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Simulation of Strong Ground Motions for a Shallow Crustal Earthquake in Japan Based on the Pseudo Point-Source Model

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ABSTRACT

The pseudo point-source model is a new source model which is simpler, and involves less model parameters, than the conventional characterized source model. So far, its applicability has been studied for subduction earthquakes and intraslab earthquakes. However, its applicability to shallow crustal earthquakes has not been studied yet. In this study, we investigate the applicability of the pseudo point-source model to a damaging shallow crustal earthquake in Japan, namely, the 2005 West Off Fukuoka Prefecture Earthquake (M_J7.0). We calculated the velocity waveforms and the Fourier spectra at strong motion observation stations and compared with the observed ones. In addition, the errors involved in the simulation were quantitatively evaluated and compared with those based on a characterized source model.

Introduction

In recent years, to evaluate and predict strong ground motions in seismic design and practice, the characterized source model, which consists of several rectangular subevents, is often used in Japan. The applicability of the characterized source model to past large earthquakes has been studied by many researchers. On the other hand, in a recent study (Nozu, 2012), a more simplified source model called the "pseudo point-source model" was proposed. In the pseudo point-source model, the spaciotemporal distribution of slip within a subevent is not modelled. Instead, the source spectrum associated with the rupture of a subevent is modelled and it is assumed to follow the omega-square model. 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. Finite size of the subevent can be taken into account in the model, because the corner frequency of the subevents is included in the model, which is inversely proportional to the length of the subevent.

The pseudo point-source model was applied to the 2011 off the Pacific coast of Tohoku Earthquake (Nozu, 2012). According to the results, in spite of its simplicity, the pseudo point-source model can explain the observed velocity waveforms at least as well as the characterized source model. In addition, the pseudo point-source model can explain the observed Fourier spectra better than the characterized source model.

To utilize the pseudo point-source model for the evaluation and prediction of strong ground motions, it is important to study its applicability to various types of earthquakes. So far, its

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applicability has been studied for subduction earthquakes (Nozu, 2012) and intraslab earthquakes (Wakai et al., 2014). However, its applicability to shallow crustal earthquakes has not been fully investigated yet. In this study, we investigate the applicability of the pseudo point-source model to damaging shallow crustal earthquakes in Japan, in particular, to the 2005 West Off Fukuoka Prefecture Earthquake (2005/03/20; M_J7.0) (see Table 1, Figure 1 and Figure 2). Strong ground motions from this earthquake caused serious damage to infrastructures including a fishery port (e.g., Hata et al., 2012a). Thus, it is significantly important to develop a source model which can explain strong ground motions from this earthquake.

Review of the Characterized Source Model

We review a characterized source model (CS model) developed for the 2005 earthquake (Nozu, 2011). In the model, to calculate strong ground motions, Kowada's method (Kowada et al., 1998; Nozu et al., 2006; 2009) was used, which takes into account the effect of sediments on both the Fourier amplitude and Fourier phase of strong ground motions as follows. First of all, the ground motion for a small earthquake (Green's function) was evaluated. The Fourier amplitude of the Green's function was evaluated as a product of the source spectrum $|S(f)|$, the path effect $|P(f)|$ and the site amplification factor $|G(f)|$. The source spectrum was assumed to follow the ω^{-2} model (Aki, 1967). As for the path effect, geometrical spreading and nonelastic attenuation were considered (Boore, 1983). As for the site amplification factor, the empirical site amplification factor from the seismological bedrock to the ground surface (Nozu et al., 2007; Hata and Nozu, 2012) was used (see Figure 3). As for the Fourier phase of the Green's function, the Fourier phase of the April 10 aftershock (see Table 1 and Figure 1) was used. Thus, we can obtain a Green's function which incorporates the effects of sediments both on Fourier amplitude and Fourier phase. It can be written in the frequency domain as follows:

$$|S(f)|\,|P(f)|\,|G(f)|\,O_s(f)\,/\,|O_s(f)|_p, \qquad (1)$$

where $O_s(f)$ is the Fourier transform of the record at the site used for the evaluation of Fourier phase, and $|O_s(f)|_p$ is its Parzen-windowed amplitude (band width of 0.05 Hz) to incorporate causality (Nozu et al., 2009). Finally, the Green's function is used for superposition similar to the procedure in the empirical Green's function method (Miyake et al., 2003).

Table 1. Parameters of the main shock and the aftershocks used for the analysis

	Date	Time (hour:min.)	Latitude* (deg.)	Longitude* (deg.)	Depth* (km)	Mj*	M_0** (Nm)	(strike, dip, rake)** (deg.)
Main shock	2005/03/20	10:53	N 33.738	E 130.175	9	7.0	7.80E+18	(122, 87, −11)
Aftershock	2005/04/20	06:11	N 33.677	E 130.287	14	5.8	1.31E+17	(312, 90, 14)

* after JMA ** after F-net (www.fnet.bosai.go.jp)

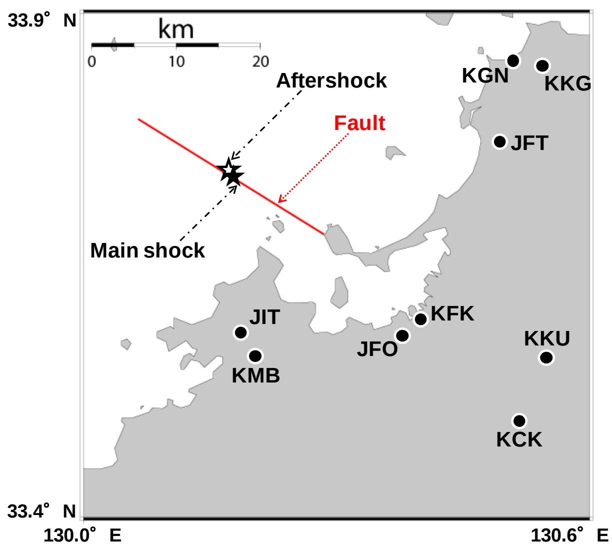

Figure 1. Location of the 2005 earthquake

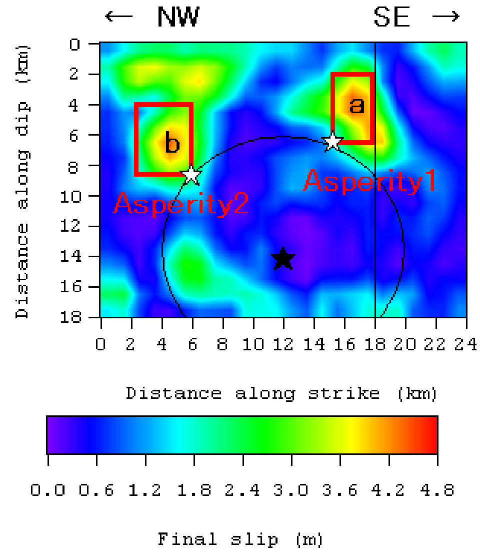

Figure 2. Asperities for the 2005 earthquake

Figure 2 shows the final slip distribution of the 2005 main shock estimated from a waveform inversion using empirical Green's functions (color contours in Figure 2; Nozu, 2007). Based on this slip distribution, a CS model was established for the event (red rectangles in Figure 2; Nozu, 2011). For the parameters of the source model, refer to Nozu, 2011. The construction of the CS model was focused on reproducing the observed velocity waveforms and the Fourier spectra. Strong ground motions were calculated based on this source model with Kowada's method and compared with the results of the pseudo point-source model.

Construction of the Pseudo Point-Source Model

In the pseudo point-source model (PPS model), the source spectrum associated with the rupture of a subevent is assumed to follow the omega-square model. 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. In the inverse Fourier transform, a causal time history is generated by using a smoothing technique (Nozu et al., 2009). Finally, by summing up contributions from the subevents, strong ground motions from the entire rupture can be obtained.

Table 2. List of parameters for the pseudo point-source model for the 2005 earthquake

	Location*** Latitude (deg.)	Location*** Longitude (deg.)	Location*** Depth (km)	Rupture Time (h:m:s)	Seismic Moment M_0 (Nm)	Corner Frequency (Hz)
Subevent_1	33.715	130.216	7.2	10:53:43.0	1.0E+18	0.66
Subevent_2	33.780	130.105	9.2	10:53:43.7	0.8E+18	0.48

*** Based on the characterized source model by Nozu (2011)

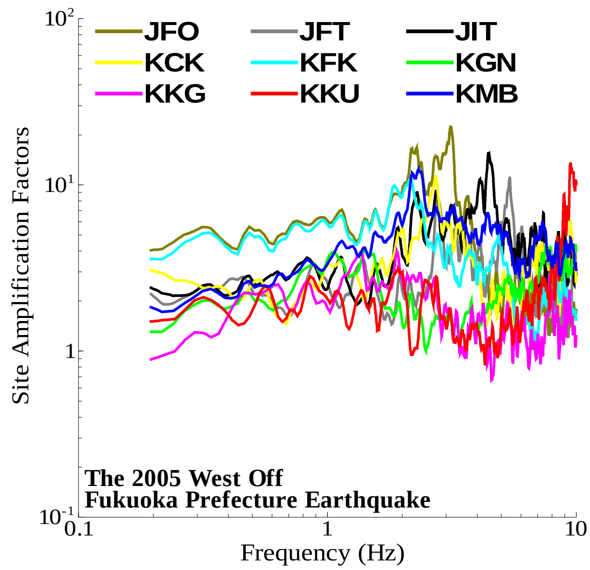

Figure 3. Empirical site amplification factors

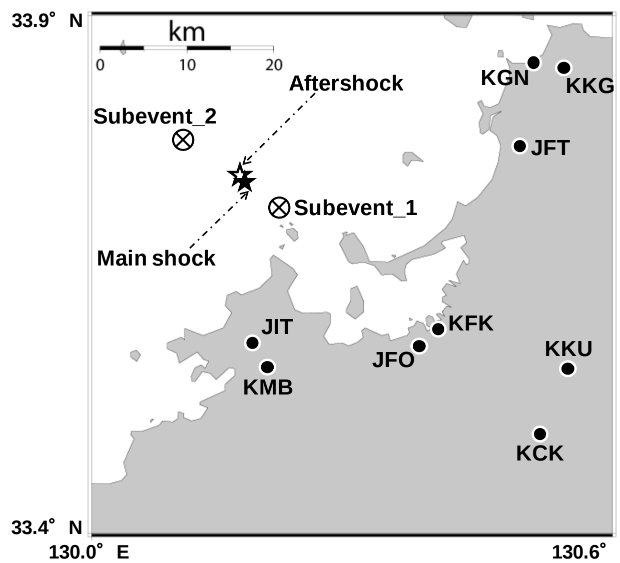

Figure 4. PPS model for the 2005 earthquake

Parameters of the PPS model were basically determined referring to the parameters of the CS model mentioned above. The location and rupture time of each subevent were determined referring to the location and rupture time of corresponding asperity. In terms of the rupture time, we performed minor adjustment to be consistent with the observed velocity waveforms. The seismic moment of each subevent was initially determined from the seismic moment of the corresponding asperity and it was adjusted to be consistent with the observed velocity waveforms. We calculated the corner frequency of each subevent by Brune's equation (Brune, 1970; 1971) from the area of the corresponding asperity, assuming a shear wave velocity of 3.5 km/s, which is a typical value for the source region of crustal earthquakes in Japan (e.g., Nozu, 2011). The locations and parameters of the pseudo point-source model which were identified by the above process are shown in Figure 4 and Table 2.

Based on the constructed pseudo point-source model, we calculated strong ground motions at strong motion observation stations. A medium density of 2.7×10^3 kg/m^3 and a shear wave velocity of 3.5 km/s were assumed, which are typical values for crustal earthquakes (e.g., Nozu, 2011). The mean value of 0.63 was used for the radiation coefficient. Another mean value of 0.71 was used for *PRTITN* (Boore, 1983), which is a coefficient indicating the partition of energy into two horizontal components. The Q value estimated in a past study (Kato, 2001) was used to represent the path effects. The strong motion stations (Aoi et al., 2004; Nishimae, 2004) were selected so that they include stations which were used for the construction of the characterized source model in the past study (Nozu, 2011).

We used the records of the aftershocks which occurred near the subevents to consider the path and site effects appropriately. In particular, we adopted the records of the April 20 Aftershock (see Figure 4 and Table 1).

Results of Strong Motion Simulation

Figure 5 shows the observed (black) and synthetic (red or green) Fourier amplitude spectra at strong motion stations for the 2005 main shock. The spectra were smoothed with a Parzen window with a band width of 0.05Hz. It should be noted that the spectra were corrected for the non-linear behaviour of shallow soil deposits from the engineering bedrock to the ground surface using the equivalent linear analysis (Yoshida et al., 2002) and the model for the shallow soil layers (Ooi and Fujiwara, 2013). In Figure 5, the agreement between the observed and synthetic Fourier spectra is quite satisfactory for the PPS model. In the case of the CS model, the synthetic Fourier spectra involve artificial peaks and troughs, which are not present in the observed Fourier spectra. Figure 6 and Figure 7 show the observed (black) and synthetic (red or green) velocity waveforms (0.2-2 Hz) at strong motion stations for the 2005 main shock. In Figures 6 and 7, again, the agreement between the observed and synthetic velocity waveforms is quite satisfactory for the PPS model. The CS model also explains the observed waveforms well, but it failed in explaining the later phases at some stations in this case.

In the following, the errors involved in the simulation based on the PPS model are quantitatively evaluated and compared with those based on the CS model. As an index of the errors involved in the Fourier amplitude spectra, the DFS (Difference of Fourier Spectrum) value is introduced, referring to the DGS value (Hata et al., 2012b; 2012c; 2014). The DFS value is defined as the integration of the log ratio of the synthetic spectra with respect to the observed spectra in the frequency range from 0.2Hz to 10Hz as shown in the following equation.

$$DFS = \sum \left| \log\left(\frac{FS_{Syn.}(f)}{FS_{Obs.}(f)} \right) \right| \cdot \Delta f$$

(2)

Here, $FS_{Obs.}(f)$ and $FS_{Syn.}(f)$ are the observed and synthetic Fourier spectra. On the other hand, following the author's previous study (Hata et al., 2013), we evaluated the errors involved in the velocity waveforms based on the DVW (Difference of velocity waveform) value in the following equation.

$$DVW = \sqrt{\frac{\int_{t_1}^{t_2} \left| VW_{Obs.}(t) - VW_{Syn.}(t) \right|^2 dt}{\int_{t_1}^{t_2} \left| VW_{Obs.}(t) \right|^2 dt}}$$

(3)

Here, $VW_{Obs.}(t)$ and $VW_{Syn.}(t)$ are the observed and synthetic velocity waveforms. The interval of integration is from t_1= 0.0 s to t_2= 50.0 s (see Figure 6 and Figure 7). The errors thus evaluated are compared in Figure 8. The errors involved in the results of the PPS model are smaller than those of the CS model especially for the Fourier spectra.

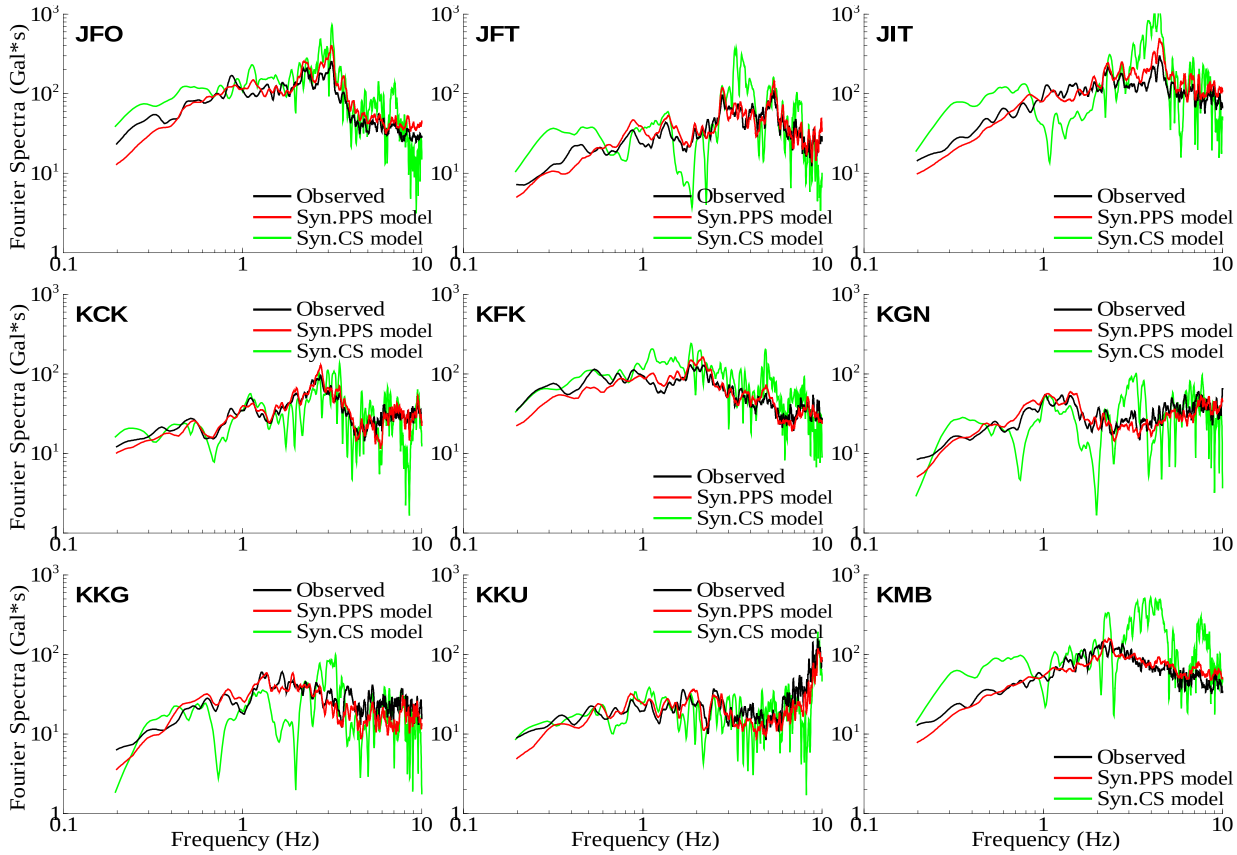

Figure 5. Observed and synthetic Fourier spectra

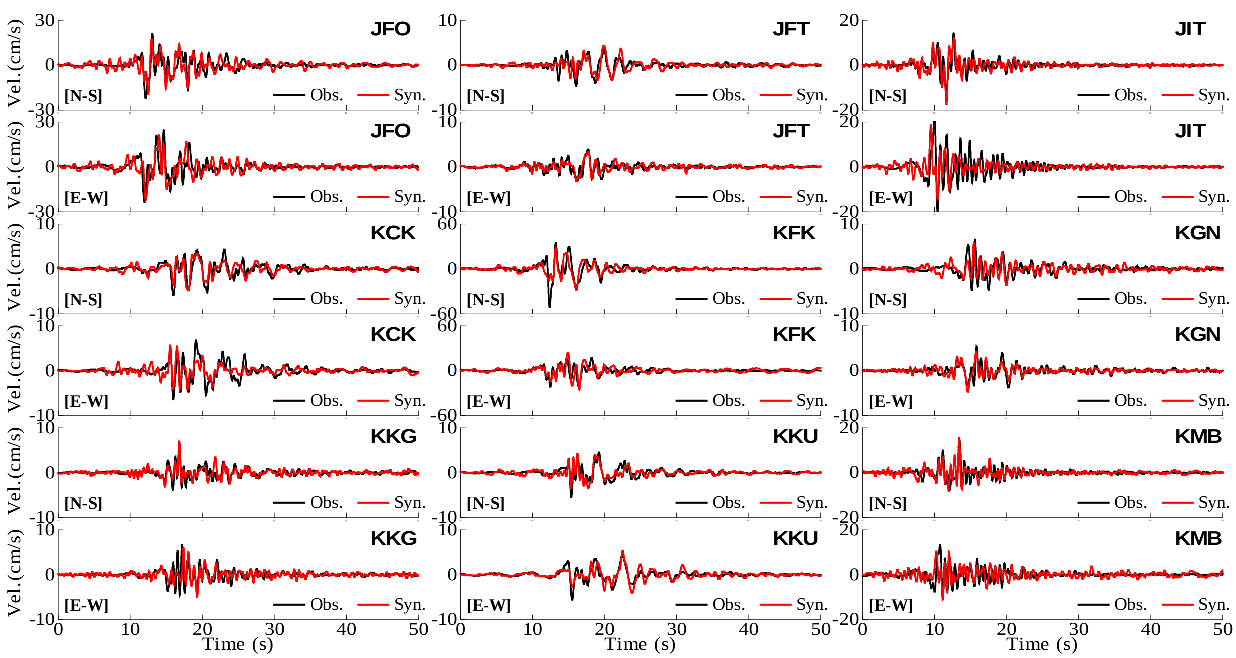

Figure 6. Observed and synthetic velocity waveforms (0.2-2 Hz) (PPS model)

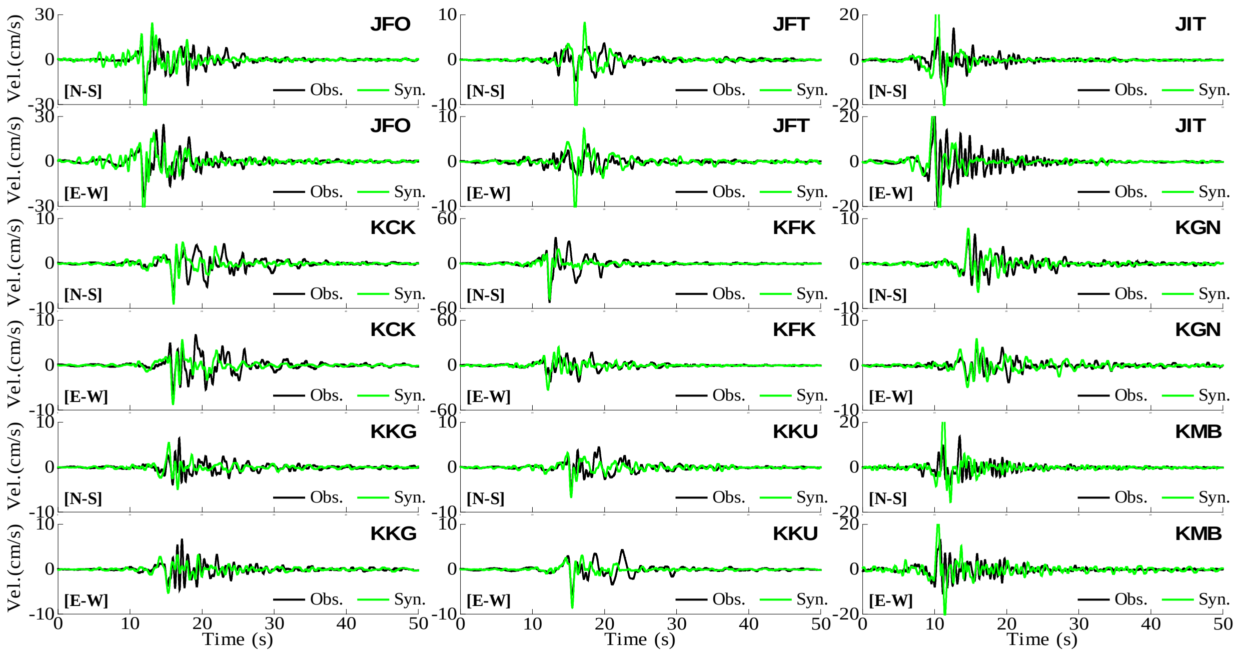

Figure 7. Observed and synthetic velocity waveforms (0.2-2 Hz) (CS model)

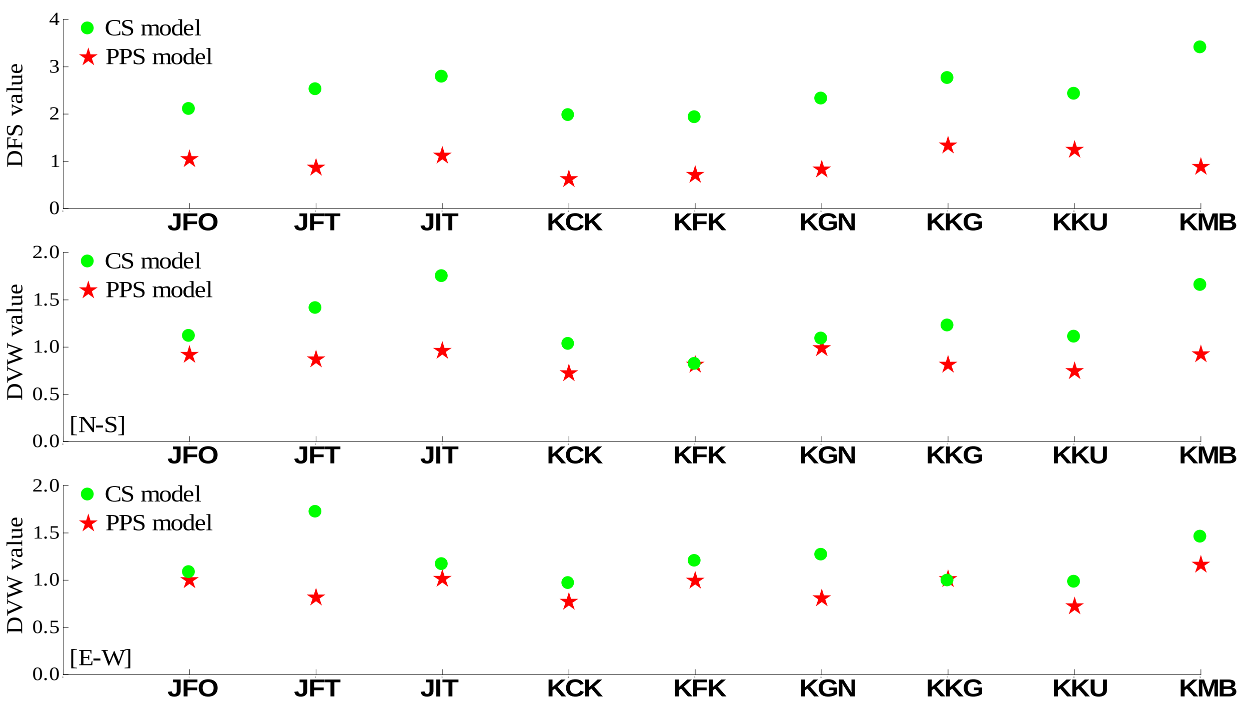

Figure 8. Errors involved in the simulation based on the PPS and CS models

Summary and Conclusions

The pseudo point-source model is a new source model which is simpler, and involves less model parameters, than the conventional characterized source model. So far, its applicability has been studied for subduction earthquakes and intraslab earthquakes. However, its applicability to shallow crustal earthquakes has not been studied yet. In this study, to examine the applicability of the model to a shallow crustal earthquake, a pseudo point-source model was developed for the 2005 West Off Fukuoka Prefecture Earthquake. The velocity waveforms (0.2-2Hz) and the Fourier spectra (0.2-10Hz) at strong motion stations calculated with the pseudo point-source model agree well with the observed ones, indicating the applicability of the pseudo point-source model to shallow crustal earthquakes. Moreover, the errors involved in the simulation based on the pseudo point-source model were quantitatively evaluated and compared with those based on the characterized source model. The errors involved in the results of the pseudo point-source model were smaller than those of the characterized source model especially for the Fourier spectra. It should be noted that an averaged radiation coefficient was assumed and the effect of rupture directivity was neglected in our study. The excellent results presented in this article may be suggesting that the roles played by these effects (the effects of radiation pattern and the influence of rupture directivity) were not significant at least for the 2005 earthquake. To further develop and test the methods, results of the pseudo point-source model and the characterized source model should be compared for different earthquakes that have been recorded in Japan and elsewhere.

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