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TESTING THREE-DIMENSIONAL BASIN STRUCTURE MODEL OF THE OSAKA BASIN, JAPAN, ESTIMATED BY WAVEFORM INVERSION

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ABSTRACT

Ground motions observed inside a sedimentary basin in the period range of ~2-20 sec, often referred to as long-period ground motions, are significantly influenced by the three-dimensional subsurface structure. We have proposed a waveform inversion method to estimate the three-dimensional topography of the sediment/bedrock boundary of a sedimentary basin. The main advantage of this method is that it can directly improve the model's ability to reproduce the ground motion waveforms in time domain, not only for the body-wave portion but also for the later phases, which have strong presence in long-period ground motions inside sedimentary basins. We applied the method to an existing three-dimensional Osaka basin structure model (initial model) using ground motion data from two regional M5 earthquakes and obtained an updated model. In this paper, we further investigate the appropriateness of the updated model for strong motion prediction purposes by carrying out ground motion simulations for other target earthquakes. The target earthquakes here are events occurred in the vicinity of the source regions of the anticipated megathrust earthquakes in Nankai trough, southwest Japan. We compare the ground motion simulation results with the observed ground motions, for both the initial and the updated model, in terms of aspects of velocity waveforms and velocity response spectra at strong motion stations densely distributed inside the basin.

INTRODUCTION

Constructing detailed 3-D underground velocity structure models is one of the most important requirements for strong motion prediction. In large-scale plains and sedimentary basins, long-period ground motions (period approximately 2s and longer) with large amplitudes and long duration are often observed during large earthquakes even though they are several hundreds of kilometers apart from the earthquake source region. For example, the 2011 Off the Pacific Coast of Tohoku earthquake (M9.0) brought, not to mention the devastating disaster to eastern Japan, long-period ground motion to the Osaka basin that is located in western Japan, approximately 600-800 km away from the source region. Long-period ground motions shook high-rise buildings for as long as ten minutes in the city of Osaka, causing emergency stops of elevators and partial damages to the interior of the buildings (e.g. Osaka Prefectural Government, 2011). Detailed knowledge of the basin structure is necessary to understand and predict long-period ground motion, as they are strongly amplified and change their aspects when propagating through sedimentary basins, reflecting the velocity structure of the basin. The boundary of the sediment and the seismic bedrock plays an especially important role when a sharp contrast in *S*-wave velocity exists.

Recently, we have presented a method to estimate the boundary shape (i.e. interface topography of sediment and seismic bedrock) of a three-dimensional (3D) basin velocity structure by waveform inversion, using real seismic data observed in the Osaka sedimentary basin (Iwaki and Iwata, 2011). The method is an extension of that proposed by Aoi (2002), in which the model parameters that defines the topography of the basin boundary are estimated by minimizing the L2-norm of the difference between the observed and synthetic waveforms. The main purpose of this method is to construct a 3D basin velocity structure model of the Osaka basin that can reproduce the complicated wave propagation within the basin. Waveform inversion analysis for estimation of the 3D basin boundary topography

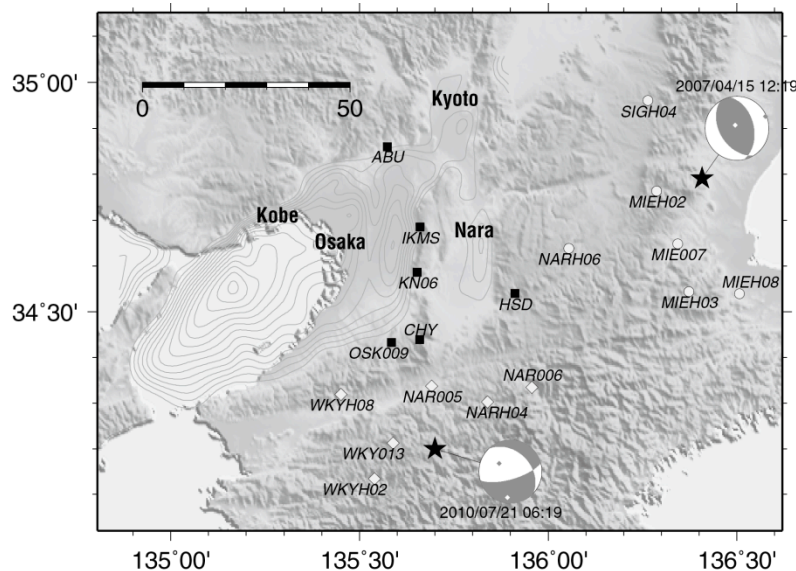
had not been applied to real field and real seismic record before.

Iwaki and Iwata [2011] proposed a new basin model estimated by waveform inversion using two regional M5 earthquakes. For the purpose of use in strong motion prediction, it is important to test if the estimated model is valid for simulating ground motion from other earthquakes. Today, as the long-term occurrence potentials of the anticipated mega-thrust earthquakes along Nankai trough (Nankai, Tonankai and Tokai earthquakes; Headquarters for Earthquake Research Promotion, 2011), prediction of long-period ground motion in sedimentary basins in western Japan has become a critically important issue. Therefore we are especially interested in ground motion simulation for earthquakes near the Nankai trough source region. In this paper, we first briefly introduce the waveform inversion method for estimation of the basin boundary shape. Then, we discuss the applicability of the estimated basin structure model by performing a ground motion simulation of a M6.5 earthquake that occurred near the Nankai trough.

WAVEFORM INVERSION FOR ESTIMATION OF BASIN BOUNDARY SHAPE

The Osaka sedimentary basin

Figure 1 shows the map of vicinity of the Osaka sedimentary basin, western Japan, the study area of this paper. The basin is approximately 80 km x 60 km in size, covering the most populated area in western Japan, including the cities of Osaka and Kobe. The velocity structure of the Osaka sedimentary basin has been investigated by numerous geophysical exploration surveys, such as gravity anomaly measurements, explosion refraction surveys and airgun reflection, since 1960s. After the 1995 Hyogoken-Nanbu (Kobe) earthquake, even more intensive investigations have been conducted (summarized by, e.g. Iwata *et al.*, 1998). Kagawa and his group have been constructing 3-D Osaka basin velocity structure models for long-period ground motion simulations, which have been continuously updated (e.g. Kagawa *et al.*, 1993; Miyakoshi *et al.*, 1997; Kagawa *et al.*, 2004a; Iwata *et al.*, 2008). They have incorporated the seismic-bedrock depth information obtained from various exploration results and interpolated them using a 2-D cubic B-spline function.



*Fig. 1. Map of the study area. Stars indicate the epicenters of target earthquakes by JMA. Rock-site stations outside the basin used to constrain the source parameters are shown on the map. The contour lines are the bedrock depth distribution of the model by Iwata *et al.* [2008], the initial model in this study.*

Target earthquakes and seismic stations

We chose two moderate-sized earthquakes (2007/4/15 12:19 and 2010/07/21 06:19 JST = UT + 9 hrs; M_w 5.0 for both) as the target earthquakes for the waveform inversion as shown in Figure 1. The source depth and the epicentral distance are approximately 10 km deep and 90 km to the east of the basin for the 2007-event, respectively, and 60 km deep and 60 km to the southeast for the 2010-event. For the FD simulations we assumed point sources using the epicenter provided by Japan Meteorological Agency (JMA). The mechanisms and depths are estimated by waveform fitting at the rock stations outside the basin (Figure 1).

In Figure 2, we show the basin stations used in the inversion scheme for each of the two target earthquakes. The strong motion stations

are maintained by the following networks and organizations: the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) (Kagawa *et al.*, 2004b), municipalities of Osaka prefecture, K-NET and KiK-net by the National Research Institute for Earth Science and Disaster Prevention (NIED) (Okada *et al.*, 2004), the strong motion network project of 10 electric power companies (Denkyo-net), Kansai Electric Power Co., Inc. (KEPCO), Kansai International Airport Co., Ltd (KIAC), and JMA.

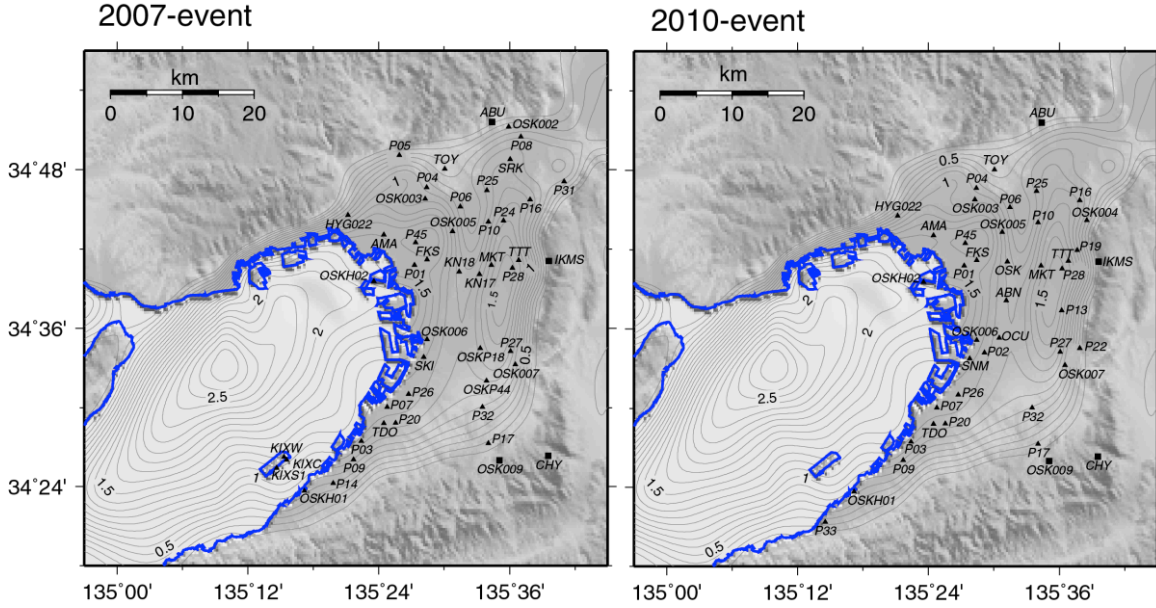


Fig.2. Sediment-site stations used for the waveform inversion for each of the two target earthquakes. The contour lines are the bedrock depth distribution of the basin model by Iwata *et al.* [2008].

Inversion procedure

The observation equation to be solved is $u(\mathbf{m}) \approx u^{\text{obs}}$ where \mathbf{m} is the model parameter vector that defines the boundary shape of the basin. \mathbf{u} and \mathbf{u}^{obs} are the synthetic and observed ground velocities, respectively, for three components for the two earthquakes. The observation equation is linearized and solved iteratively following the process of Aoi [2002]. In the l th iteration, the observation equation is linearized with regard to \mathbf{m}^l , the model parameter obtained in the $(l-1)$ th iteration, by taking Taylor series around \mathbf{m}^l up to the first order

$$u_i(\mathbf{m}^l) + \sum_{k=1}^K \frac{\partial u_i}{\partial m_k} \bigg|_{\mathbf{m}=\mathbf{m}^l} \delta m_k^l \approx u_i^{\text{obs}} \quad (i = 1, 2, \dots, N) \quad (1)$$

where K and N are the numbers of the model parameters and data (product of the numbers of time step, seismic stations, earthquakes, and components), respectively. Using finite-difference approximation to the partial derivatives, the Jacobian matrix can be numerically computed as

$$A_{ik} \equiv \frac{\partial u_i}{\partial m_k} = \left[u_i(\mathbf{m}^l + \Delta \mathbf{m}_k^l) - u_i(\mathbf{m}^l) \right] \Delta m_k \quad (2)$$

where $\mathbf{m} + \Delta \mathbf{m}_k = (m_1, m_2, \dots, m_k + \Delta m_k, \dots, m_K)^T$ with the model perturbation Δm set to 0.2, corresponding to ~ 100 m perturbation in bedrock depth. We solve the system for $\delta \mathbf{m}^l$ by the singular value decomposition method (Lawson and Hanson, 1974). The updated model for the next iteration is given by $\mathbf{m}^{l+1} = \mathbf{m}^l + \delta \mathbf{m}^l$. Iteration continues until the following residual converges.

$$\text{residual} = \frac{1}{N} \sum_{i=1}^N \left[u_i^{\text{obs}} - u_i(\mathbf{m}) \right] \quad (3)$$

We used the Osaka basin structure model by Iwata *et al.* [2008] as the initial model in our inversion analysis. As stated before, the bedrock topography of the model is described by a B-spline function, whose coefficients are defined at the nodes distributed every 4.5 or 9.0 km over the basin area. We treated the coefficients as the model parameters to be estimated by waveform inversion.

The basin velocity structure model is composed of three homogeneous sedimentary layers on the seismic bedrock (Table 1). The bedrock topography (i.e. the interface between the bottommost sediment and the bedrock) z is a function of position, and the depths of the top surfaces of sedimentary layers 2 and 3 are given by r_1z and r_2z , where r_1z and r_2z are proportionality constants. We chose the values of r_1 and r_2 to 0.12 and 0.41 (Iwaki and Iwata, 2011), which is slightly smaller than those given in Iwata *et al.* [2008].

The synthetic waveforms are computed by the 3D finite difference (FD) method of Pitarka [1999] using 3D velocity structure models in the period range of 3-10s with the minimum grid size of 125m and 62.5m in horizontal and vertical directions, respectively. The quality factor for the attenuation in the FD simulation follows the period dependence $Q(T)=Q_0T/T_0$ (Graves, 1996), where T is period (s), Q_0 is a reference Q -value given in Table 1 and the reference period $T_0 = 3.0$ s. For ground motion simulations, we combined a crustal velocity structure model of Iwata *et al.* [2008] with the basin models.

Table 1. Medium parameters and depth of the upper surface of each layer in the basin model used in this study. The depth of the seismic bedrock z is the unknown parameter, and $r_1=0.12$, $r_2=0.41$.

	V_p (km/s)	V_s (km/s)	ρ (kg/m ³)	Q_0	Depth (km)
Sedimentary Layer 1	1.60	0.35	1700	175	0.0
Sedimentary Layer 2	1.80	0.55	1800	275	r_1z
Sedimentary Layer 3	2.5	1.0	2100	500	r_2z
Seismic Bedrock	5.5	3.2	2700	500	z

Inversion Results

Figure 3 shows the comparison of the waveforms computed from the initial model and the updated model after eight iterations, together with the observed waveforms. The fitting of the synthetic and observed waveforms improved at most of the stations for both earthquakes. Figure 4 shows the comparison of bedrock depth distributions of the initial and the estimated model after eight iterations. The bedrock depth of the updated model is smaller than the initial model in the area near AMA and FKS by approximately 250m. Meanwhile, bedrock depth increased by 100-200 m in the northern area around SRK.

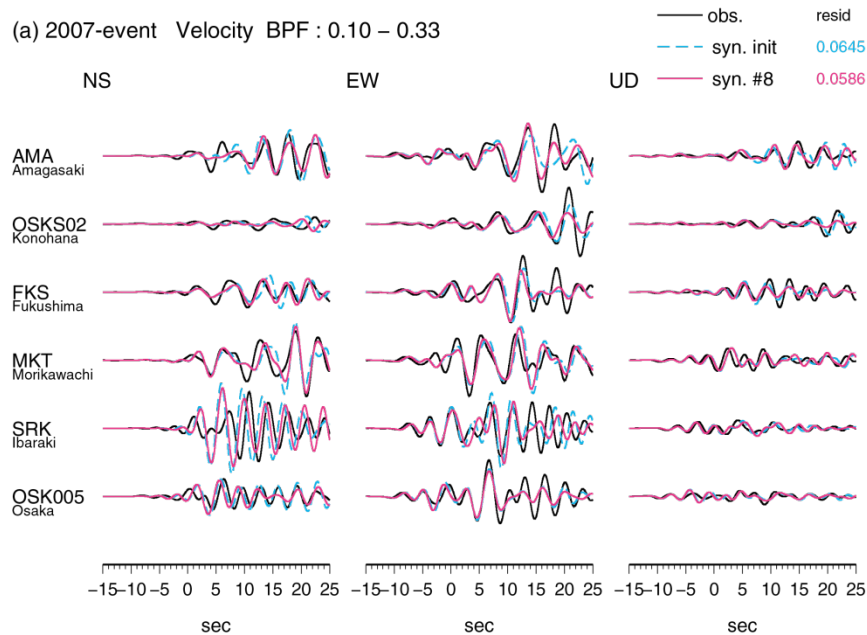


Fig. 3. Examples of comparisons between the observed waveforms (black), the synthetic waveforms computed from the initial model (blue), and those computed from the estimated model (pink) for (a) 2007-event and (b) 2010-event.

The waveforms are ground velocities bandpass filtered at 3-10s. The time axis indicates the lapse time from S-wave onset.

Nankai and Tonankai earthquakes (Figure 5). Although the epicenter is ~250 km apart from the basin, the earthquake produced long-period ground motion that lasted for several-minutes long with a sufficient signal-to-noise ratio. In Iwaki and Iwata [2010] we have performed a ground motion simulation of this earthquake using 3D velocity structure model by Iwata *et al.* [2008], which composes the 3D crustal structure model including the subducting Philippine Sea Plate and the basin structure model (initial model in this study), which will be referred to as Case-0 here after. In this section, we perform the same simulation but with the updated basin structure model, which will be referred to as Case-1.

The setting of the ground motion simulation follows that of Iwaki and Iwata [2010]. The model area size is 280 km (EW) by 250 km (NS) by 70 km (depth) with the Osaka basin in the northwest corner. The minimum grid spacing in the minimum trusted period of the computation is 125 m and 3s, respectively. The source is modeled as a point source with a bell-shaped source time function. Source parameters are estimated by fitting the waveforms at six K-NET stations along the southeast coast of the Kii peninsula (see Figure 5).

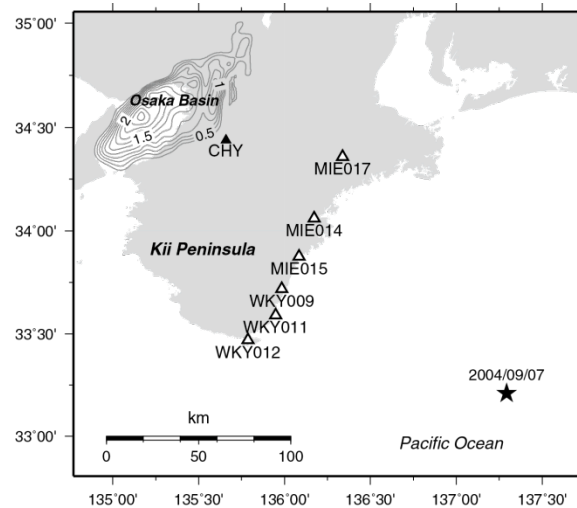


Fig. 5. Map of the study area. Star indicates the epicenter determined by JMA. The open triangles are the K-NET stations used to constrain the source parameters.

Simulation results

Figure 6 shows the comparisons of the observed waveforms and the synthetic waveforms with the different basin models: Case0 and Case1 (updated model in this study). The synthetic waveforms from the two cases are similar to each other as compared to the observed waveforms and it is rather difficult to point out the superiority of the updated model to the original model just by comparing the appearance of the waveforms.

Figure 7 shows the pseudo velocity response spectra (pSv) with 5% damping. Case1 explains the dominant period of pSv at stations AMA, OSKH02, FKS, and MKT, approximately 4 - 6s, better than Case0, which has dominant period at longer period compared to the observation. At SRK and OSK005, the discrepancies between the observation and simulation Case0 are relatively large compared to other stations, as pointed out by Iwaki and Iwata [2010]. Case1, although still insufficient, reproduces the amplitude level of the observed pSv better than Case0. Figure 8 shows the goodness-of-fit score of Iwaki and Iwata [2010] that evaluates the fit between the observed and synthetic horizontal pSv (geometric mean of the two horizontal components) in the period range of 3-14s. Improvement in the score can be seen in the northeast corner of the basin (near the station SRK) and in the center of the basin (near the station OSK005).

The updated model showed improvement in reproducing dominant periods of response spectra at the basin sites, which is an important aspect of long-period ground motion in a sedimentary basin. On the other hand, although the goodness-of-fit scores have improved for Case1 compared to Case0, the scores at many basin sites are still worse than those at rock sites outside the basin, such as CHY, near the southeast corner of the basin. For example, in the northeast area of the Osaka basin, where the scores are still relatively lower than other basin sites, velocity structure model needs more refinement. It is suggested that further investigation is required especially for more appropriate modeling inside the sediment, e.g. finer spatial parameterization. In addition, it is clear that all the factors from the source to the site should be properly evaluated in order to accomplish reliable long-period ground motion prediction for future mega-thrust earthquakes.

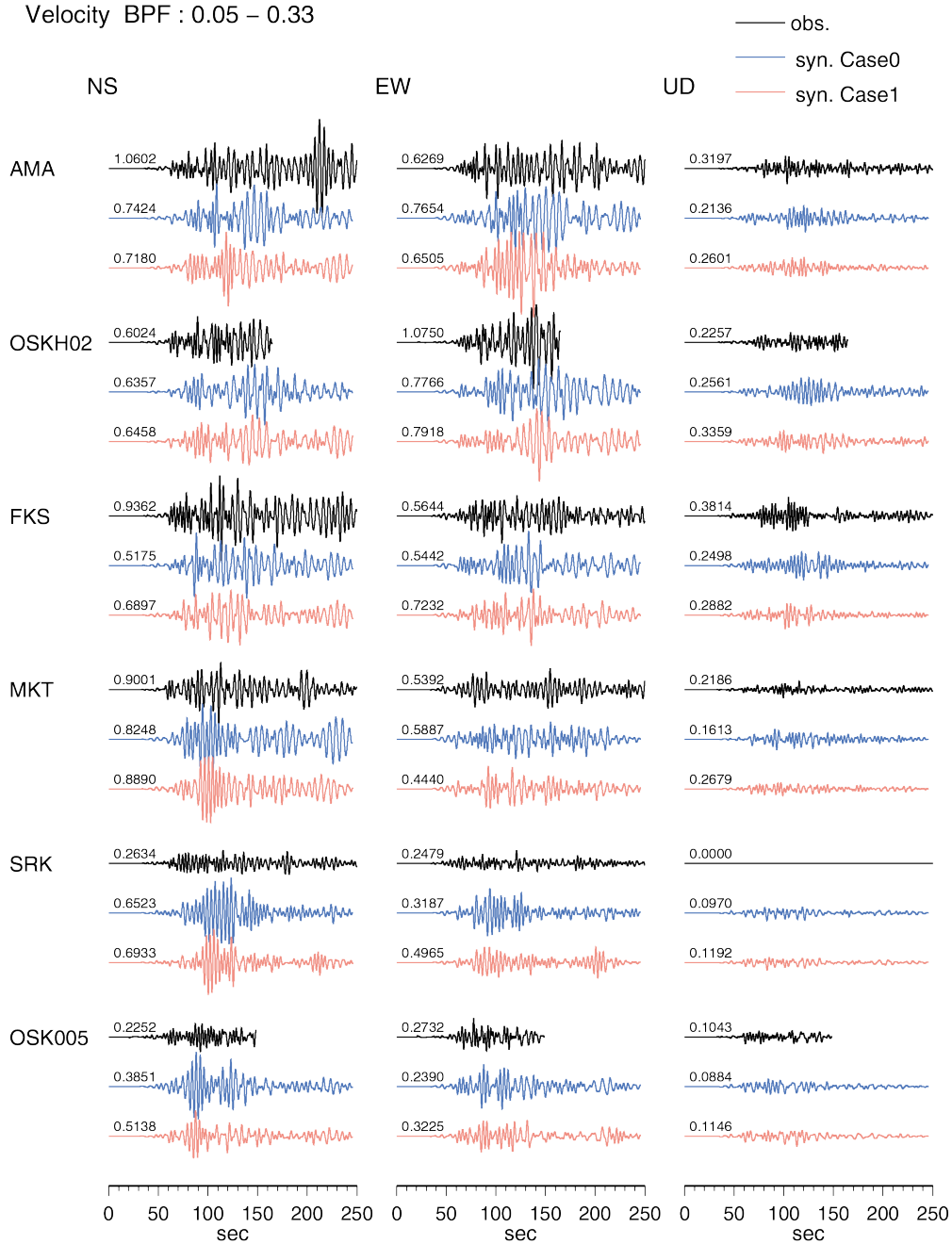


Fig. 6. Examples of comparisons between the observed waveforms (black), the synthetic waveforms of Case0 (blue; the original model) and Case1 (pink; the updated model) for the off Kii peninsula event.

Waveforms are bandpass filtered at 3-20s. The time axis indicates the time lapse from the earthquake origin. The number on the left of each trace is the maximum amplitude in cm/s. Vertical component data at SRK is not available.

pseudo vel. response ($h=0.05$)
2004/09/07/08:29

— obs.
— syn. Case0
— syn. Case1

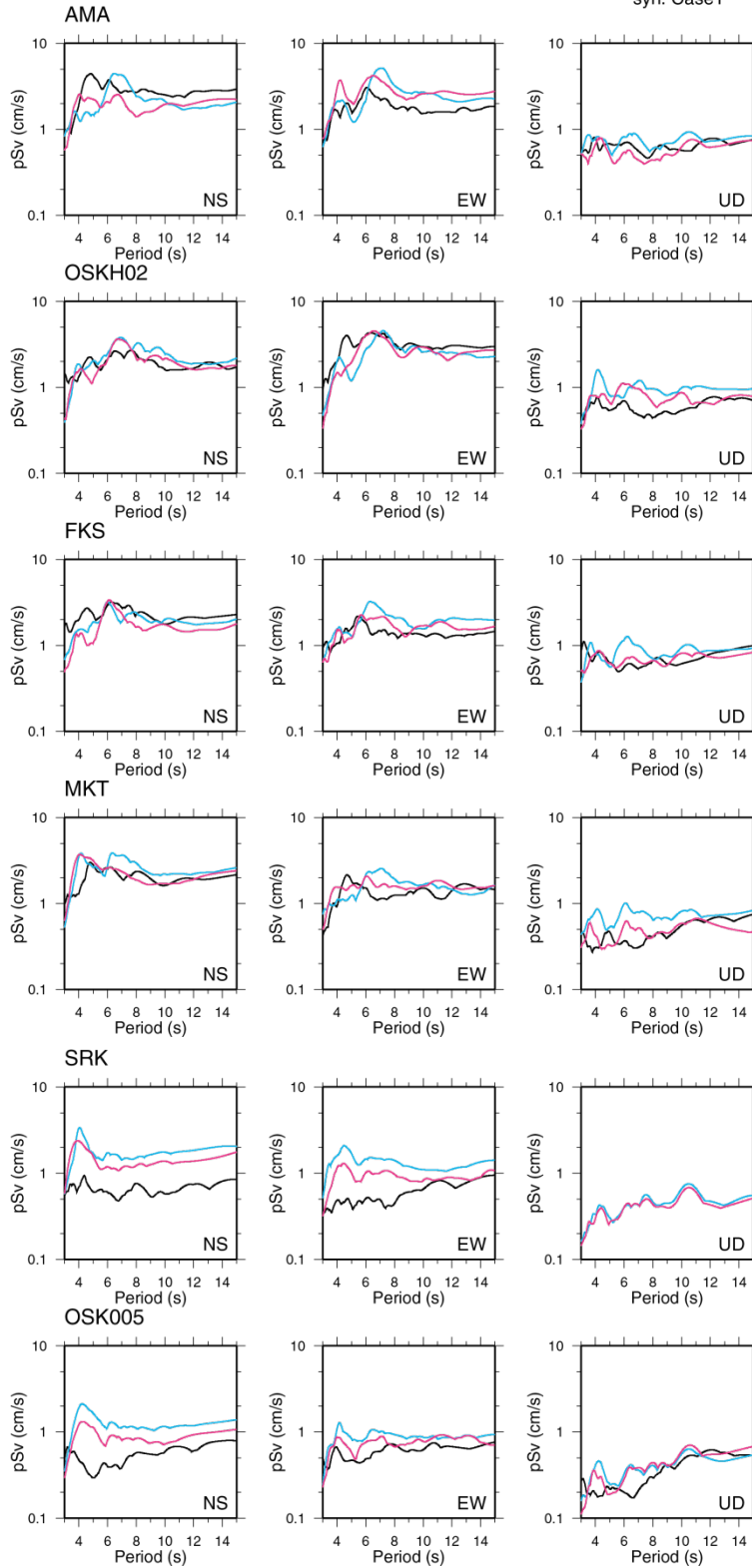


Fig. 7. Pseudo velocity response spectra (5% damping) obtained from the observed (black) and synthetic (blue for Case0, pink for Case1) waveforms. Vertical component data at SRK is not available.

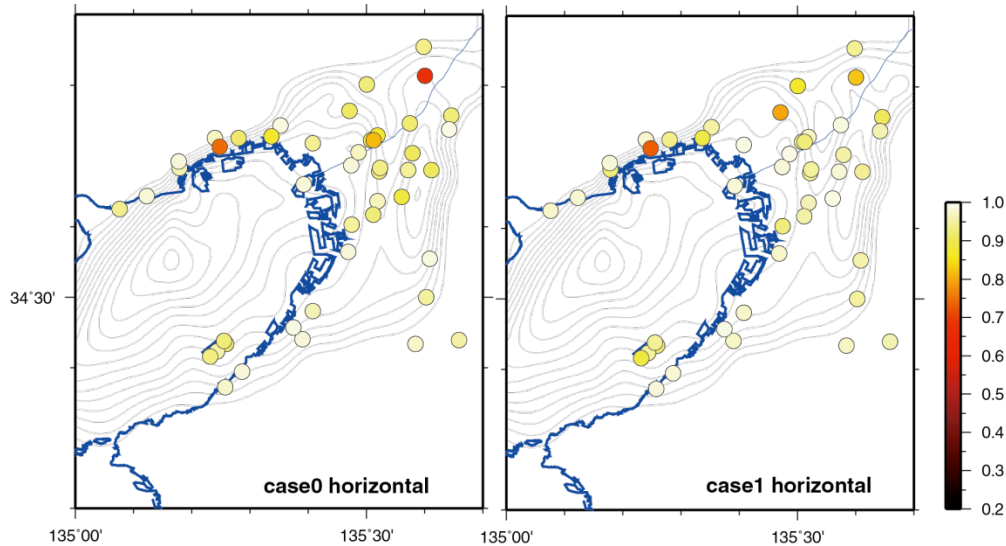


Fig. 8. Distribution of the goodness-of-fit factor of horizontal pSv for Case0 (left) and Case1 (right). Contour lines are the bedrock depth distributions of each model.

CONCLUSIONS

We investigated the applicability of the three-dimensional velocity structure model of the Osaka sedimentary basin, western Japan, obtained by waveform inversion analysis of Iwaki and Iwata [2011], for the purpose of use in long-period ground motion prediction. We performed long-period ground motion simulations under the same condition but with the different basin models: the original model by Iwata *et al.* [2008] and an updated model by Iwaki and Iwata [2011]. The target earthquake is a M6.5 earthquake that occurred off southeast Kii peninsula, approximately 250 km away from the Osaka basin, which is near the source regions of historical and hypothetical mega-thrust earthquakes along Nankai trough. The discrepancies in the dominant periods of pseudo velocity response spectra between the observation and the synthetics are smaller for the updated model compared to the original model. It was indicated that the updated model showed improvement in reproducing dominant period of response spectra, which is an important aspect of long-period ground motion in a sedimentary basin. We applied a goodness-of-fit score proposed by Iwaki and Iwata [2010] as an objective index to the horizontal component of pSv , and showed improvement of the updated model.

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