Long-period ground motions from a large offshore earthquake: The case of the 2004 off the Kii peninsula earthquake, Japan

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The 2004 off the Kii Peninsula earthquake excited long-period ground motions over a wide area of Honshu Island of Japan. This remarkable excitation was observed in the Osaka, Nobi, and Kanto basins as well as in the Omaezaki region. The record section indicates two types of developed long-period motions by the basin surface waves, either by the source or passage effect of the shallow and large offshore earthquake. Their combination resulted in the well-developed long-period ground motions observed within the distant basins as those during the 1985 Michoacan and 2003 Tokachi-oki earthquakes did. The distributions of pseudo-velocity response spectra confirmed this development at periods of 5–7 s in the Osaka and Nobi basins and of 7–10 s in the Kanto basin. The comparison of the distributions with the thicknesses of the sediments and the S-wave velocities of the surface layers shows that these characteristics of the long-period ground motions are closely related to the structures of the basins. The earthquake provided a timely warning of damaging long-period ground motions from future megathrust events in the Tonankai, Nankai, and Tokai regions.

Key words: Long-period ground motion, large offshore earthquake, response spectrum, basin structure.

1. Introduction

A large earthquake with a JMA magnitude (M_{JMA}) of 7.4 occurred at 23:57 on September, 5 2004 (local time = UT + 9 hours) off the Kii peninsula, central Japan (JMA: Japan Meteorological Agency, 2004). This was preceded by a distinct $M_{\mathrm{JMA}}7.1$ foreshock at 19:07. Both events were located beneath the Nankai trough neighboring the source regions of the 1944 Tonankai and 1946 Nankai earthquakes ($M_{\mathrm{JMA}}7.9$ and 8.0). After these megathrust events and their aftershocks, the seismicity along the Nankai trough has been so low that the 2004 off the Kii peninsula earthquake is the largest one since 1949. It is an outer-rise event with reverse faulting, which might be a precursor of a future megathrust earthquake (Lay *et al.*, 1989), so that the event is also worthy of note in relation to a future Tonankai earthquake (Earthquake Research Committee, 2001).

Since the installation of the nationwide strong motion arrays, called K-NET and KiK-net, was completed in 1996 and 2000 by the National Research Institute of Earth Science and Disaster Prevention (NIED; Kinoshita, 1998; Aoi *et al.*, 2000), the ground motions from this earthquake have been observed at 425 K-NET stations and 361 KiK-net stations. The Port and Airport Research Institute (PARI) also observed the earthquake at 33 sites. The SK-net (Seismic Kanto Research Group, 2002) collected 205 records from the seismic intensity meter arrays and 73 records from the Yokohama and Earthquake Research Institute (ERI) strong motion arrays. In total, more than 1,000 seismometers observed ground motions from the earthquake.

The CMT solutions by the NEIC/USGS and F-net/NIED indicated high-angle reverse faulting at a depth of 10 $\sim$ 11 km and a moment magnitude of 7.4 $\sim$ 7.5. Such a shallow and large offshore event often excites damaging long-period ground motions in distant basins. The worst example with over 20,000 fatalities is in Mexico City at a distance of 400 km from the 1985 Michoacan, Mexico, earthquake (Beck and Hall, 1986). Many oil tanks were damaged and two of them caught fire in the Yufutsu basin 250 km away from the 2003 Tokachi-oki, Japan, earthquake (Koketsu *et al.*, 2005). In order to examine whether the 2004 off the Kii peninsula earthquake is also such a case as the events mentioned above, we will investigate the long-period components of the ground motions using distributions of response spectra.

2. Ground Motion Records

As shown in Fig. 1, the Kanto basin extends from 300 to 450 km away from the epicenter of the earthquake. This situation is similar to that for the 1985 Michoacan earthquake and Mexico City. The Osaka and Nobi basins are located 200 $\sim$ 250 km away from the epicenter, corresponding to the Yufutsu basin for the 2003 Tokachi-oki earthquake. In addition, Tokyo, Osaka, and Nagoya — three largest cities in Japan — are situated within these basins, so we limited the target of this study to the area of Fig. 1 which includes the basins. There are about 900 stations of the K-NET, KiK-net, PARI, and SK-net in this area.

In order to figure out the characteristics of the long-period ground motion, we chose 12 stations along the line between the epicenter and downtown Tokyo (those in purple circles in Fig. 1). The record section in Fig. 2 was then constructed using the EW acceleration seismograms

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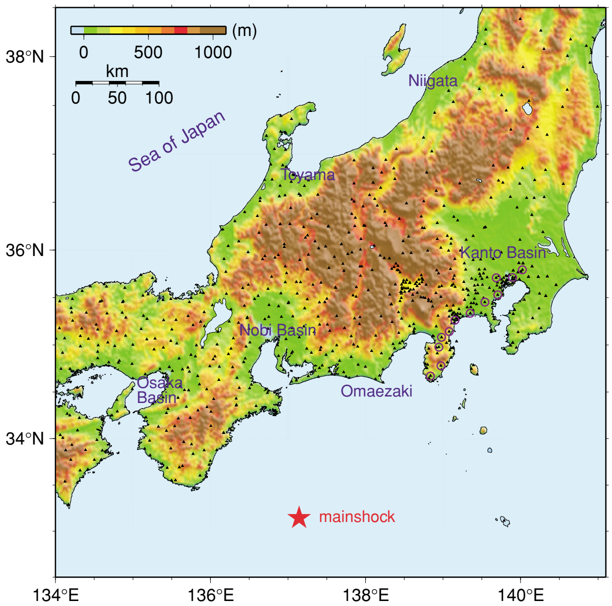

Fig. 1. Index map showing the target region of this study and its geographical and topographical setting. The red star denotes the epicenter of the 2004 off the Kii Peninsula earthquake. The strong motion seismometer stations are plotted with black triangles excluding those of the dense Yokohama array.

observed at these stations. No filter and no time reduction were applied. All the traces were normalized to their maximum amplitudes. Although we can identify only the P- and S-wave trains in the accelerograms observed outside the Kanto basin, the long-period wavetrain appears after the S-wave train in the traces within the basin.

We integrated the accelerogram at the station KNG001 to the ground velocity and lowpass-filtered it with a corner period of 2.5 s. The upper inset of Fig. 2 shows the horizontal particle motion of its portion indicated by a bracket. Since the motion is polarized in the direction transverse to the propagation path between the epicenter and the station, the long-period wavetrain consists mainly of surface Love waves produced at the western edge of the Kanto basin. They are basin surface waves which were frequently observed during distant earthquakes (e.g. Frankel *et al.*, 1991; Zama, 1992; Hatayama *et al.*, 1995; Frankel *et al.*, 2001). The particle motion at CHBH04 in the center of the Kanto basin is polarized to a somewhat different direction from the transverse one, as shown in the lower inset of Fig. 2. The reason for this is that the 3D basin structure deformed the propagation path of the basin surface wave (Koketsu and Kikuchi, 2000).

If we also integrate the accelerogram at SZOH41 outside the Kanto basin, we can find that the resultant velocity seismogram (grey trace in Fig. 2) already included developed long-period components. They must have been generated in the source region or during its passage to this station. Therefore, the combination of the source and passage effect of the shallow, large offshore earthquake worked as the input motions to the basin, and the basin surface wave resulted in the well-developed long-period ground motions observed within the basins, as for the 2003 Tokachi-oki earthquake (Koketsu *et al.*, 2005).

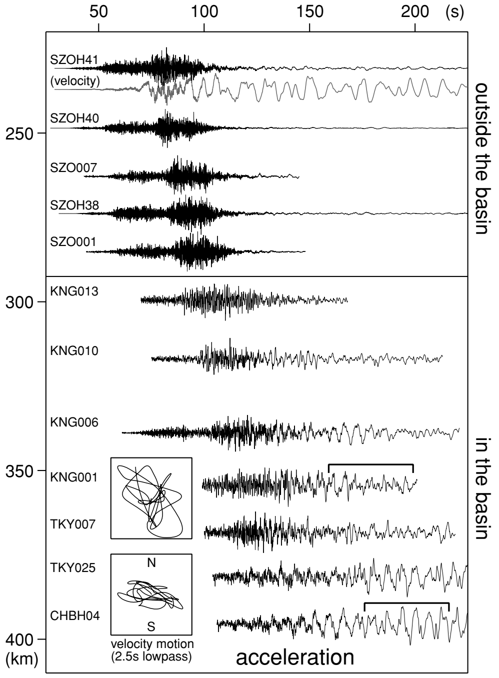

Fig. 2. Section of the EW acceleration seismograms observed at the stations indicated by purple circles in Fig. 1. All the traces are normalized to their maximum amplitudes. The grey trace in the uppermost part is the velocity seismogram at SZOH41. The two insets show the horizontal particle motions at KNG001 and CHBH04.

3. Distribution of Response Spectra

We need an index for the quantitative evaluation of the long-period ground motions themselves and their effects on engineering structures such as buildings and oil tanks. The best-known index for seismic ground motion is a seismic intensity, but the dominant period of the long-period ground motion is out of the range of the JMA seismic intensity measurement (Japan Meteorological Agency, 1996). Instead, we used the velocity response spectra, which are peak amplitudes of velocity motions of single-degree-of-freedom systems with various natural frequencies responding to seismic ground motion (e.g. Housner, 1959). The resonance due to the ground motions enlarges peak amplitudes of velocity motions at the dominant frequencies, leading to an increase in the values of the response spectra. They can be defined even in the long-period range and the single-degree-of-freedom system is used as an approximation of a target structure. The response spectra are suitable for representing the long-period ground motions because they consider long duration as well as large amplitudes. We further approximated these velocity response spectra with the pseudo-velocity response spectra (acceleration response spectra divided by natural angular frequencies) to avoid numerical problems which may arise from the integration of acceleration into velocity.

Figure 3 shows the distributions of pseudo-velocity response spectra calculated for periods of 5, 7, and 10 s. We first calculated them individually for the two horizontal components of the seismograms whose duration is longer than 120 s, and then took their geometrical means. The damping factor of the single-degree-of-freedom system is assumed to be 5%, which is the value widely used for a response analysis. For all the periods, larger response spectra were obtained in the Kanto, Osaka, and Nobi basins than in the other parts. They all confirm the development of the long-period ground motions in the basins. However, they have different features from each other depending on the period as follows. At a period of 5 s, the peak response spectra appear in the Osaka and Nobi basins (Fig. 3(a)). These peaks are weakened at a period of 7 s, while those in the major part of the Kanto basin are strengthened up to 18 cm/s (Fig. 3(b)). The peaks in the Osaka and Nobi basins finally disappear at a period of 10 s. The peak in the Kanto basin is concentrated in the eastern part with a velocity over 16 cm/s.

We emphasize the remarkable excitation of long-period ground motion in the region around the cape of Omaezaki. The large responses exist at all the periods of 5, 7, and 10 s. Kodaira *et al.* (2004) carried out seismic explorations and found thick low-velocity sediments along the profile from the Omaezaki area to the sea in its front. Tsuno *et al.* (2003) confirmed them by microtremor surveys and assumed the S-wave velocity of the 3 km-thick layer above the basement to be as low as 2 km/s. These sediments might amplify such input motions as observed at SZOH41 (Fig. 2) and generate large long-period ground motions. The valley extending from the source region to Omaezaki, which can be identified in the seabed topography (background of Fig. 3), might also be effective on this amplification.

We note that the long-period ground motions propagated across the Honshu Island to the Sea of Japan. They reached the basins of Niigata and Toyama and excited fairly strong shaking, as shown in the distributions of response spectra at periods of 7 and 10 s (Figs. 3(b) and (c)). Some parts of these long-period ground motions traveled away along the valleys in the Japan Alps region. We can track them by following the diagonal 2–4 cm/s belt from the Omaezaki area to the basin of Niigata in the distributions at periods of 7 and 10 s (Figs. 3(b) and (c)).

4. Basin Structures

The structures of the basins should greatly affect the long-period ground motions through the basin surface waves. In order to show this effect in Fig. 4, we plotted the thickness distributions of the sediments above the basement with color tones using the survey results of Aichi Prefecture (2002, Nobi basin), Afnimar *et al.* (2002, Osaka basin), and Afnimar *et al.* (2003, Kanto basin). We then overlaid them with the distributions of response spectra drawn by blue contours. Since the response peaks in the Nobi and Osaka basins are the most significant at a period of 5 s (Fig. 3(a)), we draw the contours of the response distribution at this period. For the Nobi basin, the high-response area surrounded by the 4 cm/s contour almost coincides with the thick sediments specified by the colors for thicknesses larger than 0.5 km (Fig. 4(a)).

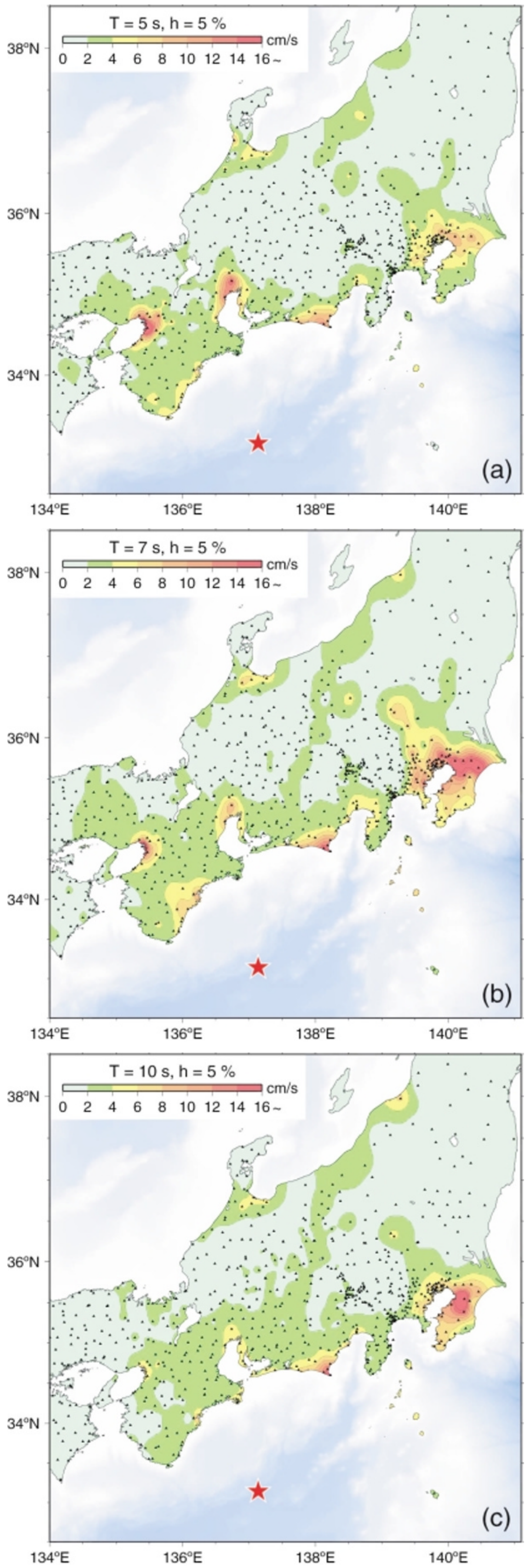

Fig. 3. Distributions of pseudo-velocity response spectra for a damping factor of 5% and natural periods of (a) 5, (b) 7, and (c) 10 s.

However, the degree of similarity between the distributions of response spectra and sediment thicknesses is reduced in the Osaka basin (Fig. 4(b)). The center of the deep sediments is located beneath the Osaka bay about 30 km away from the western shoreline of the city of Osaka, so that two-thirds of the deep-sediment area are under the sea. Since there is no seismic station in this part, the certainty of the response distribution has been lost to some extent. In spite of this uncertainty, fair agreement between the distributions of response spectra and sediment thicknesses is achieved on the land as shown in Fig. 4(b). The sediments thicker than 0.5 km are mostly surrounded by the response contour of 6 cm/s. The thin sediments and small response spectra simultaneously appear beneath the Uemachi elevation.

The situation in the Kanto basin is much more complicated than in the Nobi and Osaka basins. The significant response peak appears in the basin at a period of 7 s (Fig. 3(b)), and so the contours in Fig. 4(c) represent the response spectra at this period. The thick sediments are mostly surrounded by the 4 cm/s contour, as in the Nobi basin. This coincidence is achieved, even in the northwestern extension of the Kanto basin. However, the center of the deep sediments does not coincide with the center of the high-response area. The former is located in the southern half of the basin, while the latter is in the eastern half with a peak response of 18 cm/s. The reason for this contradiction is that large response spectra of the long-period ground motion are generated not only by thick sediments, but also by low-velocity surface layers. Yamanaka and Yamada (2002) carried out microtremor surveys and found surface layers with S-wave velocities as low as 400 m/s at the points indicated by large dots in Fig. 4(c). These low-velocity layers developed the basin surface waves and shifted the center of the high-response area to the east.

5. Discussion and Conclusions

We investigated the long-period ground motions from the 2004 off the Kii Peninsula earthquake, Japan, by using a section of accelerograms and the pseudo-velocity response spectra. The record section suggests that the basin surface waves produced considerable long-period ground motions. The source and path effects of the large offshore earthquake worked as the input long-period ground motions to the basin. The propagation of the long-period ground motions and their development in the sedimentary basins are depicted by the distributions of pseudo-velocity response spectra. As pointed out by Yamada and Iwata (2005), the sedimentary wedge may largely amplify the ground motions even before the waves enter the basin. Further quantification of the long-period ground motions from the source and path effects, and those amplified in the basin will improve the accuracy of ground-motion prediction.

The peak response spectra in the Osaka and Nobi basins indicate the development of the ground motions at periods of 5–7 s. We compared the distributions of response spectra and sediment thicknesses and found these periods to be related to the maximum thicknesses and the extents of the basins. These relations are also valid in the Kanto basin. Since the Kanto basin has thicker sediments and a larger extent, the peak responses appear at longer periods of 7–10 s.

In the Kanto basin, the low-velocity surface layers are also found to be effective on the development of the long-period ground motions. The introduction of this new factor should have resulted in the complex distribution and waveforms of the long-period ground motions. Hayakawa *et al.* (2005) reported difficulty in simulating the long-period ground motions in the Kanto basin for this earthquake. This difficulty should have demonstrated the complexity mentioned above.

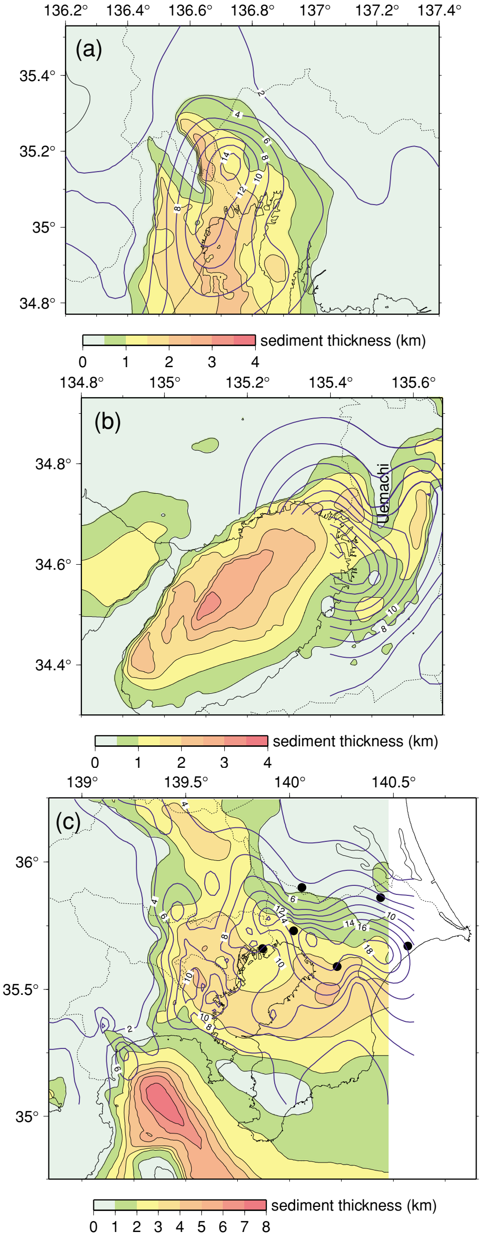

Fig. 4. Distributions of pseudo-velocity response spectra (blue contours) and thicknesses of the sediments (color tones) in the (a) Nobi, (b) Osaka, and (c) Kanto basins. The period of the response spectra and the maximum thickness on the color scale are 5 s and 4 km in (a) and (b), but 7 s and 8 km in (c).

In summary, we confirmed that the 2004 off the Kii Peninsula earthquake is as large an offshore event as the 1985 Michoacan and 2003 Tokachi-oki earthquakes with respect to long-period ground motion. Since even this far-offshore M_w7.4 event excited well-developed long-period ground motions at distant basins, we have to presume so strong long-period motions during such an M8 megathrust events as the future Tonankai, Nankai, and Tokai earthquakes, that they will damage structures with longer natural periods like tall buildings and large oil tanks. The tragedy in Mexico City and the Yufutsu basin might be reproduced to a certain extent in the Osaka, Nobi, and Kanto basins.

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