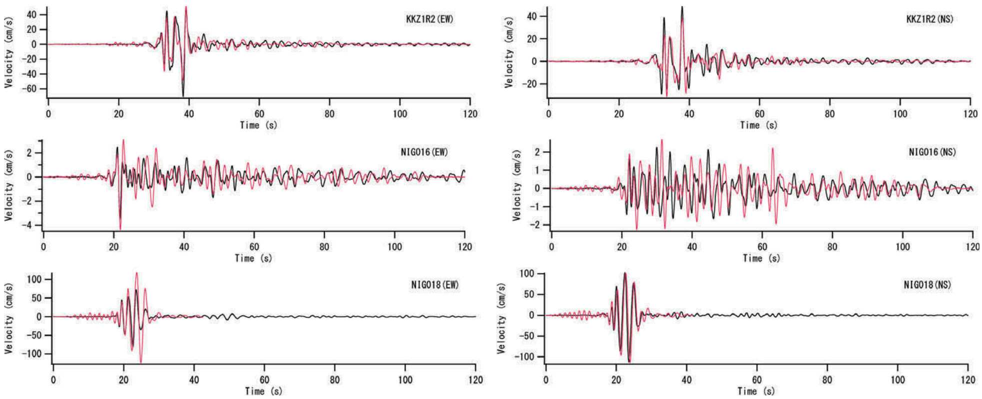

Figure 8. The recorded (black) and simulated (red) velocity waveforms (0.2-1Hz) at KKZ1R2, NIG016 and NIG018 for the 2007 Chuetsu-oki earthquake. The simulation was based on the characterized source model.

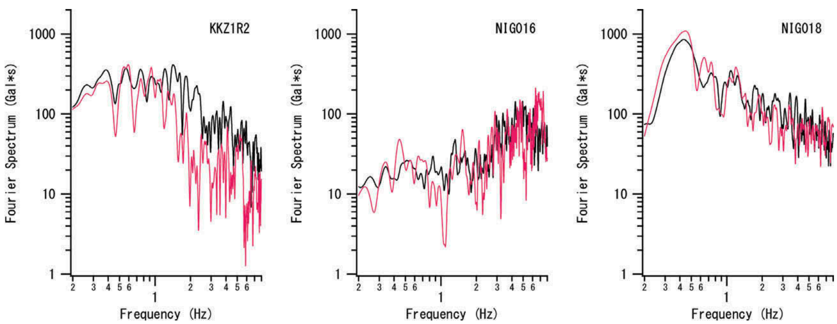

Figure 9. The recorded (black) and simulated (red) Fourier spectra at KKZ1R2, NIG016 and NIG018 for the 2007 Chuetsu-oki earthquake. The simulation was based on the characterized source model.

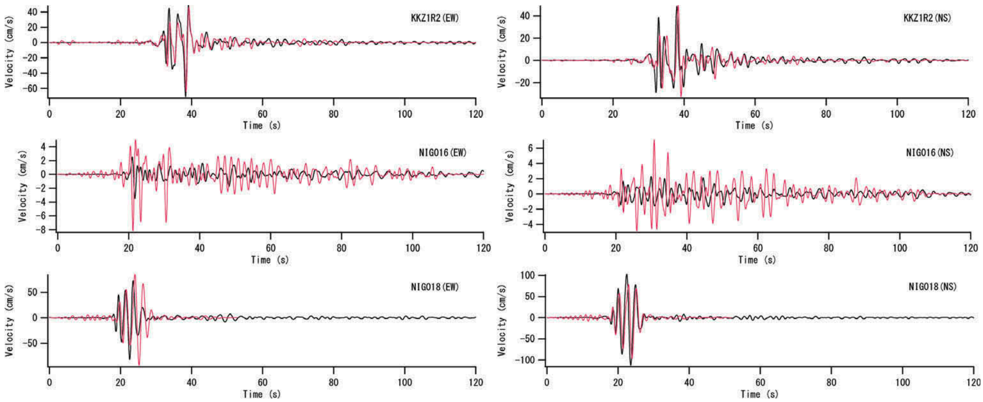

Figure 10. The recorded (black) and simulated (red) velocity waveforms (0.2-1Hz) at KKZ1R2, NIG016 and NIG018 for the 2007 Chuetsu-oki earthquake. The simulation was based on the pseudo point-source model.

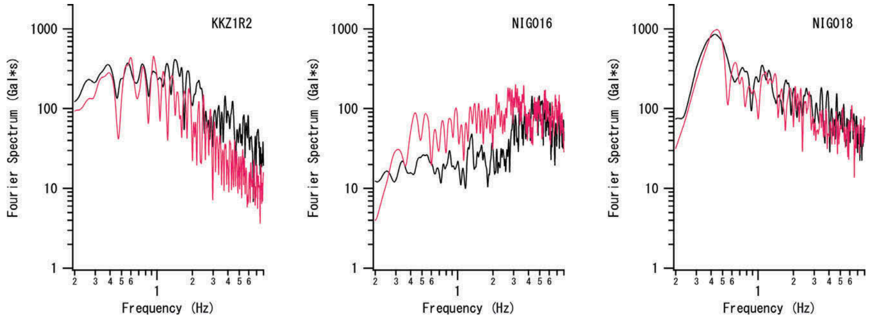

Figure 11. The recorded (black) and simulated (red) Fourier spectra at KKZ1R2, NIG016 and NIG018 for the 2007 Chuetsu-oki earthquake. The simulation was based on the pseudo point-source model.

4 DISCUSSION AND CONCLUSION

The waveforms at NIG016 for the 2007 Chuetsu-oki earthquake was well simulated with the characterized source model, however, it was overestimated with the pseudo point-source model. The discrepancy can be attributed to the backward directivity effect. The rupture of the 2007 event propagated from north-east to south-west as shown in Figure 7. It means that NIG016 was located at the backward side. In the current version of the pseudo point-source model, only one corner frequency is assigned to each subevent. Therefore, the current version of the pseudo point-source model cannot consider the difference of the corner frequencies for the forward and backward sites. In this study, the corner frequencies for the subevents of the 2007 event were determined referring mainly to the records at KKZ1R2 and NIG018 considering the importance of these near-source stations. Therefore, the corner frequencies were overestimated for the backward stations. In a future work, azimuth-dependent corner frequency should be introduced.

Nevertheless, the pseudo point-source model could simulate strong ground motions at KKZ1R2 and NIG018 for the 2007 Chuetsu-oki earthquake and at KBU and MOT for the 1995 Kobe earthquake. It means that, if the corner frequency is appropriately given, the pseudo point-source model can well simulate strong ground motions affected by forward-directivity effects. The results show the usefulness of the pseudo point-source model for engineering purposes.

ACKNOWLEDGEMENT

The authors would like to thank the National Research Institute for Earth Science and Disaster Resilience (NIED), the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) and the Tokyo Electric Power Company, Inc. (TEPCO) for providing important strong motion data.

REFERENCES

Aki, K. 1967. Scaling law of seismic spectrum, *J. Geophys. Res*. 71: 1217–1231.

Boore, D.M. 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, *Bull. Seism. Soc. Am*. 73: 1865–1894.

Brune, J.N. 1970. Tectonic stress and the spectra of seismic shear waves from earthquake, *J. Geophys. Res*. 75: 4997–5009.

Brune, J.N. 1971. Correction, *J. Geophys. Res*. 76: 5002.

Evangelista, L., del Gaudio, S., Smerzini, C., Landolfi, L., d'Onofrio, A., Silvestri, F., Santo, A., Festa, G., Iervolino, I. & Paolucci, R. 2017. Physics-based seismic input for site response: a case study in the Aterno river valley, Central Italy, *Bulletin of Earthquake Engineering*. 15: 2645–2671.

Kamae, K. & Irikura, K. 1998. Source model of the 1995 Hyogo-ken Nanbu earthquake and simulation of near-source ground motion, *Bull. Seism. Soc. Am*. 88: 400–412.

Kowada, A., Tai, M., Iwasaki, Y. & Irikura, K. 1998. Evaluation of horizontal and vertical strong ground motions using empirical site-specific amplification and phase characteristics. *J. Struct. Constr. Eng., AIJ*, No.514: 97–104 (in Japanese with English abstract).

Miyake, H., Iwata, T. & Irikura, K. 2003. Source characterization for broadband ground-motion simulation: kinematic heterogeneous source model and strong motion generation area, *Bull. Seism. Soc. Am*. 93: 2531–2545.

Nozu, A. 2012. A simplified source model to explain strong ground motions from a huge subduction earthquake – simulation of strong ground motions for the 2011 off the Pacific coast of Tohoku earthquake with a pseudo point-source model –, *Zisin*, *Journal of the Seismological Society of Japan* 65: 45–67 (in Japanese with English abstract).

Nozu, A. & Nagao, T. 2005. Site amplification factors for strong-motion sites in Japan based on spectral inversion technique, *Technical Note of the Port and Airport Research Institute* No.1102 (in Japanese with English abstract).

Nozu, A., Nagao, T. & Yamada, M. 2006. Simulation of strong ground motions based on site-specific amplification and phase characteristics, *Third International Symposium on the Effects of Surface Geology on Seismic Motion*, Grenoble, France.

Nozu, A., Nagao, T. & Yamada, M. 2008. A strong motion simulation method suitable for areas with less information on subsurface structure – Kowada's method and its application to shallow crustal earthquakes in Japan – *The 14th World Conference on Earthquake Engineering*, Beijing, China.

Nozu, A., Nagao, T. & Yamada, M. 2009. Simulation of strong ground motions using empirical site amplification and phase characteristics – modification to incorporate causality –, *Journal of JSCE, Ser. A*, 65: 808–813 (in Japanese with English abstract).

Petukhin, A., Irikura, K., Ohmi, S. & Kagawa, T. 2003. Estimation of Q-values in the seismogenic and aseismic layers in the Kinki Region, Japan, by elimination of the geometrical spreading effect using ray approximation. *Bull. Seism. Soc. Am*. 93: 1498–1515.

Satoh, T. & Tatsumi, Y. 2002. Source, path and site effects for crustal and subduction earthquakes inferred from strong motions records in Japan, *J. Struct. Constr. Eng., AIJ*, No.556: 15–24 (in Japanese with English abstract).

Wakai, A., Nagasaka, Y. & Nozu, A. 2014. A pseudo point-source model for off Miyagi intraslab earthquake on May 26, 2003, *Journal of JSCE* A1 70: I_818-I_829 (in Japanese with English abstract).

Yamada, M., Hirai, T., Iwashita, T., Kamae, K. & Irikura, K. 1999. Simulation of ground motion by the modified fault model of the Hyogo-ken Nanbu earthquake, *Program and Abstracts, The Seismological Society of Japan 1999 Fall Meeting*, A14 (in Japanese).