Damage prediction of long-period structures during subduction earthquakes - Part 1: Long-period ground motion prediction in the Osaka basin for future Nankai Earthquakes -

Hidenori KAWABE[1], Katsuhiro KAMAE[2] and Kojiro IRIKURA[3]

[1] *Assistant Professor, Research Reactor Institute, Kyoto University, Osaka, Japan*
[2] *Professor, Research Reactor Institute, Kyoto University, Osaka, Japan*
[3] *Professor, Disaster Prevention Research Center, Aichi Institute of Technology, Toyota, Japan*
Email: kawabe@rri.kyoto-u.ac.jp, kamae@rri.kyoto-u.ac.jp, irikura@geor.or.jp

ABSTRACT :

The Nankai Trough earthquakes which are subduction earthquakes with magnitude greater than 8 have occurred at intervals of 90 to 150 years. The probability of earthquake occurrence within 30-years from January 1, 2008 are estimated at 60 - 70% and 50 % for the next Tonankai and Nankai earthquakes, respectively, showing very high possibility of the earthquake occurrence. It is very important to predict the long-period ground motions from the next Nankai Trough earthquakes for mitigating their disastrous effects. In this study, we show results of the prediction of future Nankai earthquake in Part 1 and the damage prediction map of high-rise buildings in the Osaka basin in Part 2. This paper (Part 1) focuses on the prediction of the long-period (>2.5s) ground motions in the Osaka basin during future Nankai earthquake using the 3D finite difference method and an earthquake scenario proposed by the Headquarters for Earthquake Research Promotion in Japan. The characteristics of the predicted long-period ground motions for the hypothetical Nankai earthquake are related with the geometry between the source and observation points, and with the thicknesses of the sediments of the basin. The duration of the long-period ground motions in an area located in the central part of the Osaka city is more than 4 minutes, and the largest peak ground velocities (PGVs) exceed 80cm/s. The predominant period is around 6 second. These results indicate the possibility of earthquake damage due to future subduction earthquakes in large-scale constructions such as tall buildings and oil storage tanks in the Osaka area.

KEYWORDS: Long period ground motion, Subduction earthquake, Nankai Trough, Finite difference method

1. INTRODUCTION

Osaka, one of Japan's largest cities, has repeatedly suffered from disasters due to huge subduction earthquakes of magnitude greater than eight occurring along the Nankai Trough. The probability of earthquake reoccurrence within 30 years from January 1, 2008 is very high and estimated at 60–70% and 50% for the next Tonankai and Nankai earthquakes, respectively. Osaka is located inside a basin with thick sediments (about 1 to 3 km), in which long-period ground motions are strongly enhanced during these subduction earthquakes. The generation and growth of such long-period ground motions inside the Osaka basin have been examined by simulations of recordings during the Mj7.1 foreshock of the 2004 off-Kii peninsula earthquake (Yamada and Iwata, 2005). The authors indicated that long-period ground motions inside the basin are amplified and elongated not only by the three-dimensional (3D) underground structure in the basin but also by the sedimentary wedge structure along the Nankai Trough. Many long-period and low-damping structures such as tall buildings, long-span bridges, base-isolated buildings, and oil storage tanks exist inside the Osaka basin. Therefore, it is very important to predict the long-period strong ground motions from the next Tonankai and Nankai earthquakes with moment magnitudes of 8.1 and 8.4, respectively, for mitigating earthquake disasters. In this study, we present the predicted long-period ground motion characteristics inside the Osaka basin during the next Nankai earthquake occurring along the Nankai Trough, which may be of special interest to structural engineers. As a preliminary prediction for the scenario earthquakes, we used the source model from the Headquarters for Earthquake Research Promotion (hereafter, HERP) in Japan. 3D subsurface velocity structure models of the Osaka basin have already been proposed by Kagawa *et al*. (1993), Miyakoshi *et al*. (1999), and Horikawa *et al*.

(2003). These models have been constructed from geophysical and geological data such as from boreholes, seismic reflection surveys, microtremors, and gravity anomaly data. Here, we constructed a modified velocity structure model for the sedimentary basin consisting of three sedimentary layers referring to these existing models, and in 3D calculations, we considered the crustal structure outside the basin as well as the subducting oceanic plate. Finally, we pointed out the possibility of earthquake damage in large-scale constructions due to the predicted long-period ground motions.

2. NUMERICAL METHOD AND 3D VELOCITY STRUCTURE MODEL

In order to predict the long-period ground motions from the next Nankai earthquake, we used a 3D finite difference scheme, with second-order accuracy in time, fourth-order accuracy in space, and with a non-uniform spacing staggered-grid formulation (Pitarka, 1999). We set an absorbing region outside the finite computational region, and applied the non-reflecting boundary condition of Cerjan *et al*. (1985) and the A1 absorbing boundary condition of Clayton and Engquist (1977) to the corresponding region. The implementation of the attenuation into the finite difference method is based on the technique by Graves (1996), which considers Q to be identical and frequency-dependent for both P and S waves (Kawabe and Kamae, 2008). Our 3D velocity structure model consisted of a 3D crustal velocity structure model and a 3D velocity structure model of the Osaka sedimentary basin. The former was constructed based on the crustal velocity structure model (Nakanishi *et al*., 2002) and the Philippine Sea plate boundary model (Hori *et al*., 2004). The north–south cross-section of the crustal velocity structure model at longitude 136.375°E is shown in Fig. 1. The continental crust was divided into three layers: the upper crust, lower crust, and mantle wedge. The depths of the top of the lower crust and mantle wedge are 18km and 36km, respectively. The subducting oceanic plate was divided into two layers: an oceanic layer and Philippine slab with thicknesses of 2 and 5 km, respectively. The parameters of the model are summarized in Table 1. The latter model was constructed based on a couple of sedimentary basin models (Miyakoshi *et al*., 1999; Horikawa *et al*., 2003) constructed from geophysical and geological data such as boreholes, seismic reflection surveys, microtremors, and gravity anomaly data. Then, the sediment was approximately divided into three layers. The depths of each sedimentary layer and the bedrock surface are shown in Fig. 2. The parameters of the Osaka basin velocity structure model are summarized in Table 2.

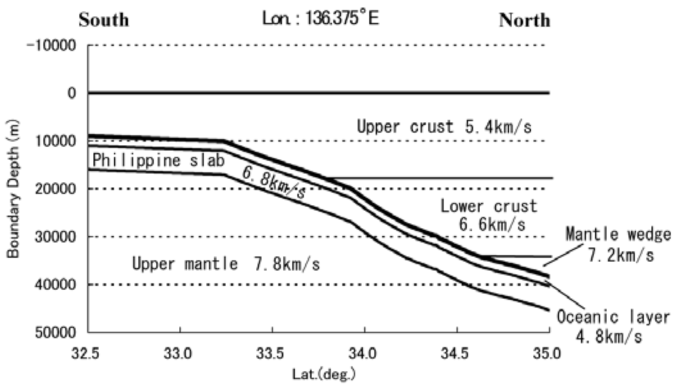
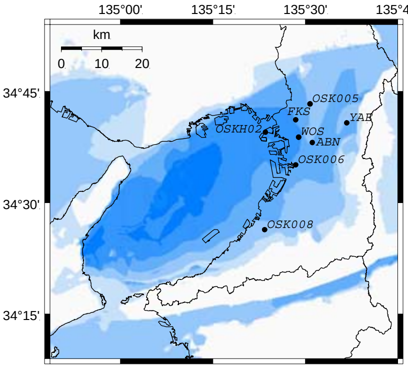


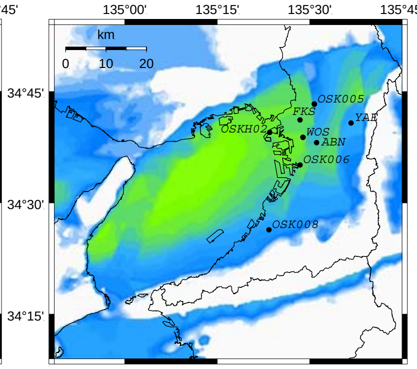
Figure 1 North–south cross-section of the crustal velocity structure model at longitude 136.375°E.

Table 1 parameters of the crustal velocity structure model.

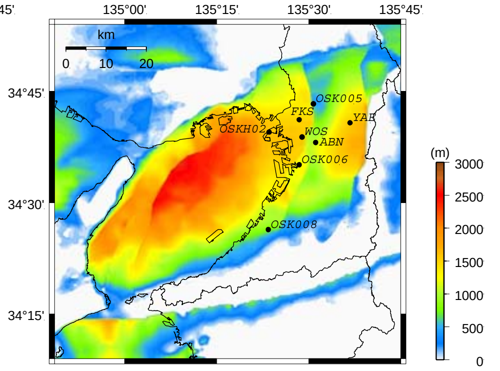
Layer	Vp (km/s)	Vs (km/s)	Density (g/cm^3)
Upper crust	5.4	3.2	2.7
Lower crust	6.6	3.9	2.8
Mantle wedge	7.2	4.3	3.0
Oceanic layer	4.8	2.5	2.6
Philippine slab	6.8	3.9	2.9
Upper mantle	7.8	4.5	3.1



(a) The depth of the boundary between the 1st and the 2nd sedimentary layer.



(b) The depth of the boundary between the 2nd and the 3rd sedimentary layer.



(c) The depth of the boundary between the 3rd sedimentary layer and the bedrock.

Figure 2 Topography of the bedrock surface and the boundaries between sedimentary layers of the Osaka sedimentary basin structure model.

Table 2 Parameters of the Osaka basin velocity structure model.

Layer	Vp (km/s)	Vs (km/s)	Density (g/cm^3)
Sedimentary Layer 1	1.6	0.4	1.7
Sedimentary Layer 2	1.8	0.55	1.8
Sedimentary Layer 3	2.5	1.0	2.1
Bedrock	5.4	3.2	2.7

3. PREDICTION OF LONG-PERIOD GROUND MOTIONS

Here, we attempted to predict long-period ground motions for the next Nankai earthquake using the 3D finite difference method. We used the characterized source models proposed by HERP as the scenarios for the next Nankai earthquake. This model was constructed based on the recipe for estimating strong ground motions from scenario earthquakes provided by Irikura *et al.* (2004). The recipe means the framework for prediction of strong ground motions including the procedures of source modeling, simulation of strong ground motions, and verification of the predicted strong ground motions. The source model is characterized by three kinds of parameters, which are called outer, inner, and extra fault parameters. The outer fault parameters are defined as entire rupture area and total seismic moment for possible earthquake. The inner fault parameters are defined as slip heterogeneity inside the fault area. The extra fault parameters are related to the propagation pattern of the rupture. The outer and inner fault parameters are basically estimated by the scaling relationships derived from statistical analysis of the source inversion results (Somerville *et al.*, 1999). We adopt the slip velocity time function proposed by Nakamura and Miyatake (2000). The location of the source and the region for the 3D finite difference computation are shown in Fig. 3. The locations of the asperities were determined from the backslip model of the Nankai Trough (Nishimura *et al.*, 2000; Zaho and Takemoto, 2000; etc.). Source parameters are summarized in Table 3. The parameters for the 3D simulation of the next Nankai earthquake are listed in Table 4. Fig. 4 illustrates the simulated peak ground velocity (PGV) distributions inside the Osaka basin for the next Nankai earthquake. This figure shows that the PGV distributions drastically change depending on the incident directions of the seismic waves in the basin with complicated underground structure. The PGVs are partially over 80 cm/s inside the Osaka basin. The areas with relative larger amplitude extend along the northern as well as southern basin edges during the next Nankai earthquake. Fig. 5 illustrates the synthesized velocity waveforms at eight stations inside the Osaka basin. The durations of the waveforms are longer than 4 min at almost all stations. Pulsive waveforms appearing at 50–70 s in time are generated by the forward rupture directivity effect due to constant rupture propagation on the asperity (Asp-3). Fig. 6 shows the distributions of pseudo velocity response spectral amplitudes of the expected ground motions in the Osaka basin for the next Nankai earthquake with a damping factor of 5%. This Fig. 9 shows that the predominant periods of the predicted long-period ground motions can be correlated with the thickness of the sedimentary layers shown in Fig. 1. Fig. 7 illustrates the pseudo velocity response spectra with a damping factor of 5%, together with the safety limit level specified on engineering bedrock, which has an S-wave velocity of about 400 m/s, as the building design regulation in Japan. The predominant periods at almost all stations located on the thicker sedimentary layer are 5–6 s. These predominant periods are supported by recordings during the 2004 off-Kii peninsula earthquake (Miyake and Koketsu, 2005). On the other hand, the predominant periods at stations located on the thinner sedimentary layer close to the basin edges (OSK005 and OSK008) are 3–4 s. These spectral levels exceed the safety limit level described above. Therefore, we can point out the possibility of earthquake damage in large-scale constructions due to the predicted long-period ground motions from the next Nankai earthquake.

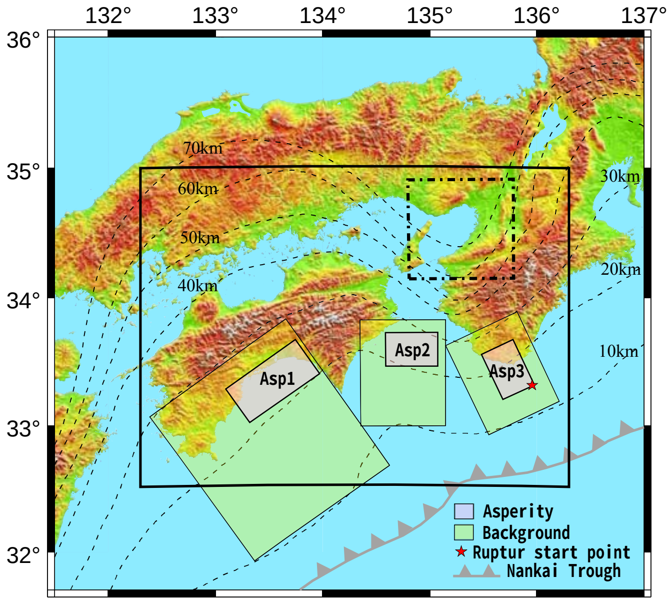


Figure 3 Maps showing the region of western Japan. The thick rectangular box depicts the region for the 3D finite difference simulation of the next Nankai earthquake. The dashed lines indicate the area of the velocity structure model of the Osaka basin. The contours show the isodepth lines of the Philippine Sea plate boundary.

Table 3 Source parameters of the next Nankai earthquake.

Area of source fault (km^2)	35800			
Average slip distribution (m)	5.70			
Seismic moment (Nm)	8.34×10^{21}			
Static stress drop (MPa)	3.0			
Rupture velocity (km/s)	3.1			
	1st Asperity (Asp1)	2nd Asperity (Asp2)	3rd Asperity (Asp3)	Background area
Area (km^2)	2672	1336	1336	30457
Slip distribution (m)	13.36	9.45	9.45	4.70
Seismic moment (Nm)	1.46×10^{21}	5.16×10^{20}	5.16×10^{20}	5.85×10^{21}
Effective stress drop (MPa)	20.1	20.1	20.1	2.7
Rise time (s)	8.34	5.90	5.90	14.52

Table 4 Model parameters for 3D simulation of the next Nankai earthquake.

Model size	271.8 km × 410.6 km × 84.0 km
Spatial discretization	0.2 km × 0.2 km × 0.1 km (Osaka basin structure model)
	0.6 km × 0.6 km × 0.6 km (Crustal structure model)
Temporal discretization	0.01s
Total time steps	25000

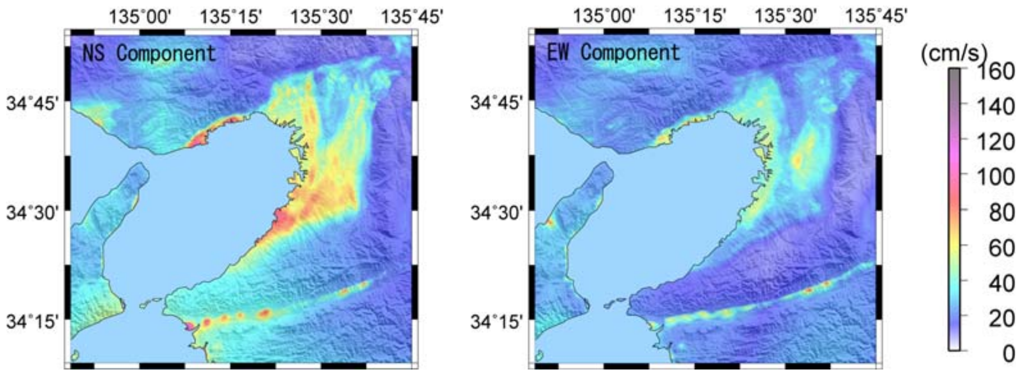


Figure 4 Simulated peak ground velocity distribution for the Nankai earthquake in the Osaka basin (0.05–0.4 Hz).

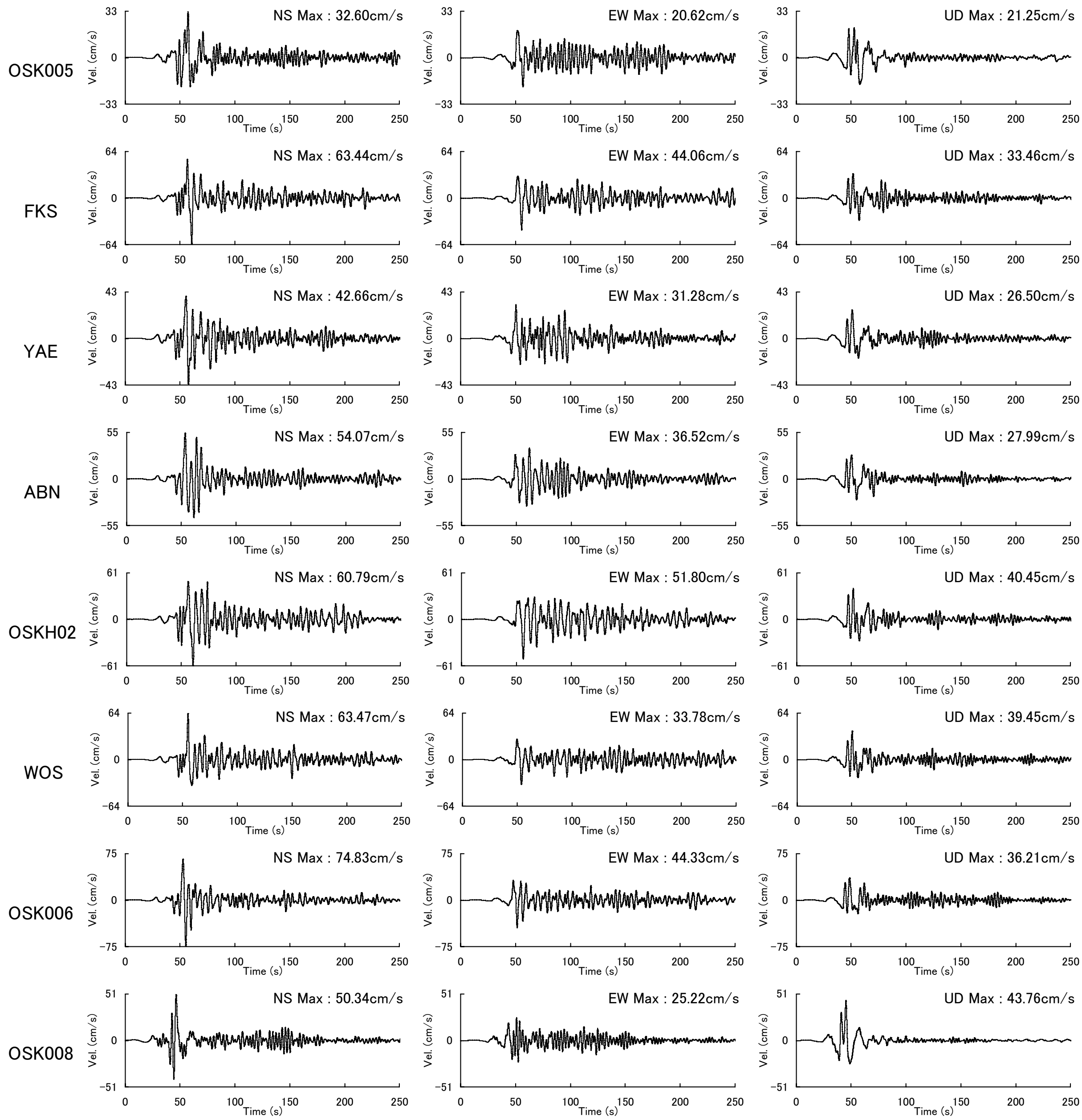
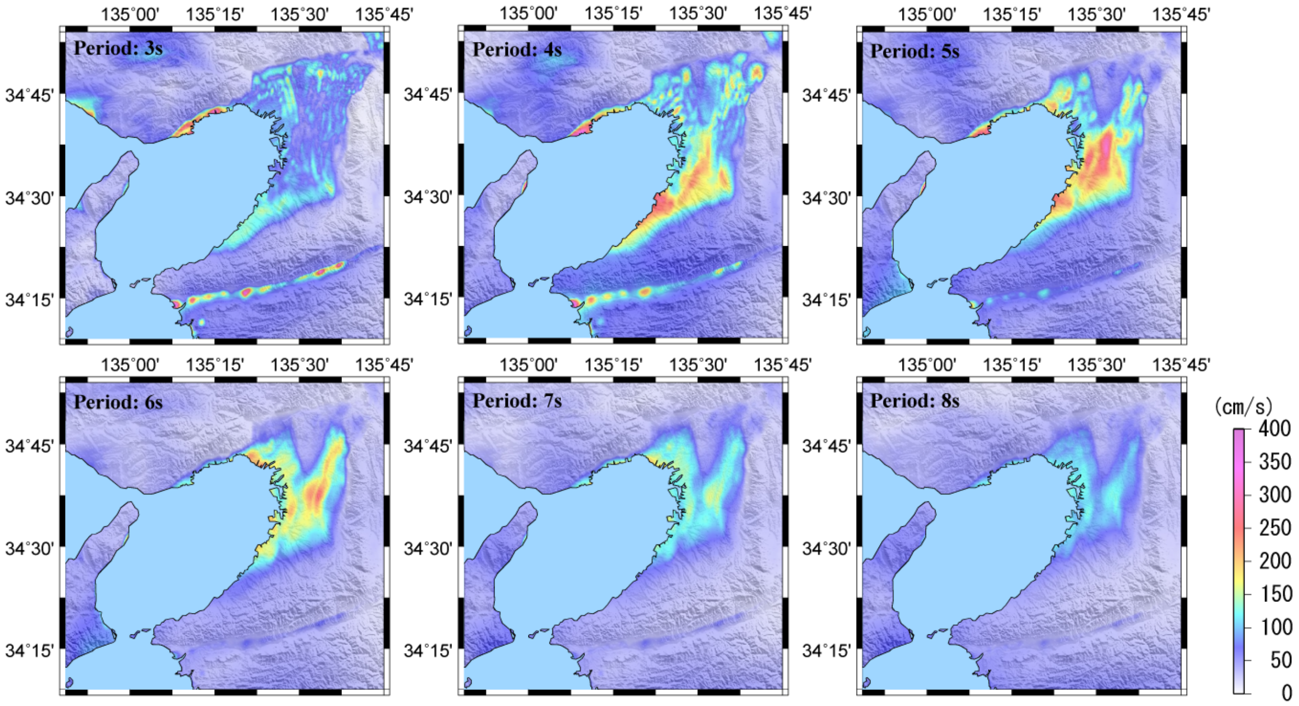
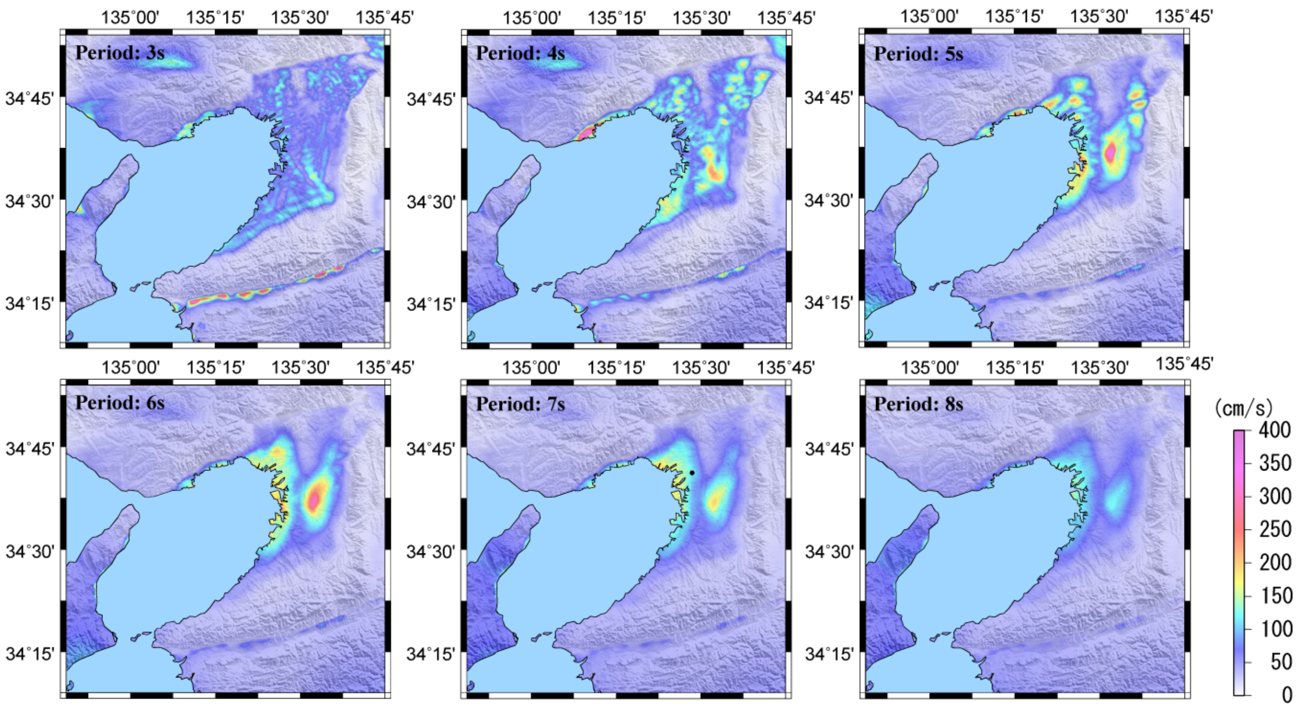


Figure 5 Synthesized velocity ground motion (0.05–0.4 Hz).



(a) NS component



(b) WE component

Figure 6 Distributions of pseudo velocity response spectral amplitudes of the predicted ground motions for the Nankai earthquake in the Osaka basin (damping factor: 5%).

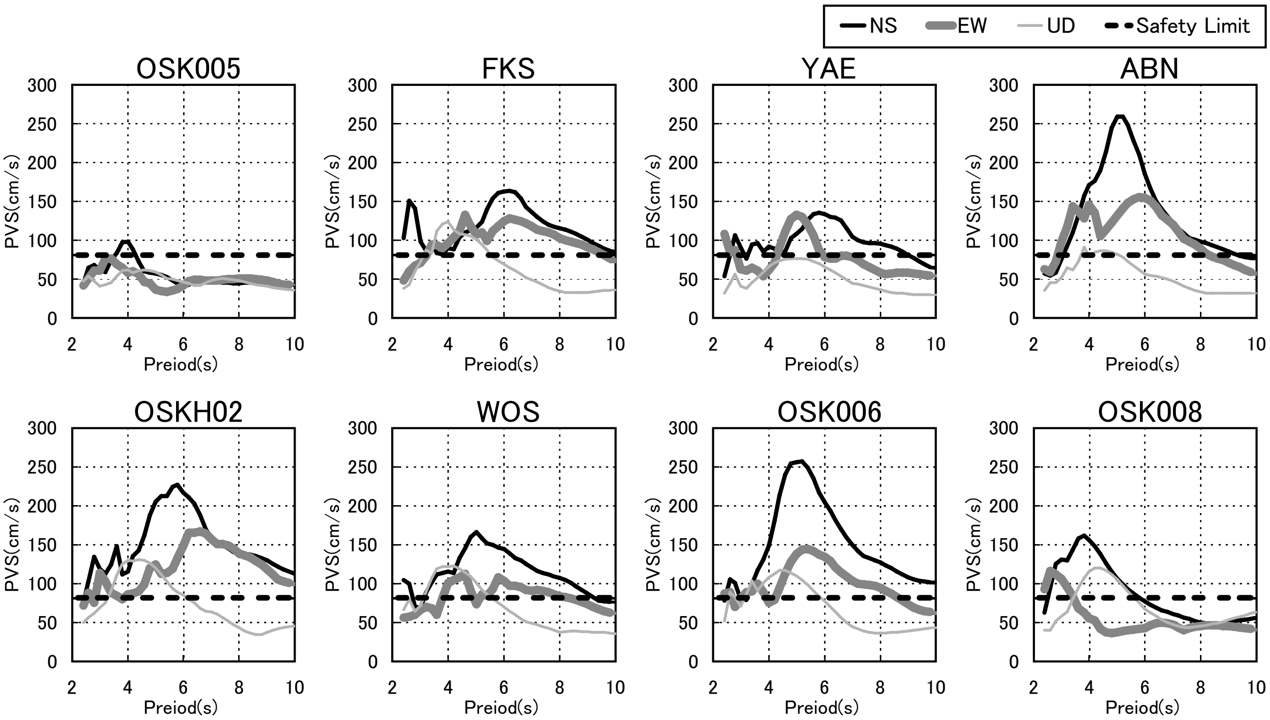


Figure 7 Pseudo velocity response spectra with 5% damping ratio and the safety limit level of the building design criterion in Japan. The safety limit level is defined for horizontal components at the engineering bedrock surface.

4. CONCLUSIONS

In this study, we predicted the long-period ground motions from the next Nankai earthquake, and showed the characteristics of the predicted long-period ground motions in the Osaka area. Furthermore, we discussed the possibility of earthquake damage from the predicted long-period ground motions. The largest peak ground velocities (PGVs) exceed 80 cm/s inside the Osaka basin during both earthquakes. The durations of the waveforms are longer than 4 min. The PGV distributions inside the Osaka basin drastically change depending on the incident directions of the seismic waves in the basin with complicated underground structure. The areas with relative larger amplitude extend along the northern as well as southern basin edges during the next Nankai earthquake. The predominant period of the predicted long-period ground motions is 4 to 6 s in the Osaka area, and the response spectral levels are beyond the safety limit level in building design regulation in Japan. These results indicate the possibility of earthquake damage in large-scale constructions due to the expected long-period ground motions. However, the current results are preliminary and should be revised using more accurate 3D underground structure models and different source scenarios. In particular, it is very important to know to what extent the predicted long period ground motions vary with plausible source parameters. We show the damage prediction map of high-rise buildings in the Osaka basin, using these long-period ground motions, in our other paper (Part 2).

ACKNOWLEDGMENTS

This work is supported by the Grant-in-Aid for Scientific Research (Basic Research (B), Grant No. 17310108) and by the Special Project for Earthquake Disaster Mitigation in Urban Areas from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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