Long-period ground motion simulation in the Kinki area during the M_J 7.1 foreshock of the 2004 off the Kii peninsula earthquakes

Nobuyuki Yamada and Tomotaka Iwata

Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan

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Long-period (5–20 s) ground motion simulations in the Kinki area during the M_J 7.1 foreshock of the 2004 off the Kii peninsula earthquakes are performed. We construct a three-dimensional underground structure model that includes the source region and Osaka basin area to confirm propagation-path effects of crustal structure on long-period ground motions. Finite difference (FD) simulations by our three-dimensional underground structure model agree well with long-period observed ground motions at several rock sites in the Kinki area. We found that a sedimentary wedge structure along the Nankai trough amplifies and elongates long-period ground motions from this event. We also examine the effect of source depth for this event by comparing the observed with synthetic waveforms. These results suggest that precise modeling of the shallower parts of the underground structure, such as the sedimentary wedge, are quite important for long-period ground motion simulation of the hypothetical Nankai and Tonankai earthquakes.

Key words: Long-period ground motion simulation, foreshock of the 2004 off the Kii peninsula earthquakes, Kinki area, FDM, underground structure model.

1. Introduction

Two large earthquakes with M_J 7.1 and 7.4 rocked Honshu from Kanto to Kyushu on 5 September 2004 (Japan Meteorological Agency, 2004). These events occurred off the Kii Peninsula in the shallower part of the subducting Philippine Sea Plate. They are located as the source region of the expected Tonankai earthquakes. During those events, many strong ground-motion records were obtained by the nationwide networks K-NET and KiK-net of NIED (The National Research Institute for Earth Science and Disaster Prevention), and local networks such as CEORKA (The Committee of Earthquake Observation and Research in the Kansai Area). Well-developed, long-period ground motions were commonly observed at the stations in large sedimentary basins such as the Osaka basin and the Kanto basin (e.g., Iwata *et al*., 2004; Miyake and Koketsu, 2005).

The characteristics of long-period ground motion in sedimentary basins during a large earthquake are one of the most important issues for mitigating earthquake ground motion disaster. Recently, many oil tanks at Tomakomai, located in the Yufutsu sedimentary basin, were damaged by the long-period ground motions during the 2003 Tokachi-oki earthquake (Coffin and Hirata, 2003), although Tomakomai is about 200 km away from the source region. The amplification and elongation of long-period ground motions generated from this large event occurred because of propagation effects within the large sedimentary basin (e.g., Koketsu *et al*., 2005).

The Osaka sedimentary basin is located about 150 km away from the source regions of the hypothetical Tonankai and Nankai earthquakes. From now on, will just call these regions the 'source regions'. The headquarters for earthquake promotion reported that a long-term evaluation of occurrence potentials of the next Nankai and Tonankai earthquakes are 50 to 60 percent within 30 years from 2005. Modern mega-cities such as Osaka and Kobe in the Osaka sedimentary basin have never experienced long-period ground motions from an M8-class earthquake. Therefore, it is very important to predict long-period ground motions in this area during hypothetical large earthquakes along the Nankai trough. To accomplish quantitative long-period ground-motion simulations, we need to construct a three-dimensional underground structure model including the source regions and the Kinki area. The underground structure models in this area have been constructed by several researchers (e.g., Kagawa *et al*., 2002; Yamada and Iwata, 2004). However, it has been hard to validate them because of little ground-motion data from events in or near the source region, especially from the viewpoints of long-period ground motion (e.g., Yamada and Iwata, 2004; Hayakawa *et al*., 2005).

Sufficient-quality ground-motion data in the wide period range from the 2004 off the Kii peninsula earthquakes enable us to confirm the validity of the underground structure model. In this paper, we simulate the long-period ground motions in the Kinki area during the M_J 7.1 foreshock of a sequence of the 2004 off the Kii peninsula events. They will be used to predict long-period ground motions from the hypothetical Nankai and Tonankai earthquakes.

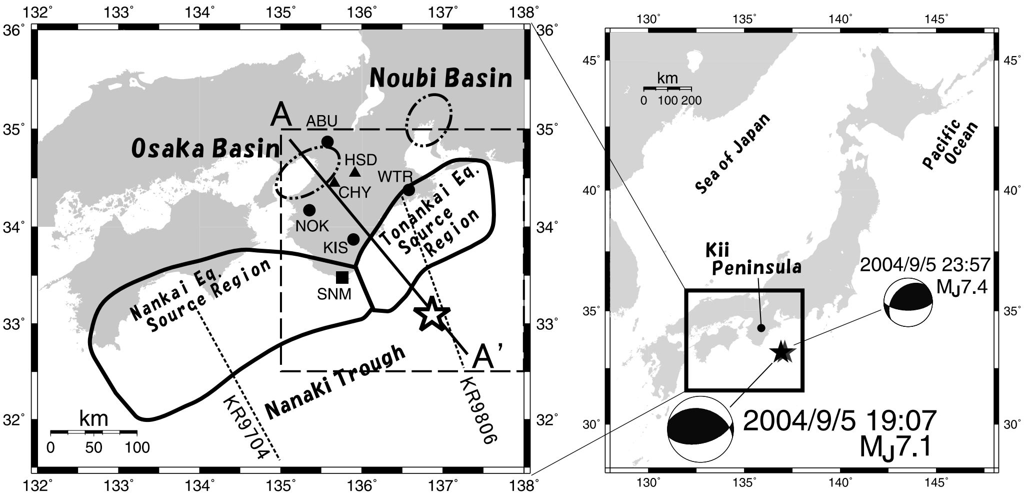

Fig. 1. Maps of the study area. (Right) Locations of the epicenters and mechanism solutions are shown. The target event is the foreshock of M_J 7.1. The main shock of M_J 7.4 earthquake occurred five hours after the foreshock (Japan Meteorological Agency, 2004). (Left) Detailed map of the rectangular area in the right figure. Station positions are indicated by the closed square (ERI), circles (NIED) and triangles (CEORKA), respectively. The star denotes the epicenter of the target event. The rectangular area with broken lines indicates an FD calculation area for long-period ground-motion simulation, and the area with bold curves indicate the source region of the hypothetical Nankai and Tonankai earthquakes. The A-A′ line shows the location of the profile in Fig. 2. KR9704 and KR9806 indicate the exploration survey lines by Nakanishi *et al.* (2002) and Obana *et al.* (2003).

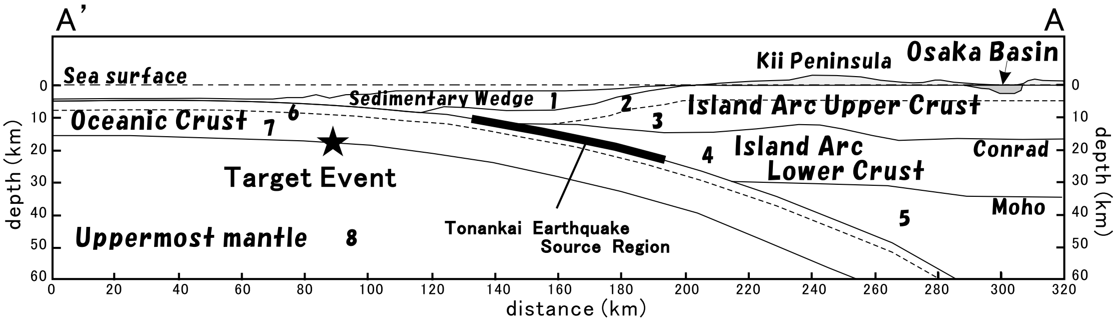

Fig. 2. Schematic cross-section of the underground structure along the A-A′ in Fig. 1. The star denotes the hypocenter of the M_J 7.1 event, and the thick line indicates the source region of the hypothetical Tonankai earthquake. The layer numbers correspond to those shown in Tables 1 and 4.

2. Construction of 3D Propagation-Path Model

Although the characteristics of long-period ground motion in a sedimentary basin such as the Osaka basin are controlled by not only the basin input motions but also the basin structure, we focus our attention on the former. The input motions are further controlled by the three-dimensional underground structure model between the source region and the Osaka basin, which we will call the ‘3D propagation-path model’. As shown in Fig. 1, we construct the 3D propagation-path model in the region enclosed within the broken square. We also show rock site stations in this figure.

For the 3D propagation-path model, we refer to several previous studies—the depth contour map of Philippine Sea plate provided by Nakamura *et al.* (1997), the depth of the Conrad and Moho discontinuities obtained by Zhao *et al.* (1994), and the results of seismic explorations along the lines KR9704 and KR9806 in Fig. 1 (Nakanishi *et al.*, 2002; Obana *et al.*, 2003). We also refer to the 3D underground structure models by Furumura *et al.* (2003) and Yamada and Iwata (2004). In our propagation-path model, we assumed eight homogeneous layers. Figure 2 shows a schematic cross-section of the propagation-path model along the A-A′ line in Fig. 1. The density, P-wave velocity (Vp) and S-wave velocity (Vs) of each layer are shown in Table 1. For Vp and density we follow the previous studies, and Vs is derived assuming $Vp/Vs = 1.7$.

We introduce the sedimentary wedge produced by the subduction of the Philippine Sea plate to the 3D propagation-path model, as shown by layer 1 in Fig. 2. It lies parallel to the Nankai trough and its maximum thickness of the wedge is about 7 km, as reported by Nakanishi *et al.* (2002). The distributions of several layer boundaries of the 3D propagation-path model are shown in Fig. 3. Figure 4 shows the north-south profile of this model by the discreted data with 1 km for FD calculation along the line through the hypocenter. We don’t consider seawater and surface topography in our model.

3. Ground Motion Simulation

The three-dimensional FD ground motion simulations, which are mainly based on Graves (1996), are carried out with same procedure described by Yamada and Yamanaka (2001). Some parameters of this FD calculation are listed in Table 2. The period range of the calculation is 5–20 s and the time duration of synthetic waveforms is set to be 240 s.

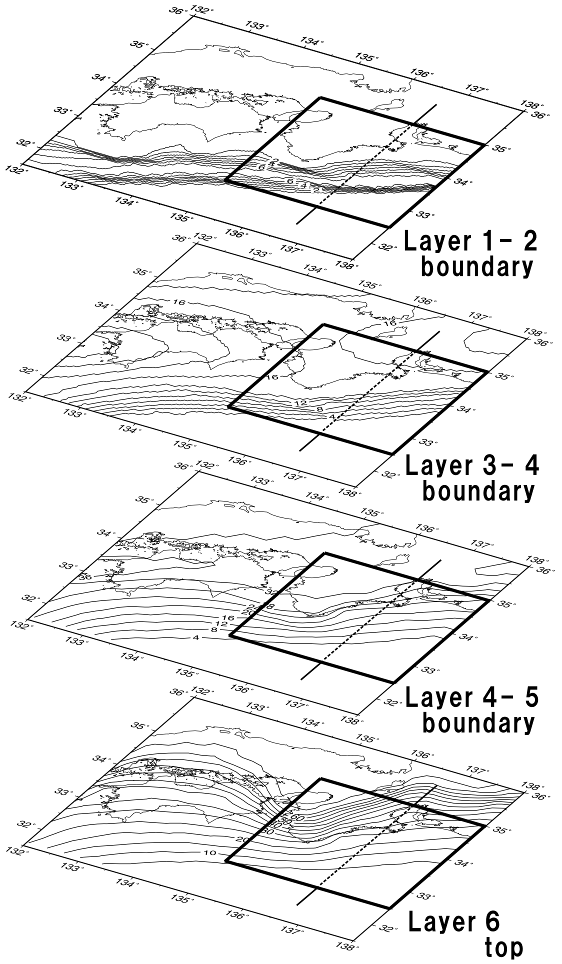

Fig. 3. Depth contour maps of layer boundary in the 3D propagation-path model. Each contour corresponds to the basement of the sedimentary wedge, Conrad discontinuity, Moho discontinuity, and the top of the Philippine Sea Plate, respectively. The ground motion simulation area is surrounded by a thick rectangle. The dotted line indicates the line of profile in Fig. 4. Numbers on contour lines show the depth in km.

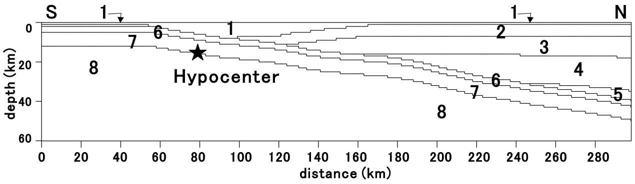

Fig. 4. Vertical cross-section of the 3D FD velocity model along the north-south profile crossed the hypocenter of the M_J 7.1 event. The numbers correspond to the layer numbers, as shown in Table 1.

Table 1. Media parameters of each layer of the underground structure model. Boundary shapes of this model are shown in Figs. 3 and 4.

Layer No.	ρ (g/cm^3)	Vp (km/s)	Vs (km/s)	Q
1	2.00	2.00	1.10	200
2	2.50	5.50	3.23	300
3	2.70	6.00	3.53	500
4	2.80	6.70	3.94	600
5	3.20	7.80	4.60	700
6	2.40	5.00	2.90	300
7	2.90	6.80	4.00	600
8	3.20	8.00	4.70	1000

Table 2. Model parameters for FD calculation.

Model dimensions	299×292×75
Grid spacing	1.0 km
Time step	0.061859 s
Total time step	3880 (240.0 s)

Table 3. Source parameters for the simulation.

latitude	33.09
logitude	136.63
depth	18 km
strike	N280°E
dip	42°
rake	105°
	point source
source duration	15.0 s (7.5 s×2)

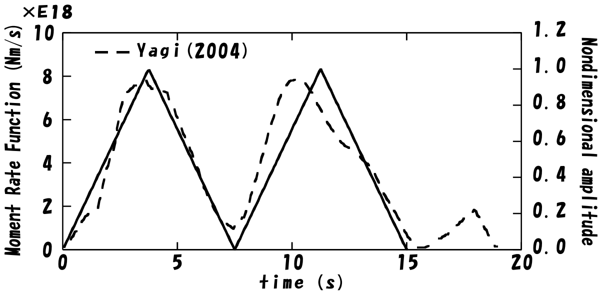

Fig. 5. The source time function obtained by Yagi (2004) is the broken line (hand-digitized), and the assumed simplified source time function that consists of two continuous isosceles triangles is the solid line in this ground motion simulation.

The target event is the M_J 7.1 foreshock of the 2004 off the Kii peninsula earthquake on 5 September at 19:07 (JST). The epicenter and source mechanism are shown in Fig. 1 and their parameters are listed in Table 3. Referring to the source-time function obtained by Yagi (2004), we assumed a point source with a simplified source-time function consisting of two continuous isosceles triangles, with a common base time length of 7.5 s. We compare the source time function of Yagi (2004) with that we assumed in Fig. 5. The M_0 is set to be 5.3×10^{19} Nm. We locate the source at a depth of 18 km, which corresponds to the hypocenter depth of Yagi (2004).

A comparison of the observed ground velocities with the synthetic velocities at the rock site stations are shown in Fig. 6. These observed waveforms are obtained by the broadband seismographs network (F-net) of NIED (ABU, KIS, NOK, and WTR), the strong motion seismographs network of CEORKA (CHY and HSD), and the Earthquake Research Institute, University of Tokyo (SNM). All the waveforms are band-pass filtered with a period range from 5 to 20 s. The synthetics reproduce the observations fairly well. Our 3D propagation-path model is so reasonable that

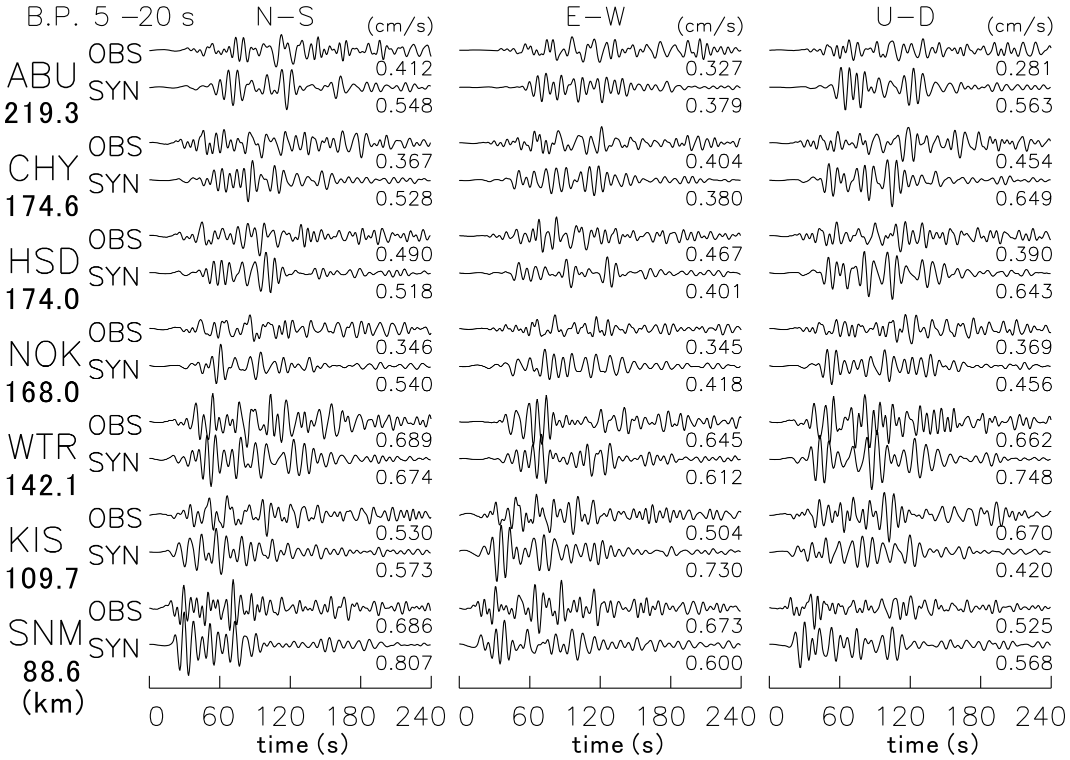

Fig. 6. Comparisons of observed ground-velocity records with simulated ones for the 3D propagation-path model. All traces are band-pass filtered from 5 to 20 s, with same amplitude scale. Top and bottom traces for each station show the observed motion and the synthetics, respectively. The peak velocity amplitude of each trace is shown at below each trace in cm/s. The epicentral distances in km are put below each station code. Station locations are indicated in Fig. 1.

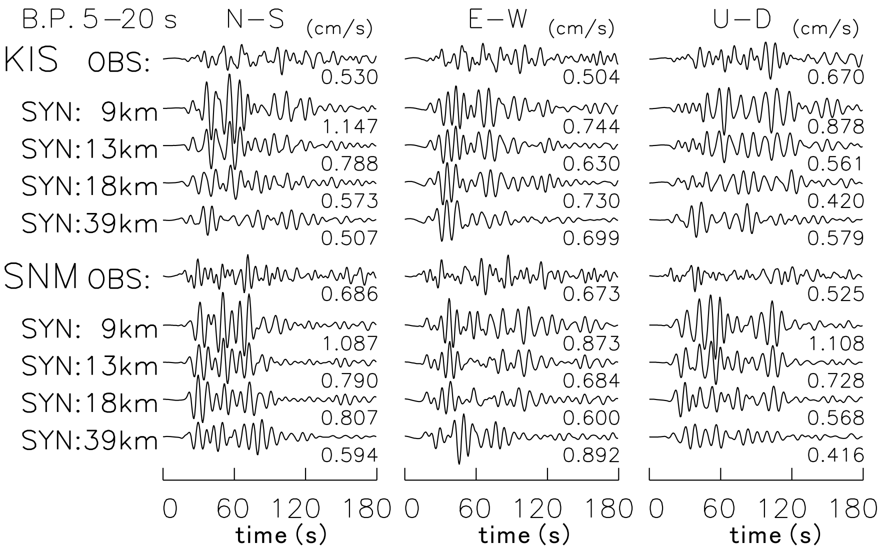

Fig. 7. Comparisons of observed ground velocities with synthetics at SNM and KIS for four different source depth cases. All traces are band-pass filtered from 5 to 20 s, and scaled to the same amplitude. From top to bottom, the observation and the synthetics of the four cases are shown.

the long-period feature of the observed ground motions at the rock sites is recovered well. It is noted that the observed record even at SNM, which the closest station to the epicenter, has duration as long as several minutes. As the source duration is 15 s (7.5 s × 2), this long duration may be caused by the very thick sedimentary wedge between the source and stations.

Here we show effects of the source depth and the velocity structure on the synthetics to confirm the validity of our model. First, the synthetic waveforms for various source depths are shown in Fig. 7. We consider four source depths of 39 km (JMA), 18 km (Yagi, 2004), 13 km (F-net), and 9 km (much shallower case). The other source parameters and the 3D propagation-path model are fixed to those in Tables 1 and 3. The comparison in Fig. 7 indicates that, in the case of the depth of 9 km, the synthetic ground velocities overestimate the observations, while the amplitude of the later phase after the *S*-wave arrival is too small in the

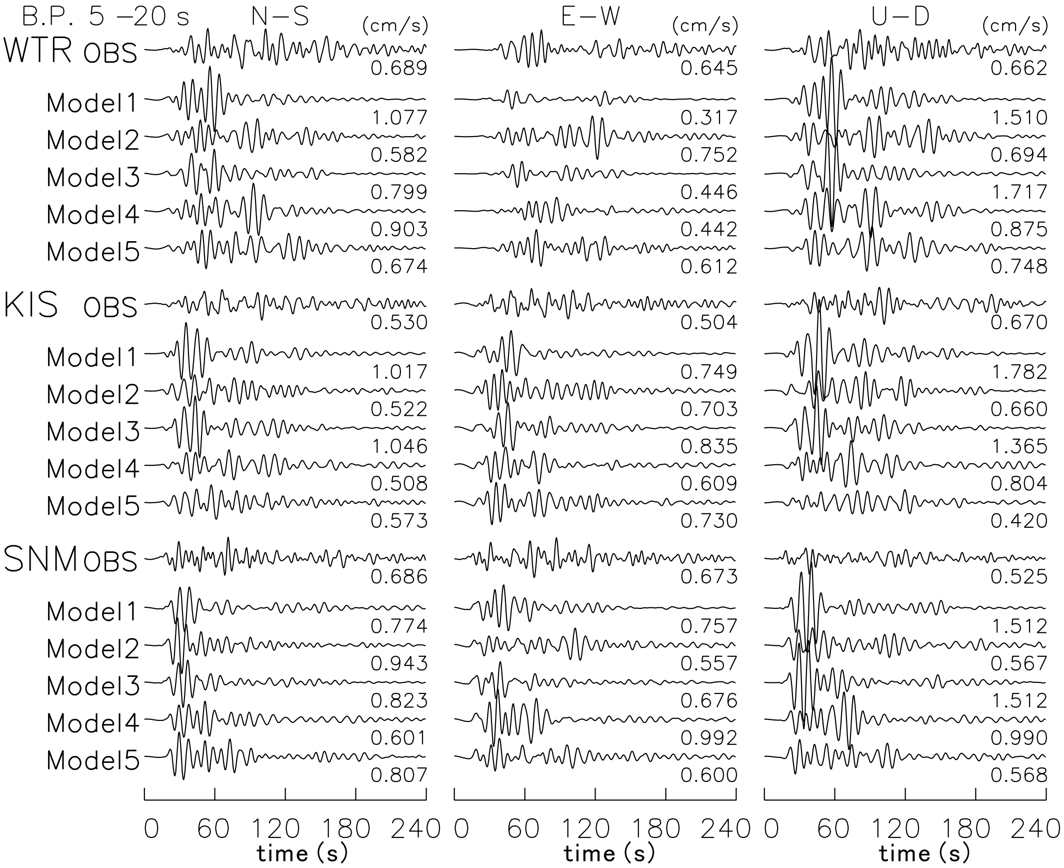

Fig. 8. Comparisons of observed ground velocities with synthetics at SNM, KIS, and WTR for five different velocity models as shown in Table 4. All traces are band-pass filtered from 5 to 20 s, and scaled to the same amplitude. From top to bottom, the observation and the synthetics of the five cases are shown.

Table 4. S-wave velocity in km/s of each layer for five different underground structure models.

Layer No.	Model 1	Model 2	Model 3	Model 4	Model 5 (reference model)
1	**3.23**	1.10	**3.23**	**1.65**	1.10
2	**3.23**	3.23	**3.23**	3.23	3.23
3	3.53	3.53	3.53	3.53	3.53
4	3.94	3.94	3.94	3.94	3.94
5	4.60	4.60	4.60	4.60	4.60
6	2.90	**4.70**	**4.70**	2.90	2.90
7	4.00	**4.70**	**4.70**	4.00	4.00
8	4.70	**4.70**	**4.70**	4.70	4.70

synthetics for the depth of 39 km. On the contrary, the synthetics for the depths of 13 and 18 km reproduce the observations well. Therefore, we adopted the source depth of 18 km for the simulations in Fig. 6.

Second, we test the effects of the medium velocities in the 3D propagation-path model on the synthetic waveforms. We introduce five different velocity models whose Vs are listed in Table 4. The ratio of Vp and Vs is kept at 1.7 in the whole model. We are mainly concerned with the effects of the sedimentary wedge and the oceanic crust, so that only the velocities at these parts are varied. 'Model 5' is a reference model, which was used for the simulation in Fig. 6. Model 1 does not include a sedimentary wedge, while Model 2 does not include the oceanic crust in the subducting slab. Model 3 is a combination of Models 1 and 2. Model 4 is almost the same as Model 5, but its sedimentary wedge has a higher velocity. Figure 8 shows the synthetic waveforms for these underground structure models and those observed at the KIS, SNM, and WTR stations. The synthetics for Model 1 have a shorter duration than that for the reference model (Model 5) and a larger amplitude of the direct S-wave part at these stations. In the comparison with the synthetics for Models 2 and 5 or those for Models 1 and 3, we confirmed that the removal of the oceanic crust from the subducting slab results in a distinct phase at about 100 s that does not appear in the observed waveforms. Models 4 and 5 have different Vs in the sedimentary wedge. The later-phase arrivals at about 60 to 80 s for the lower Vs model (Model 5) agree better with those of the observations.

4. Conclusion

We performed long-period (5–20 s) ground motion simulations during the M_J 7.1 foreshock of the 2004 off the Kii peninsula earthquake in the Kinki area. We constructed a 3D propagation-path model that included the source region and Osaka basin area. It consists of the subducting Philippine Sea slab, crust, and sedimentary wedge. Our 3D propagation-path model with an appropriate source model reproduces well the observed long-period ground motions at several rock sites in the Kinki area. We also found that the sedimentary wedge amplifies and extends the duration of long-period ground motions from this event. These results suggested that the precise modeling of the shallower part in the underground structure including the sedimentary wedge is quite important for long-period ground motion simulation of hypothetical Nankai and Tonankai earthquakes. On a basis of this simulation, we are now starting to simulate ground motions using the more appropriate 3D propagation-path model including Osaka basin in order to explain observed long-period ground motion in the Osaka basin.

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N. Yamada (e-mail: yamada@egmdpri01.dpri.kyoto-u.ac.jp) and T. Iwata