LONG-PERIOD GROUND MOTION CHARACTERISTICS IN OSAKA BASIN, WESTERN JAPAN, FROM STRONG MOTION RECORDS OF LARGE EARTHQUAKES

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ABSTRACT :

Site-specific ground motion characteristics such as horizontal-to-vertical Fourier amplitude spectral ratio (HV) of seismograms have been commonly used to study underground velocity structure beneath each site. In this paper, we studied the relation between the long-period (3-20 sec) ground motion characteristics and the three-dimensional (3D) underground velocity structure in the Osaka sedimentary basin, western Japan, using HV of seismic records from large earthquakes and an existent 3D basin velocity structure model. First we demonstrated that HV of coda-part of the seismic records from eleven events with various azimuth and depth had site-specific stable values, independent of events. Then we compared the observed HV with 1DHV and 3DHV, where 1DHV is the theoretical ellipticity of the fundamental mode of Rayleigh wave obtained from one-dimensional (1D) velocity structure beneath each site and 3DHV is the HV obtained from a 3D ground motion simulation of a M6.5 event. Comparison of the peak periods of HV and 1DHV did not correspond with that of HV and 3DHV at several deep sedimentary stations. The spatial distribution of 1DHV peak and 3DHV suggested that 3DHV is affected by two- or three-dimensional structure of the model. These results emphasized the importance of 3D waveform modeling for constructing a reliable basin velocity structure model.

KEYWORDS: Long-period ground motion, sedimentary basin structure, H/V spectral ratio

1. INTRODUCTION

Amplified and prolonged ground motions at a period range of about 1-10 sec and longer are often observed in distant major sedimentary basins during large-scale earthquakes. In Japan, there are several major sedimentary basins that have high risk of being exposed to seismic hazard by long-period ground motion, such as Kanto, Tokachi, Nobi, and Osaka Plains. In order to predict long-period ground motion inside a basin due to a huge earthquake, it is necessary to construct appropriate velocity structure model that covers from the source to the sedimentary basin, which should be revised and validated based on observed seismograms. The three-dimensional (3D) velocity structure of the sedimentary basin should be especially accurately studied, as its great influence on amplification and complicated propagation of long-period seismic waves has been demonstrated by a number of studies, for example in Kanto Plain (e.g., Koketsu and Kikuchi, 2000) and Osaka Plain (e.g., Hatayama *et al.*, 1995).

Site-specific ground motion characteristics such as horizontal-to-vertical Fourier amplitude spectral ratio (HV) of seismograms have been used as a key to study the underground velocity structure. As a number of studies have pointed out the influence of the ellipticity of fundamental mode of Rayleigh wave on the peak period of HV obtained from microtremor (e.g., Lachet and Bard, 1994) and also from late S-coda wave of seismic records (e.g., Satoh *et al.*, 2001), HV from microtremor or seismic records is often applied to estimation of velocity structure by comparing it with the theoretical ellipticity of fundamental mode of Rayleigh wave computed from one-dimensional (1D) velocity structure model. For example, Suzuki *et al.* (2005) estimated one-dimensional underground velocity structure using the HV of seismograms of M>5 earthquakes to improve the 3D deep subsurface velocity structure around Lake Biwa.

Such approach is on the assumption that HV is site-specific and that it corresponds to 1D underground velocity structure beneath each site. In this paper, we study the long-period ground motion characteristics in the Osaka sedimentary basin, western Japan, based on HV from the seismic records of large earthquakes focusing on the effect of 3D structure on the HV when the geometry of the basin is complex. We first demonstrate that the stable site-specific HV characteristics can be obtained from earthquakes with various azimuths and depths. Then we compare the observed HV with 1DHV and 3DHV, where 1DHV is the theoretical ellipticity of the fundamental mode of Rayleigh wave derived from 1D horizontally stratified models and 3DHV is the HV computed from a 3D ground motion simulation of a M6.5 event using 3D velocity structure model.

2. OBSERVED LONG-PERIOD GROUND MOTION CHARACTERISTICS IN OSAKA BASIN

The Osaka sedimentary basin is filled with the late Cenozoic sediments (Ikebe *et al.*, 1970) and surrounded by the Rokko Mountains (northwest), Hokusetsu Mountains (northeast), Ikoma Mountains (east), Izumi Mountains (south), and Awaji Island (west). It has an ellipsoid shape with a length of 60 km in the NE-SW direction and a width of 40 km in the NW-SE direction, and has the Osaka bay in the center (Figure 1). The Osaka basin has been well investigated by many seismic exploration surveys, such as boring information, microtremor explorations, and gravity explorations, which have contributed to the consequent construction of the detailed 3D basin velocity structure models (e.g., Horikawa *et al.*, 2003; Iwata *et al.*, 2008; Kagawa *et al.*, 2004a). Applicability of these models for long-period ground motion simulation has been investigated by 3D waveform modeling (e.g., Iwaki and Iwata, 2008). Figure 2 shows the bedrock depth distribution from the recently presented 3D basin structure model by Iwata *et al.* (2008).

We use the velocity-type strong motion data recorded at the stations by the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA; Kagawa *et al.*, 2004b) during seven major shallow (<50 km) earthquakes (S1-S7 in Figure 1) and four deep (>400 km) earthquakes (D1-D4 in Figure 1) with magnitudes 6.5 and larger, all of which considered to have enough S/N ratio in the period range of our interest (3-20 sec). The stations used in this study are shown in Figure 2. The description of the earthquakes is listed in Table 1. Two time windows are used to calculate velocity amplitude spectra, *S*-wave part and coda part. The *S*-wave part is a 30-seconds window starting at the *S*-wave onset, and the coda part is a 240-seconds window starting 60 sec after *S*-wave onset. Figure 3 shows examples of the velocity amplitude spectra at FKS and TOY, a deep sediment site and a relatively shallow sediment site (see Figure 2). The spectra show various amplitudes and peaks in *S*-wave part, reflecting the various source and path characteristics. In particular, among the four deep events, D2 and D4 that occurred near Vladivostok, Russia, have noticeably small amplitudes in this period range compared to other events. On the other hand, the spectra in coda part at FKS have similar peak periods, even for D2 and D4, suggesting that site effect at FKS become powerful in coda part.

Table 1 Hypocenter information by JMA for the earthquakes used in this study

	Origin Time (JST)	Latitude (deg)	Longitude (deg)	Depth (km)	M_{JMA}
S1	2000/10/06 13:30:17.94	34.2742	133.3490	8.96	7.3
S2	2001/03/24 15:27:54.50	34.1323	132.6937	46.4	6.7
S3	2004/09/05 19:07:07.50	33.0331	136.7937	37.6	7.1
S4	2004/09/05 23:57:16.81	33.1375	137.1413	43.5	7.4
S5	2004/09/07 08:29:36.27	33.2091	137.2928	40.9	6.5
S6	2005/03/20 10:53:40.32	33.7392	130.1763	9.24	7.0
S7	2007/03/25 09:41:57.91	37.2207	136.6860	10.7	6.9
D1	1998/08/20 15:40:53.85	28.8906	139.9123	467	7.1
D2	1999/04/08 22:10:34.19	43.5510	130.9900	633	7.1
D3	2000/08/06 16:27:13.30	28.8210	140.0860	444.74	7.2
D4	2002/06/29 02:19:33.01	43.5038	131.3923	589	7.0

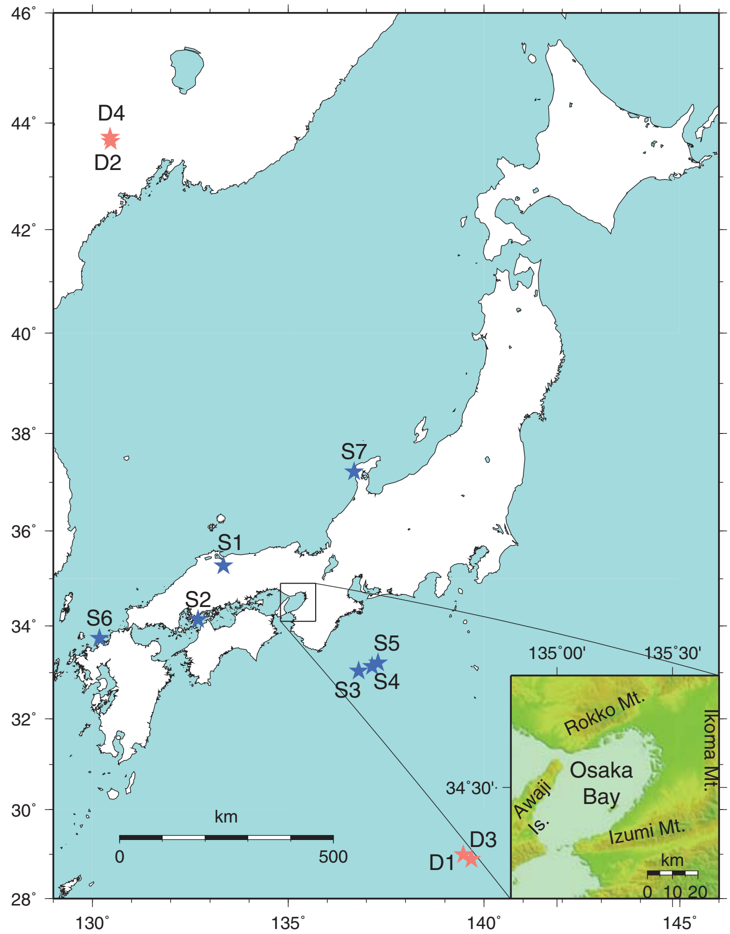

Figure 1 Map of the study area. A geographical map of the Osaka basin is shown on the bottom right corner. Blue stars and red stars indicate the hypocenter (by JMA) of the earthquakes S1-S7 and D1-D4, respectively

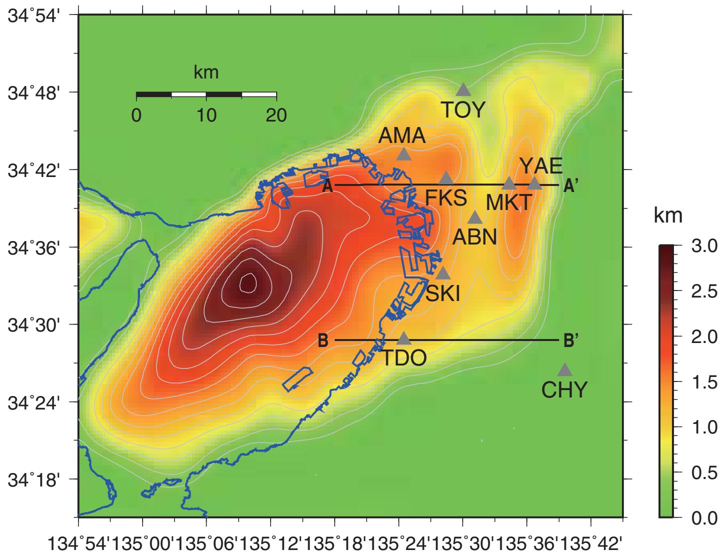

Figure 2 Bedrock depth distribution of the basin velocity structure model by Iwata *et al.* (2008). The closed triangles denote the locations of the strong motion stations used in this study. Lines A-A' and B-B' are the profiles used to compare 3DHV and 1DHV peak period

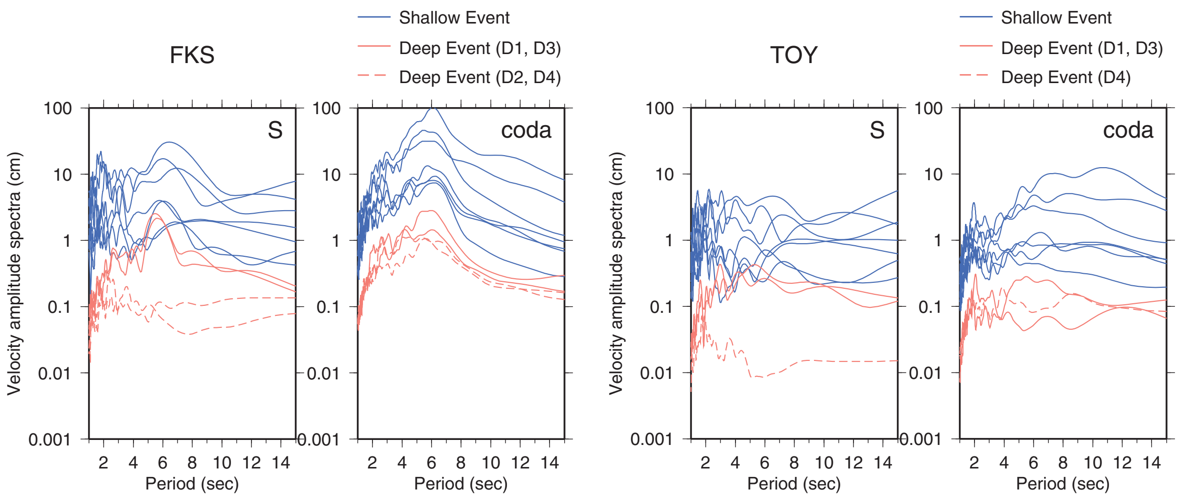

Figure 3 Velocity amplitude spectra of S-part (left panel) and coda-part (right panel) of the events S1-S7 (blue traces) and D1-D4 (red traces). D2 and D4 are indicated by dashed lines

We took the geometric mean of the two horizontal components of the Fourier spectra of coda divided by the vertical component to obtain the HV. The HV from each event S1-S7 and D1-D4 show stable values near the peak periods regardless of whether it is a shallow or a deep event (Figure 4). The HV show peak periods at around 5 to 6 s at deep sedimentary sites (AMA, FKS, SKI, TDO, MKT, and YAE, see Figure 2) and around 3 sec at relatively shallow sedimentary site (TOY). Hereafter, we will refer to the observed HV of coda part simply as "HV". The theoretical ellipticity curves of fundamental mode of Rayleigh wave computed from 1D velocity structure beneath each site (1DHV) are also drawn for comparison. The peak periods of HV and 1DHV agree with each other at ABN, SKI, and TDO, while the peak period of 1DHV is longer than that of HV by less than 1 sec at FKS, YAE, and MKT.

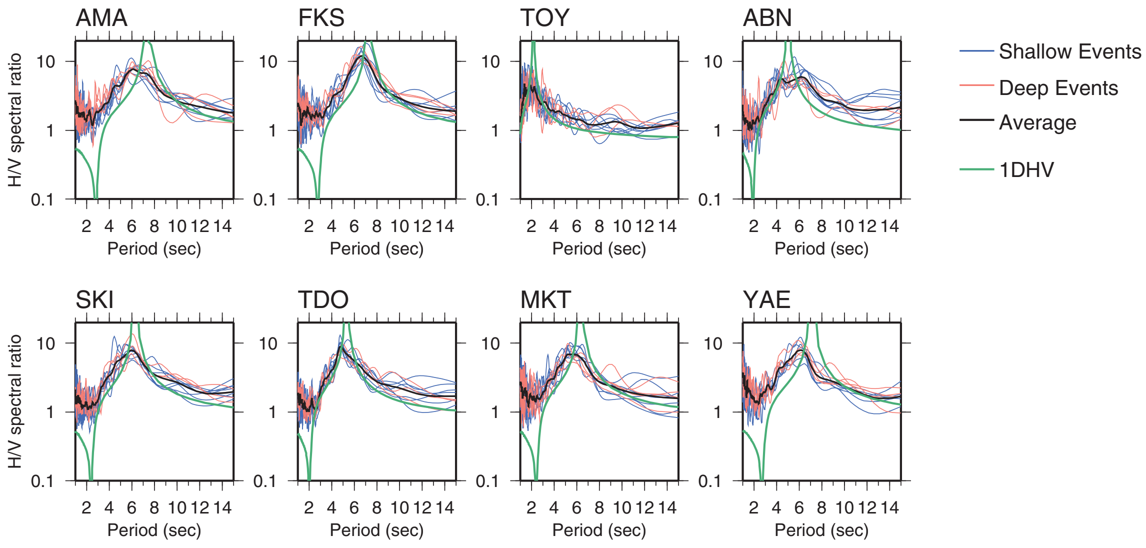

Figure 4 HV spectral ratio of S1-S7 (blue traces) and D1-D4 (red traces) using coda-part. Black trace indicates the average. 1DHV obtained from the 1D velocity structure beneath each station is also shown (green trace)

3. COMPARISON OF HV, 1DHV, AND 3DHV

3.1. 3D Long-period Ground Motion Simulation

Here we compare the observed HV with 3DHV obtained from 3D ground motion simulation in order to examine the effect of 3D underground velocity structure. A long-period ground motion simulation of the event S5, whose hypocenter is off Kii peninsula, approximately 250 km away from the center of the Osaka basin, was performed by a 3D finite-difference method (Pitarka, 1999) up to period 3 sec. using the crustal and basin velocity structure model by Iwata *et al.* (2008). The source is modeled as a double couple point source (Table 2). We adopted the epicenter determined by Japan Meteorological Agency (JMA) and the source mechanism by F-net of the National Research Institute for Earth Science and Disaster Prevention (NIED), and estimated the source duration and the source depth so as to fit the waveforms at K-NET strong motion stations (by NIED; Kinoshita,1998) along the southeast coast of Kii peninsula. Figure 5 shows some examples of the synthetic waveforms compared with the observed waveforms. The synthetic waveforms at CHY, a rock site that is 202 km distant from the epicenter, show very good agreement with the observed waveforms. At the stations inside the basin, the synthetic waveforms reproduce the large amplitudes and the long durations of the observed waveforms reasonably well. Figure 6 shows the comparison of the HV and 3DHV calculated from the coda part of the synthetic waveforms. The 3DHV have peaks at longer periods compared to the HV at AMA, FKS, and TDO by 1-2 sec, which is larger than the difference between HV and 1DHV peaks. The peak of the 3DHV is consistent with that of HV at MKT and is at shorter period than that of HV at YAE, which contradict the relation between HV and 1DHV peaks.

Table 2 Source parameters for the ground motion simulation

	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Duration (sec)	M_0 (Nm)
S5	11.0	290	54	114	4.0	6.0×10^{18}

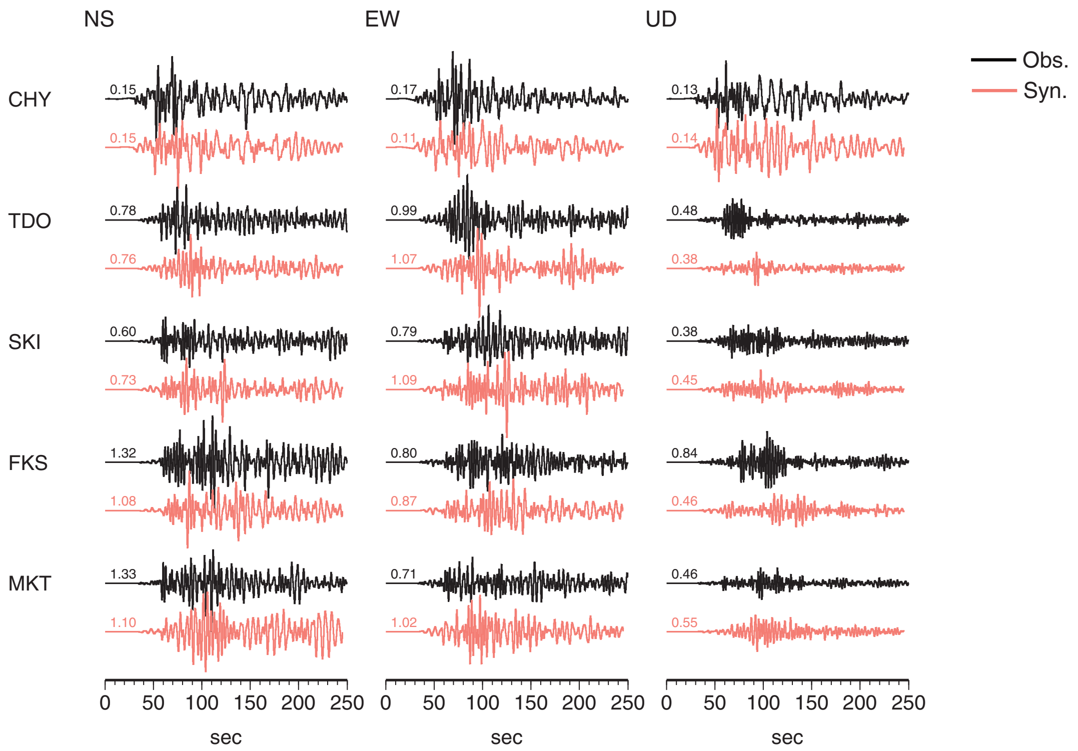

Figure 5 Comparison of the observed (black trace) and synthetic (red trace) velocity waveforms (bandpass filtered at 3-20 sec) at a rock site station (CHY) and sedimentary site stations (TDO, SKI, FKS, and MKT). The number on the left of each waveform indicates the maximum amplitude in cm/s

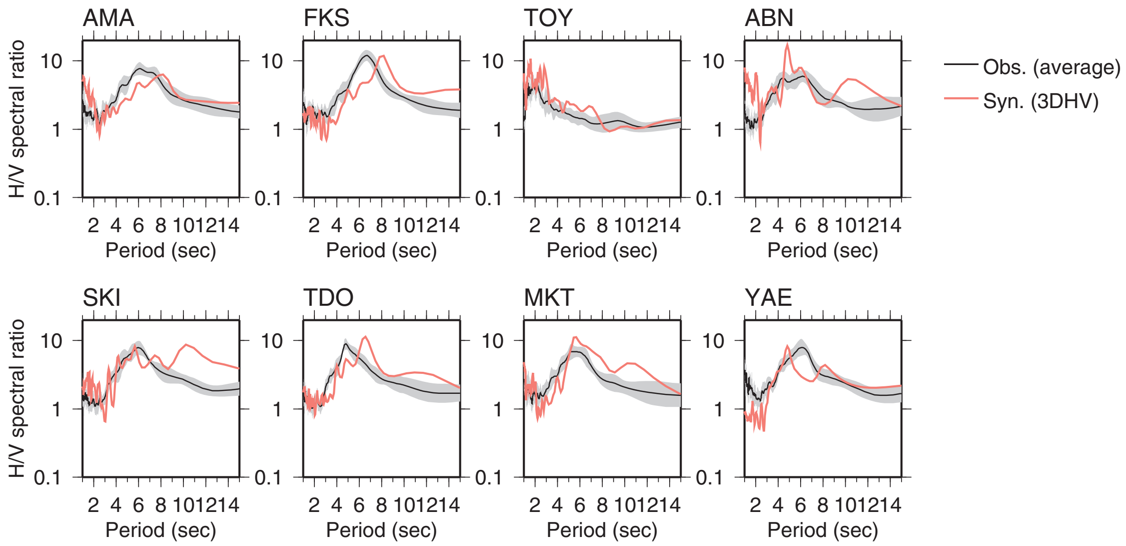

Figure 6 Comparison of the average observed HV (black trace) with standard deviation (gray shade) and 3DHV obtained from the ground motion simulation (red trace)

3.2. Comparison of 1DHV Peak and 3DHV

Comparison of the observed HV with 1DHV and 3DHV has suggested that 3DHV do not necessarily correspond to those of the 1DHV at some stations in the Osaka basin. We calculated 3DHV and 1DHV every 1 km along two latitudinal lines A-A' and B-B' in Figure 2 that are adjacent to YAE, MKT, FKS, and TDO in order to see the spatial distribution of 3DHV and 1DHV peaks (Figure 7). Although the peak periods of 3DHV and 1DHV roughly correspond to each other, there are some zones with noticeable discrepancy between them. Stations MKT and YAE are located between Ikoma mountains and an elevation where the bedrock depth geometry forms either side of the valley. The 3DHV have peaks at shorter period compared to the 1DHV peaks in these areas. On the other hand, in the western part of the lines around FKS and TDO, the bedrock depth becomes deeper toward the Osaka bay and the 3DHV have peaks at longer periods compared to the 1DHV. It is suggested that the HV peaks are controlled by the two- or three-dimensional underground structure of areas with some spatial extent.

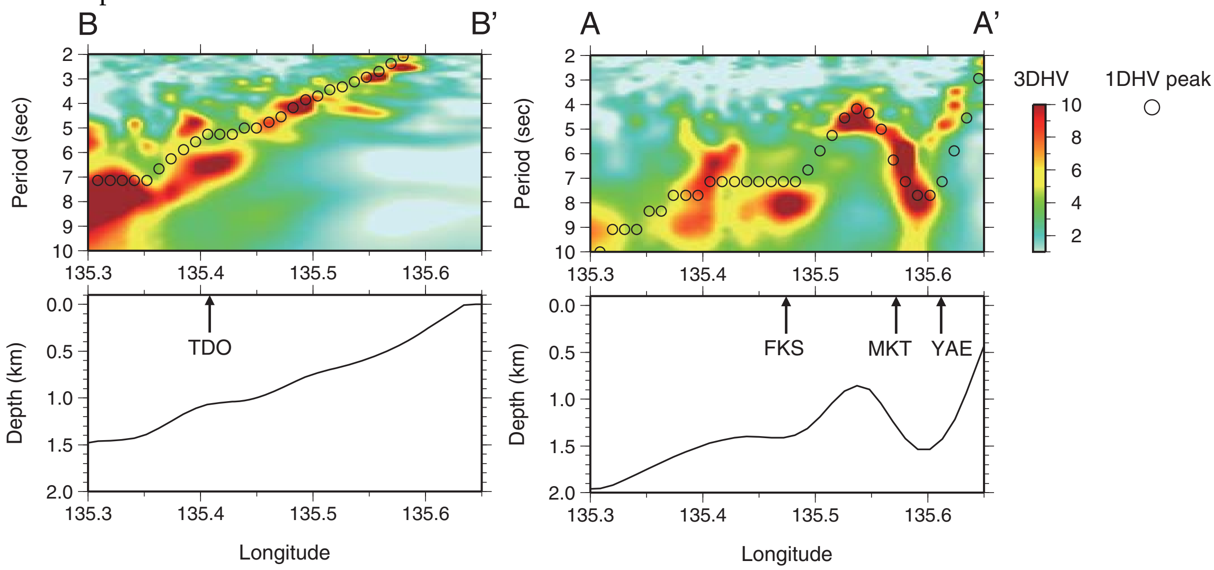

Figure 7 Cross-section views of 3DHV spectra (top, color) and 1DHV peaks (top, open circles) and the bedrock depth (bottom) along latitudinal lines A-A' and B-B' in Figure 1. Arrows indicate the location of stations

4. CONCLUSIONS

We studied the relation between the long-period ground motion characteristics and the 3D underground velocity structure model in the Osaka sedimentary basin, using the HV of seismic records from large earthquakes and the 3D basin velocity structure model by Iwata *et al.* (2008). Site-specific HV characteristics could be obtained from coda-part of the seismic records from eleven earthquakes with various azimuths and depths; the HV showed peak periods at around 5 to 6 sec at deep sediment sites (AMA, FKS, SKI, TDO, MKT, and YAE) and around 3 sec at a relatively shallow sediment site (TOY). The average HV was then compared with the 1DHV obtained from the 1D velocity structure beneath each site and 3DHV obtained from 3D ground motion simulation of a M6.5 event. Comparison of the peak periods of 1DHV and HV did not correspond to that of 3DHV and HV at some stations. For example, at station YAE, the peak period of 1DHV was longer than HV by 1 sec while the peak period of 3DHV was shorter than HV by more than 1 sec. Other examples are FKS and TDO, where the difference in peak period of 1DHV and HV is very small while the peak period of 3DHV was longer than HV by more than 1 sec. We examined the spatial distribution of 3DHV and 1DHV peak along latitudinal lines that pass through such stations, and showed that the spatial change in bedrock depth geometry might cause the difference in the peak periods of 3DHV and 1DHV. It was suggested that 3DHV is influenced by two- or three-dimensional structure of an area with some spatial extent and that 3D waveform modeling is important for constructing a reliable sedimentary basin velocity structure model.

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