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CONSTRUCTIVE INTEREFERENCE OF LONG-PERIOD SEISMIC WAVES IN HORIZONTAL PLANE IN URBANIZED AREA DURING 2011 TOHOKU EARTHQUAKE IN JAPAN

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Abstract

The anomalous amplification of the long-period ground motions in the Osaka and Ise Bay areas in the western part of mainland Japan during the 2011 Tohoku earthquake was investigated in this study. One of the most symbolic phenomena during the 2011 Tohoku earthquake was the strong motion recorded at the top of a 55-story steel office building located in the Osaka Bay area more than 700 km away from the epicenter and the damage to the inside of the building. The top of the building experienced large drift, and the records indicate one-sided displacement exceeding 1.3 m, which is the largest disclosed displacement of any super high-rise building in Japan. This can only be explained by the targeted amplification of the long-period ground motions within the sedimentary layers of the Osaka Basin. Similar site amplification was also observed in the Ise Bay area. The contours of the peak values of the pseudo velocity response spectra with a 5% damping factor in the Osaka and Nobi Plain areas indicate the local anomalous amplification of long-period ground motions with a predominant period of 6–7 s at coastal sites.

To elucidate the interference mechanism of the long-period seismic waves in the Osaka and Nobi Plains, the three-dimensional (3D) finite difference method was used for wave propagation analysis incorporating an arbitrarily heterogeneous geologic structure. This method requires a large amount of computational time and storage to simultaneously consider the rupture of the seismic faults for the 2011 Tohoku earthquake and geologically model the Osaka and Nobi Plains. Therefore, the sedimentary basin-like structure of the Osaka and Nobi Plains is considered assuming the incident wave field from the epicenter of the 2011 Tohoku earthquake. The ground motions recorded at sites in the Osaka and Nobi Plains during the 2011 Tohoku earthquake were well reproduced by the 3D calculations. The agreement between the observed and calculated ground motions at the coastal sites indicates that the large amplification of the ground motions was caused by the 3D effect of the wave interference in the complex subsurface structure of the Osaka and Nobi Plains. This paper focuses on the amplification mechanism of long-period ground motions in the Osaka Plain.

The 3D effect of the ground motion amplification in the Osaka Plain was compared with the 2D model results using soil responses at horizontally arrayed sites under Ricker wavelet incidence. At sites in the Osaka Bay area, the peak amplitudes of 3D response waveforms and their Fourier amplitude were larger than those of the 2D response. Snapshots of the wave components reveal that the third pulse has a distinctive amplitude because of the constructive interference of the multiple passing waves in the 3D structure. The amplification area was small and limited partly by the concentration of the multiple passing waves in the Osaka Bay area.

Keywords: long-period seismic wave, 2011 Tohoku earthquake, sedimentary basin, constructive interference

1. Introduction

During the 2011 off the Pacific Coast of Tohoku Earthquake (M_W9.0) in Japan, hereafter referred to as the 2011 Tohoku earthquake, damage to buildings along the coastal area in eastern Japan was severe, mainly because of the immense force of the resultant tsunami (Architectural Institute of Japan, 2011). In landfilled areas and throughout the alluvial land along the Tone River in Chiba Prefecture, serious soil liquefaction also occurred, leading to the tilting of a number of traditional Japanese wooden houses. However, serious structural damage caused by ground shaking, including collapse, seems to have generally been lighter than expected considering this was the largest-magnitude earthquake ever to have hit Japan.

In terms of ground shaking, seismic waves generated by the rupture of the huge seismic fault spread and traveled into the Osaka and Nobi Plains, where thick sedimentary layers exist on the seismic bedrock. Seismic waves were reflected and amplified within the sedimentary basins, generating ground motions with long predominant periods and durations known as “long-period ground motions.” The long-period ground motions influenced the dynamic behavior of structures with long natural periods, including high-rise buildings and fluid reservoirs.

The influence of these motions on long-period structures has been the subject of many engineering studies in Japan since the 2003 Tokachi-Oki earthquake (M_W8.3) in Hokkaido, Japan. The long-period ground motions observed in the sedimentary Yufutsu Plain, far from the epicenter, are considered to be one plausible cause of the damage to several oil tanks located in Tomakomai in the central part of the Yufutsu Plain. The occurrence of the Tokai, Tonankai, and Nankai earthquakes along the western part of the Japanese archipelago had a serious effect on the dynamic behavior of the long-period structures densely constructed in the Kanto, Nobi, and Osaka Plains because of their resonance with the long durations of the ground motions.

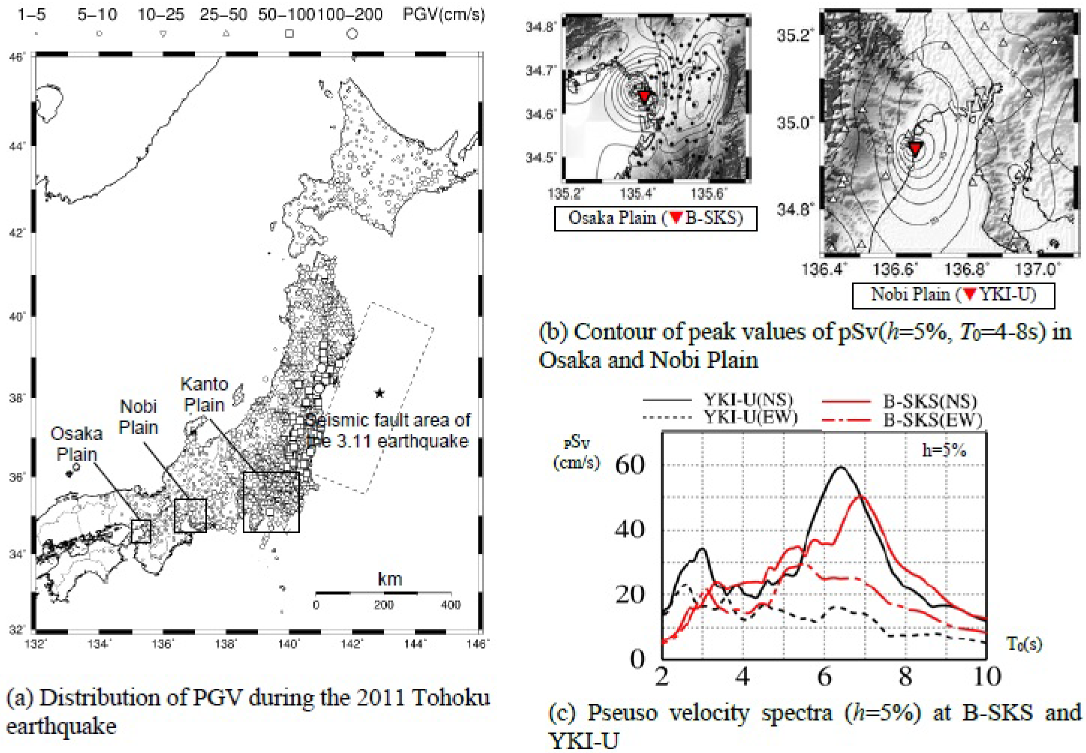
One of the most symbolic phenomena during the 2011 Tohoku earthquake was the strong motion recorded at the top of a 55-story steel office building located in the Osaka Bay area over 700 km from the epicenter and the damage to the inside of the building (BRI, 2011). The top of the building experienced large drift, and the records indicate one-sided displacement exceeding 1.3 m, which is the largest recorded displacement of any super high-rise building in Japan. This can only be explained by the targeted amplification of the long-period ground motions within the sedimentary layers of Osaka Basin. Similar site amplification was also observed in the Ise Bay area.

In this study, the amplification mechanism of the long-period ground motions in the Osaka and Ise Bay areas was investigated using a three-dimensional (3D) geological model of the Osaka and Nobi Plains.

2. Observed Ground Motions in Osaka and Ise Bay Area

During the 2011 Tohoku earthquake, over 3000 strong motions were recorded by dense seismic networks in Japan. Fig. 1(a) shows the distribution of the peak ground velocities synthesized in two horizontal directions. Observation sites include K-NET and KiK-net sites from the National Research Institute for Earth Science and Disaster Prevention (NIED), the Japan Meteorological Agency (JMA), local governments, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the Port and Airport Research Institute (PARKI), the Building Research Institute (BRI), and East Nippon Expressway Company Limited (NEXCO East). The peak ground velocity (PGV) gradually attenuated radially from the epicentral area. In the Kanto Plain, the PGVs were reduced to 25–50 cm/s compared with more than 50 cm/s in the eastern part of Japan adjacent to the epicentral area. In the Osaka and Nobi Plains, the PGV is generally less than 10 cm/s.

The contours of the peak values of the pseudo velocity response spectra (${}_{P}S_{V}$) with a damping factor *h* of 5% in the Osaka and Nobi Plain areas are shown in Fig. 1(b). The response spectra were calculated for synthesized motions in two horizontal directions with a period of range of 4–8 s. These contours indicate the local anomalous amplification of long-period ground motions in coastal sites around B-SKS, which is the site of the 55-story steel office building, and YKI-U. The response spectra at B-SKS and YKI-U were significantly amplified in the period range of 6–7 s in the north–south (NS) direction, as shown in Fig. 1(c).



(a) Distribution of PGV during the 2011 Tohoku earthquake

(b) Contour of peak values of pSv(h=5%, T_0=4-8s) in Osaka and Nobi Plain

(c) Pseuso velocity spectra (h=5%) at B-SKS and YKI-U

Fig. 1. PGV distribution during the 2011 Tohoku earthquake and anomalous amplification of long-period ground motions in coastal area of the Osaka and Nobi Plains in the western part of mainland Japan.

Focusing on the amplification of long-period ground motions in the Osaka Plain area surrounded by a series of mountain range-forming sedimentary basin structures (Miyakoshi et al., 2013) (Fig. 2), the basin structure in the east–west (EW) direction is mainly characterized by two faults, the Ikoma and Uemachi faults, running in the NS direction. The depth of the seismic bedrock changes abruptly at these two faults. Complex geological soil conditions complicate wave propagation in the basin, leading to the dependence of the amplification characteristics of ground motions on not only the site effect but also the source effect, including the arrival direction of seismic waves.

Figure 3 shows the velocity waveforms and velocity response spectra of the observed ground motions at 10 sites with a 5% damping factor in the EW direction across the Ikoma and Uemachi faults, which are shown in Fig. 2. OSKH02 is located in the coast of Osaka Bay. From OSKH04, which is in the mountain area, the ground motions were amplified in the sedimentary basin sites, TTT and MRG, because the site amplification included effects of constructive interference caused by the thrust-type subsurface structure of the Ikoma fault. The PGV at EBC diminished with gradually decreasing sediment thickness toward the tip of the Uemachi fault. The bedrock depth abruptly drops again across the blind thrust of the Uemachi fault, and ground motions were again amplified in the western part from FKS. The PGVs at B-SKS and OSKH02 were amplified to 13 times that at OSKH04, which is located in the mountain area. The ground motions at the sites in the coastal area have a predominant component around 6–7 s. The increase in the long-period component (6–7 s) of the response spectra at B-SKS and OSKH02 was significant compared with that at OSKH04. This is a plausible cause for the severe shaking and drift of the abovementioned super high-rise building at B-SKS.

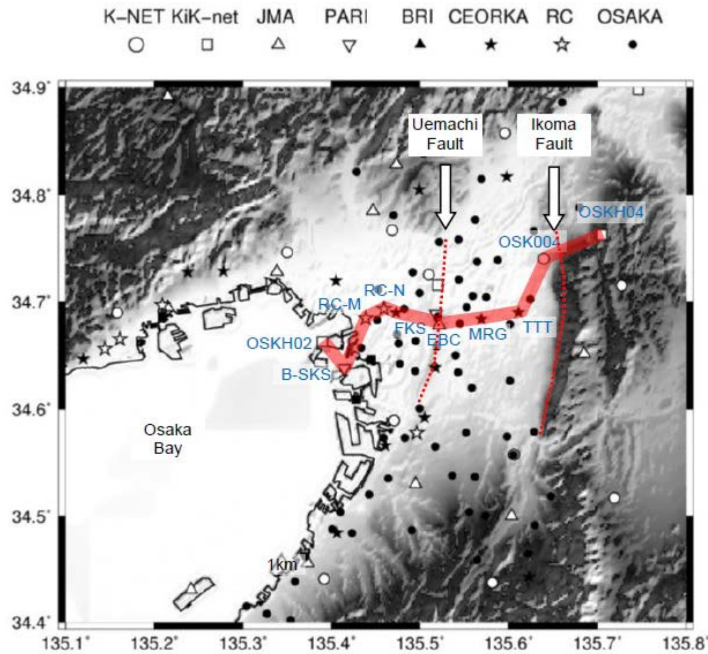
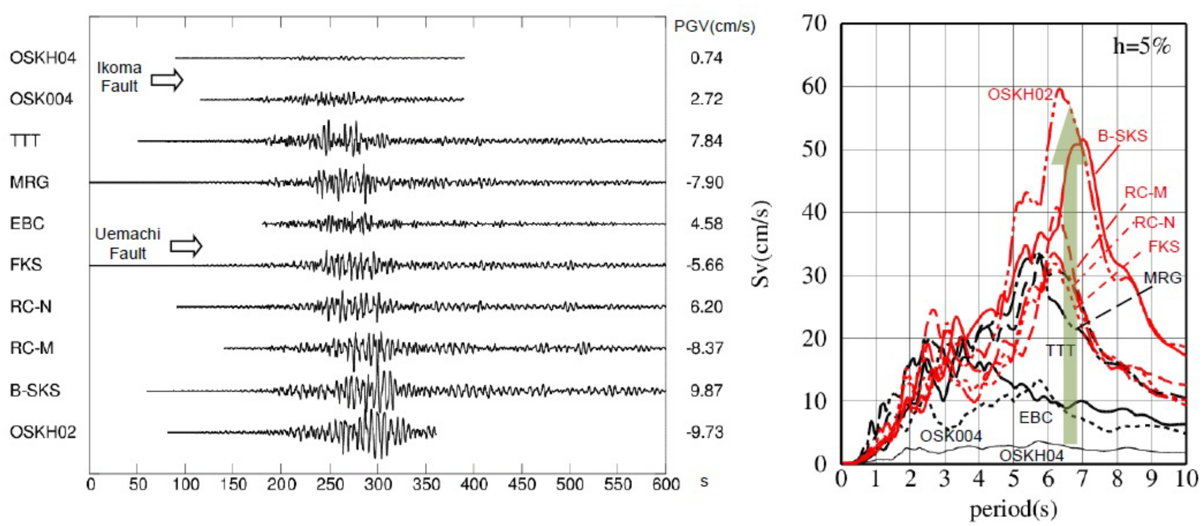


Fig. 2. Map of strong motion observation sites in Osaka area surrounded by mountain range.



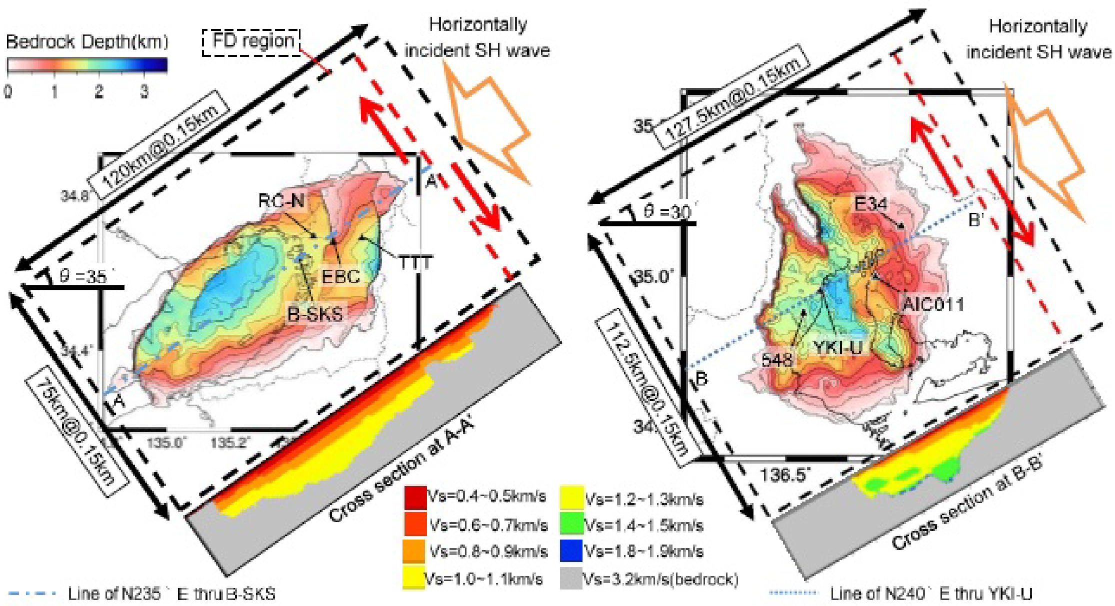
(a) Velocity waveforms (b) Velocity response spectra

Fig. 3. Velocity waveforms and response spectra of recorded motions in NS direction for 10 sites in Fig. 2.

3. Three-Dimensional Finite Difference Model of Osaka and Nobi Basin Structures

The cause of the large amplification of the long-period ground motions by a factor of more than 10 in the coastal area of Osaka Bay from the bedrock site was investigated. To determine the amplification mechanism of the long-period ground motions in the Osaka and Nobi Basins, the 3D finite difference (FD) method was used to analyze the wave propagation incorporating an arbitrarily heterogeneous geologic structure.

The 3D FD method requires a large amount of computational time and storage for the simultaneous consideration of the rupture of the seismic faults during the 2011 Tohoku earthquake and the detailed geological modeling of the Osaka Plain. Therefore, the sedimentary basin-like structure of the Osaka and Nobi Plains in Fig. 4 is considered assuming that the incident wave field from the epicenter of the 2011 Tohoku earthquake comprises horizontal planar waves; this assumption is based on a preliminary full 3D FD calculation with a coarser grid spacing.



(a) Osaka Plain (b) Nobi Plain

Fig. 4. Contours of bedrock depths for Osaka and Nobi Plains. The rectangular block outlined with a broken line is the model region of the 3D FD calculation. The cross sections below show the 2D configurations of the subsurface structures passing through B-SKS and UKI-U with the depth scale magnified by a factor of 5.

Table 1. Soil profile for FD model of Osaka Plain

No.	V_S (km/s)	V_P (km/s)	ρ (t/m^3)	Q values
Sedimentary layer 1	0.4	1.62	1.77	80
Sedimentary layer 2	0.5	1.79	1.80	100
Sedimentary layer 3	0.6	1.91	2.00	120
Sedimentary layer 4	0.7	2.01	2.05	140
Sedimentary layer 5	0.8	2.12	2.07	160
Sedimentary layer 6	0.9	2.28	2.10	180
Sedimentary layer 7	1.0	2.43	2.15	200
Sedimentary layer 8	1.1	2.59	2.20	220
Sedimentary layer 9	1.2	2.75	2.25	240
Seismic bedrock	3.2	5.40	2.70	640

The contours of the bedrock depths in the Osaka and Nobi Plains are shown in Fig. 4. The geological model was obtained from reports compiled by the Osaka Municipal Government (2004) and provided by the Headquarters for Earthquake Research Promotion in Japan and Horikawa et al. (2008) for the Osaka and Nobi Plains, respectively. Sediments existing around the main elliptical region of each sedimentary basin were trimmed and replaced by bedrock. As an example, the soil profile for Osaka Plain is given in Table 1. The sediments on the seismic bedrock were categorized into more than nine layers. The minimum shear wave velocity was 0.4 km/s for the top sedimentary layer.

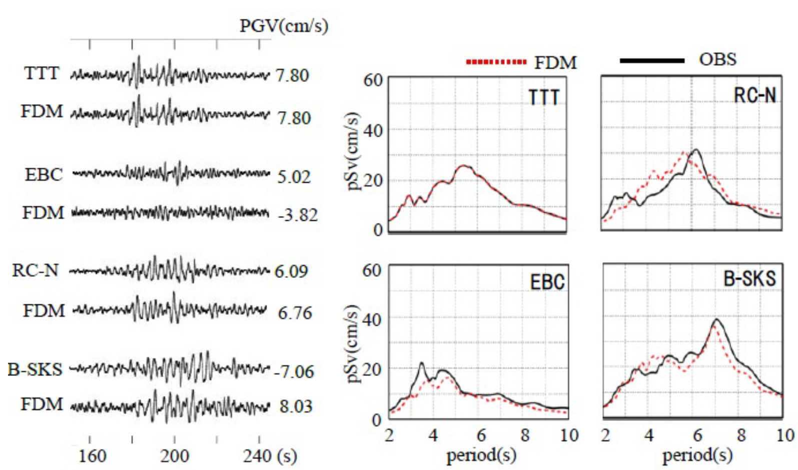
The rectangular block outlined with a broken line in Fig. 4 is the model region for the 3D FD calculation. The region is inclined counterclockwise by 35° or 30° with respect to the wave field traveling from the epicenter of the 2011 Tohoku earthquake to the Osaka Plain. The SH-wave was applied at the left edge of the region in the form of the lateral slip of a vertical fault. A numerically efficient FD technique combining nonuniform and discontinuous grid spacings (Nagano, 2003) was used for the 3D wave propagation analysis. The entire soil region was divided at 5.5km in depth into two regions modeled by different nonuniform grid spacings. In the top region, small areas in the Osaka and Nobi Plain areas (minimum S-wave velocity: 0.4 km/s) have a grid spacing of 150 m in the horizontal directions and 100 m in the vertical direction, allowing the propagation of a seismic wave component with a period of more than 2 s. The remainder of the top region and the entire bottom region have a 750-m grid spacing, which is five times that of the horizontal directions of the finer grids.

The cross sections underneath the contours in Fig. 4 show the 2D geological configurations through B-SKS in the N55°E direction in the Osaka Plain and through YKI-U in the N60°E direction in the Nobi Plain. The 2D cross section model used the same region and grid spacings as the 3D analysis to determine the effect of 3D geology on ground motion amplification.

4. Validation of Ground Motion Simulation During 2011 Tohoku Earthquake

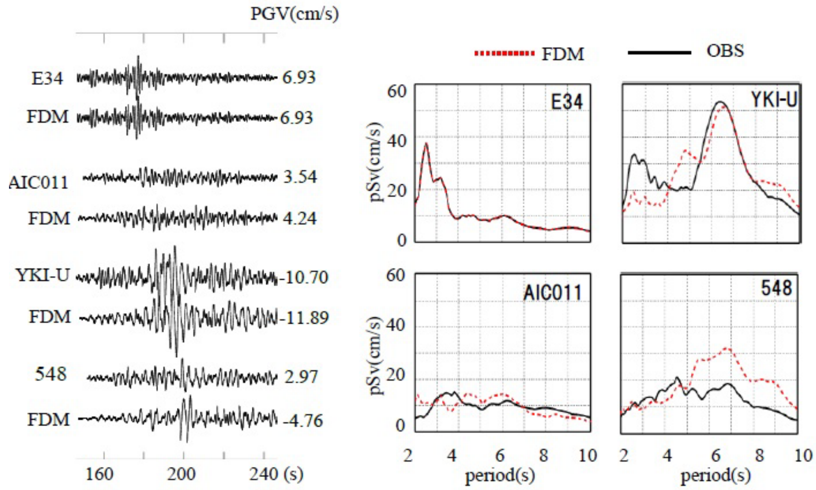
Ground motions during the 2011 Tohoku earthquake in the Osaka and Nobi Plains were synthesized using the 3D FD method. First, a combination of the Ricker wavelets with predominant periods of 6 and 3 (or 2.5) s was used as the horizontally incident SH-wave. In the Osaka Plain, the incident wave was defined such that the velocity waveform rotated in the N325°E direction was identical to that at TTT using convolution operations in the frequency domain. The same procedure was applied to the Nobi Plain case, where the incident wave was defined such that the velocity waveform rotated in the N330°E direction was identical to that at E34. All observed and synthesized ground motions were bandpass filtered from 2 to 10 s.

Synthesized velocity seismograms at four sites in Fig. 4 are shown in Figs. 5(a) and 6(a) in the target directions during the 2011 Tohoku earthquake. The ${}_{P}S_{V}$ (h = 5%) of the calculated motions and those of the observed ground motions are shown in Figs. 5(b) and 6(b). As expected, the observed velocity seismograms at TTT and E34 were the same as those obtained using the FD method because the incident waves in the calculation were specified to match those observed at the sites.



(a) Velocity waveforms (b) ${}_{P}S_{V}$(h=5%)

Fig. 5. Synthesized velocity seismograms and comparison of observed and calculated ${}_{P}S_{V}$ in the N325°E direction at four sites in the Osaka Plain during the 2011 Tohoku earthquake.



(a) Velocity waveforms (b) $_{P}S_{V}$(h=5%)

Fig. 6. Synthesized velocity seismograms and comparison of observed and calculated $_{P}S_{V}$ in the N330°E direction at four sites in the Nobi Plain during the 2011 Tohoku earthquake.

As shown in Fig. 5, in the Osaka Plain, the synthesized and observed ground motions were small at EBC, which is located east of the Uemachi fault, because of the constraining effect of the blind thrust-type fault bedrock (Fig. 3). At RC-N and B-SKS passing through the Uemachi fault, the ground motions were amplified in the thick sedimentary region; this amplification was well reproduced in the 3D FD analysis. The velocity response spectra at these three sites were also consistent with those of the observed motions. The good agreement between the calculated and observed ground motions at B-SKS indicates that the ground motions were largely amplified because of the 3D effect of wave interference in the elliptical subsurface structure of the Osaka Plain.

As shown in Fig. 6, in the Nobi Plain, the observed ground motions were also well simulated by the 3D FD analysis in terms of not only the temporal phase characteristics of the ground motions but also their predominant periods. The ground motions at YKI-U were largely amplified and were well reproduced by the FD calculation.

Other sites close to cross sections A–A′ and B–B′ (Fig. 4) were also tested, and the calculation and observation results were found to be in good agreement, demonstrating the validity of the assumption of planar wave incidence.

The following sections focus on the amplification characteristics of ground motions in the Osaka Plain using pulse-type incidence and present a detailed investigation of the 3D geological effects.

5. Long-Period Ground Motion for Pulse-Type Incidence in Osaka Plain

A pulse wave was applied as a horizontally incident SH-wave impinging at the left edge of the region. A Ricker wavelet with a predominant period of 6 s was used, based on the response spectra at Osaka Bay sites during the 2011 Tohoku earthquake (Fig. 3). The waveforms of soil responses in the N335°E direction at the 10 sites in Fig. 2 are shown in Fig. 7.

The peak values normalized by peak pulse amplitude at the sedimentary sites were larger than those at the bedrock site OSKH04 by a factor of 3–4. Later phases that prolonged the duration of motions are noticeable, as a consequence of the trailing surface waves induced at the thrust-type discontinuity between the rock and sediments at the Ikoma and Uemachi faults. At EBC, which is located at the tip of the Uemachi fault, the amplitude of the soil response was small because the sediment thickness was small and the traveling wave tended to be reflected or defocused in the surrounding thick sediment area. From the Uemachi fault to the coastal sites, the soil responses were again amplified because of the blind thrust-type discontinuity between the rock and sediments of the Uemachi fault. At the coastal sites, B-SKS and OSKH02, the amplitude and duration were large because of the surface waves.

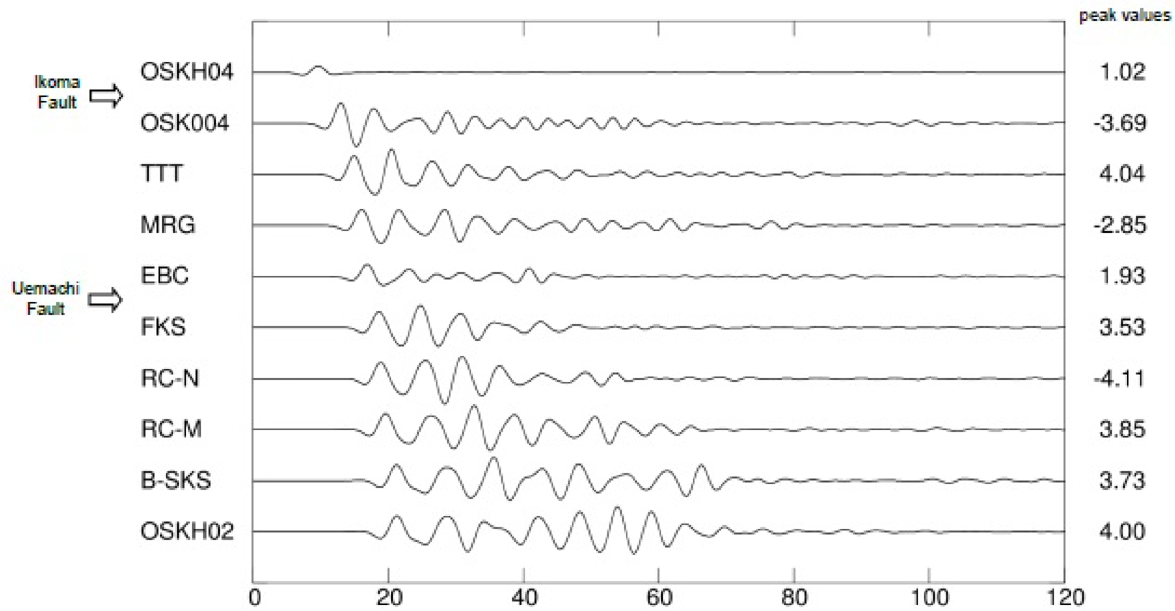


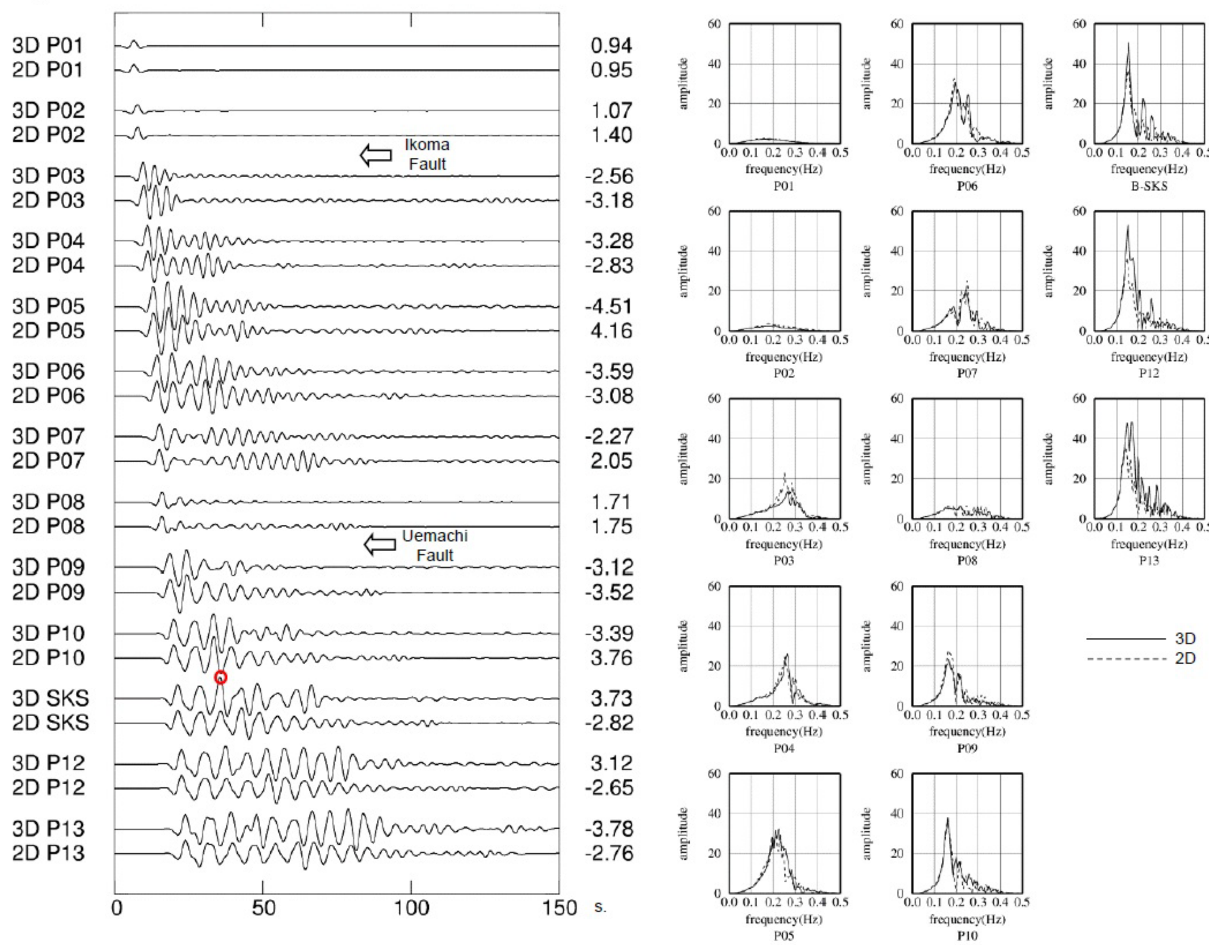
Fig. 7. Waveforms of soil responses in the N325°E direction at 10 sites in the Osaka Plain for Ricker wavelet incidence. Peak values are normalized by peak pulse amplitude.

6. Three-Dimensional Effect of Ground Motion Amplification

To elucidate the 3D effect of the ground motion amplification in the Osaka Plain during the 2011 Tohoku earthquake, the horizontally arrayed sites were selected such that they passed through B-SKS in the N55°E direction, and the soil responses at these sites were investigated under Ricker wavelet incidence. FD calculations were also performed for the hypothetical 2D model through B-SKS in Fig. 4(a) to determine the 3D effects of wave propagation. The calculation conditions, grid spacing, time increment, location of the seismic fault, and incident wave were the same as in the 3D case described above to avoid numerical errors due to dispersion. A Ricker wavelet with a predominant period of 6 s was used as the incident SH-wave.

The calculated waveforms in the 3D and 2D soil response at 13 sites in the N325°E direction are shown in Fig. 8(a). The selected sites were located at intervals of 0.4 km in the N55°E direction, including B-SKS as the 11th site. P01 is located in the bedrock area, and the soil response at this site was almost identical to the incident Ricker wavelet. P03 is located in the sedimentary site adjacent to the Ikoma fault, and the amplitude of the soil response increased at this site. P08 is located at the tip of the blind thrust of the Uemachi fault. Passing through the Uemachi fault, the amplitude of the soil response is again amplified, and the response durations were prolonged by secondary induced waves at the Uemachi fault. Differences between the 3D and 2D responses were negligible from P01 to P09. However, from B-SKS to P13, the peak amplitudes of the 3D response were noticeably larger than those of the 2D response. At P12 and P13, the amplitudes of the later phases of the 3D response were also larger than those of the 2D response.

Differences between the 3D and 2D responses are also observable in the amplitude spectra of the Fourier transform of the ground motions, as shown in Fig. 8(b). From P01 to P10, the amplitude of the 3D response at 6 s (0.17 Hz) was almost identical to that of the 2D response. At B-SKS, P12, and P13, the Fourier amplitudes of the 3D response at 6 s were larger than those of the 2D response. These results indicate that the amplification of the long-period ground motion at B-SKS is augmented by the 3D effect of the wave propagation in the elliptical shape of the Osaka Plain.



(a) Calculated waveforms (b) Fourier amplitude spectra

Fig. 8. Comparisons of 3D and 2D synthesized seismograms and amplitude spectra of the Fourier transform for Ricker wavelet incidence.

To clarify the 3D wave propagation characteristics in the Osaka Plain, contours of the soil response amplitude in the N325°E direction are shown at several time steps as snapshots in Fig. 9. The first pulse traveled into the Osaka Plain at *t* = 10.8 s. The wave propagated into the sedimentary layers at *t* = 16.2 s and was amplified at the edge of the Ikoma fault. Next to the Uemachi fault, the response amplitude was reduced because of the constraining effect of the blind thrust-type fault bedrock. The first positive pulse reached B-SKS at *t* = 21.2 s, passing through the machi fault. The observed first and second positive pulses were in fair agreement with those obtained in the 2D analysis at B-SKS (Fig. 8). The third pulse with a large amplitude occurred at *t* = 34.8 and 37.8 s in the positive and negative directions, respectively. The peak at 34.8 s is indicated by an open red circle in the 3D B-SKS waveform in Fig. 8(a). At these times, the amplifying area was small and limited partly by the concentration of multiple passing waves in a very small area around B-SKS as a result of the 3D effect. The trailing wave groups reached B-SKS, and the surface wave was reflected within the central part of the Osaka Plain.

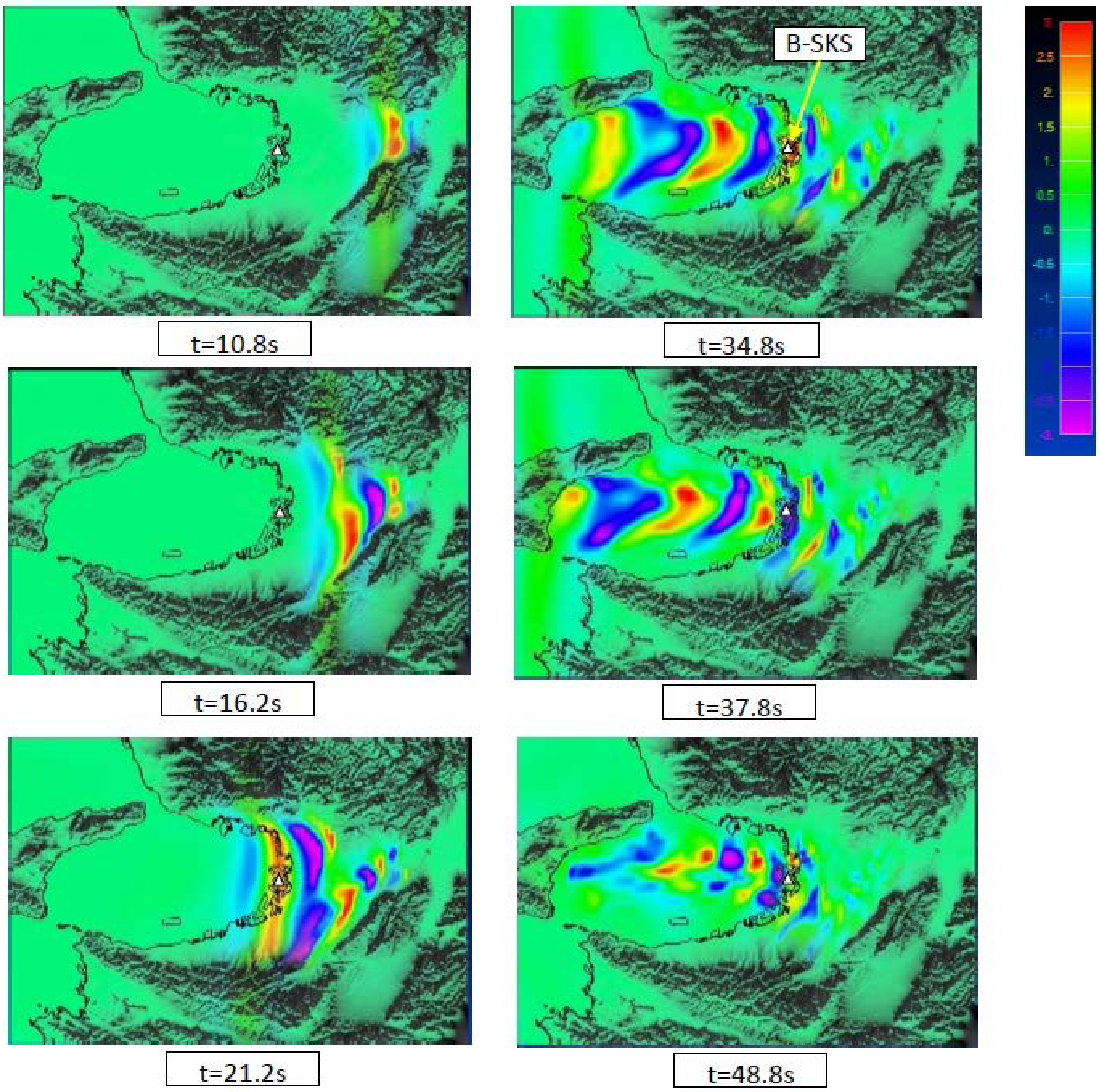


Fig. 9. Snapshots of wave components in the N325°E direction for Ricker wavelet incidence. The open triangle indicates the location of B-SKS.

7. Conclusions

The anomalous amplification of long-period ground motions in the Osaka and Ise Bay areas in the western part of mainland Japan during the 2011 Tohoku earthquake were investigated in this study. The contours of the peak values of the $_{P}S_{V}$ (h = 5%) in the Osaka and Nobi Plain areas indicate the local anomalous amplification of long-period ground motions in coastal sites. This can only be explained by the targeted amplification of the long-period ground motions within the sedimentary layers of the Osaka and Nobi Plains. The increase in the response spectra at sites in the Osaka Bay area is significant, and the long-period components (approximately 6–7 s) of the spectra were amplified by a factor of more than 10 compared with those at the bedrock site.

To elucidate the cause of this remarkably large response in relation to the input motion of a building, this paper addressed the amplification of the long-period ground motions in sedimentary basin-like geology of the Osaka and Nobi Plains in the Osaka and Ise Bay areas during the 2011 Tohoku earthquake.

The amplification of the long-period ground motions in the Osaka and Ise Bay areas was investigated using the 3D FD method for wave propagation analysis considering the 3D geological subsurface structures of the Osaka and Nobi Plains assuming that the incident wave field from the epicenter of the 2011 Tohoku earthquake was equivalent to horizontal planar wave. The velocity seismograms and response spectra of the 2011 Tohoku earthquake were well reproduced by the FD calculation in terms of both the amplitude and phase.

The amplification mechanism of the long-period ground motions was investigated in detail focusing on the wave propagation in Osaka Plain. The 3D effect of the ground motion amplification in the Osaka Plain was compared with the results of the 2D model using soil responses at horizontally arrayed sites under Ricker wavelet incidence. At sites in the Osaka Bay area, the peak amplitudes of the 3D response waveforms and their Fourier amplitude were larger than those of the 2D response. Snapshots of the wave components reveal that the third pulse had a large amplitude because of the constructive interference of the multiple passing waves in the 3D structure in the Osaka Bay area. The large amplification of the ground motions was caused by the 3D effect of the wave interference in the elliptical subsurface structure of the Osaka Plain.

8. Acknowledgements

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