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A STUDY ON THE LONG PERIOD GROUND MOTIONS OBSERVED IN OSAKA BAY AREA

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Abstract

Through the 2011 off the Pacific coast of Tohoku earthquake, large long period ground motions were observed in Osaka bay area and high-rise building with natural period around 7 seconds suffered considerable damage. In the area, strong ground motions with accelerometers at ground surface and in bedrock at 2000m deep were observed. The spectral amplitude ratio between the two sensors at around 6 seconds was about 50 times. The same phenomena were observed at the site through the 2000 western Tottori earthquake and the 2004 off the Kii peninsula earthquake.

The bedrock depth at the site is estimated as 1550 m from previously conducted geophysical surveys. Predominant period of ground motions in Osaka bay area has been assumed about 6 seconds due to the thick sedimentary structures.

From minute analysis of the data, it is found that amplitude ratios are smaller in beginning portions of the record, while the ratios grow larger with elapsed times. Amplification ratios in the beginning are around ten times that can be explained from sedimentary responses of vertical incident body waves. However, ratios in the later part are around several tens and it might be caused by node and antinode of surface waves at observed points. The results suggest that the large amplitude long period waves might affect on other thick sediment area even by distant earthquakes.

Keywords: Long period ground motion, Osaka bay area, The 2011 off the Pacific coast of Tohoku earthquake

1. Introduction

Osaka bay area locates at almost center of Osaka sedimentary basin that consists of Osaka plain and Osaka bay. The basin structure has been studied by compiling geophysical investigation data (e.g. Kagawa et al. [1] and Iwata et al. [2]). The maximum depth of bedrock is over 3000 m at eastern part of the Osaka bay and the thickness of the sediment along Osaka bay side is estimated as 1600 to 2000 m.

In and around the Osaka bay area, long period ground motions with predominant period around 6 seconds have been observed through the past magnitude 7 class earthquakes with hypocentral distance around 200 km, for example the 2000 western Tottori earthquake, Mj7.3 and the 2004 off the Kii peninsula earthquake, Mj7.4. The 2011 off the Pacific coast of Tohoku earthquake, Mw9.0 generated large long period component and they propagate efficiently as surface waves and arrived to the Osaka bay area after over 500 km travel. Ground motions with period around 6 to 7 seconds were amplified in the area (Sato et a. [3]) and one high-rise building with natural period around 7 seconds vibrated sympathetically and suffered remarkable damage (Building Research Institute [4]), despite no other sufferings were reported in the area.

In the Osaka bay area, KiK-net (Aoi et al. [5]) observation site OSKH02 operated by National Research Institute for Earth Science and Disaster Resilience (NIED) has recorded strong ground motion at ground surface and in bedrock (see Fig.1). The spectral amplitude ratios between the sensors at two different depths were about 30 times at period around 6 seconds through the three earthquakes. The predominant period 6 seconds can be explained by bedrock depth 1550 m estimated at the site. The amplification ratio 50 times, however, is significantly larger than theoretical amplification ten times expected by sedimentary responses of vertical incident body waves using previously provided velocity structure model (Kagawa et al. [1]).

In this paper, through minute analysis of the observed data at OSKH02 and other strong ground motion sites with previously estimated velocity structure model, the cause of large amplification at period around 6 seconds between bedrock and ground surface is illustrated.

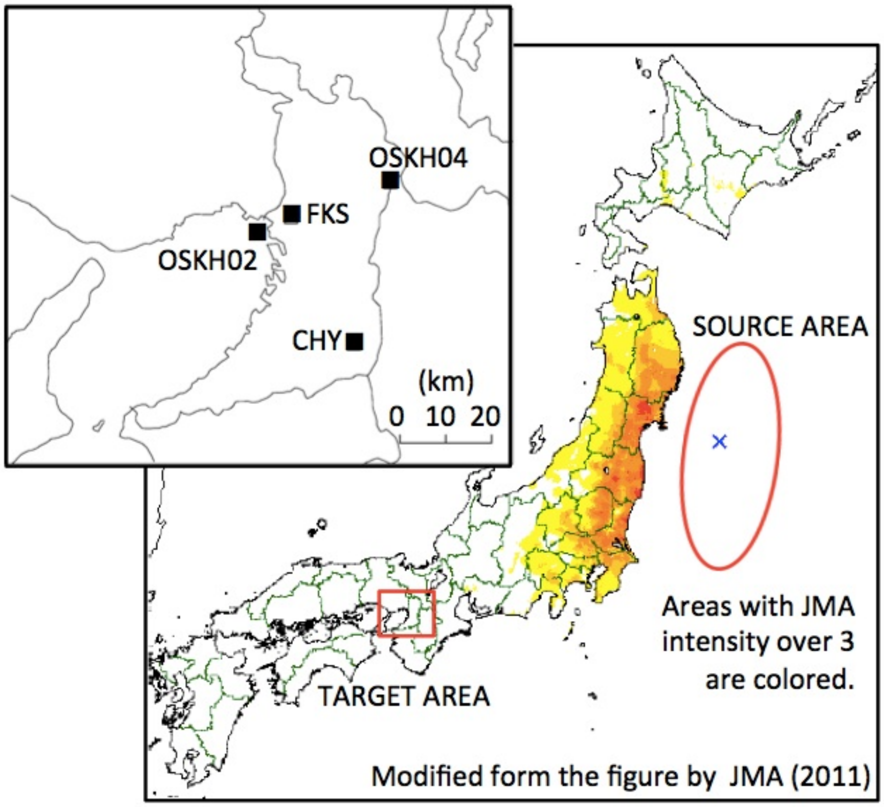

Fig. 1 Target area and source area of the 2011 off the Pacific coast of Tohoku earthquake
Sites treated in this study are indicated in the top left panel.

2. Observed long period ground motions in the Osaka bay area

2.1 Large long period ground motion in the Osaka bay area

Strong ground motions generated by the 2011 off the Pacific coast of Tohoku earthquake, Mw9.0 were felt in the Osaka bay despite of long propagating distance over 500 km. Velocity type seismometers (Kagawa et al. [6]) recorded several tens minutes waveforms in the area. Velocity waveforms and relative velocity response spectrum with damping 0.05 at mountain area (CHY) and sedimentary site (FKS) are shown in Fig.2. FKS site locates about 5 km inside from bay side. Ground motion at CHY dominates in very long period component over 20 seconds and waveforms at FKS have detailed vibrations with large amplitude that are indicated by spectral peaks around 6 seconds in the response spectrum.

Fig. 3 shows as same panel as Fig.2 but for KiK-net site OSKH02 located at reclaimed island in Osaka bay area. The observed accelerograms are integrated into velocity traces to emphasize long period components. Original acceleration waveform is provided by NIED but its duration is limited below 300 seconds. From the waveforms in Fig.3, however, it can be seen that main portion of large wave packets are well recorded comparing those with the wave traces at FKS site close to OSKH02 site. Response spectra at the two sites have almost common predominant characteristics, and OSKH02 has larger peaks than that at FKS site. It can be concluded that the record at OSKH02 has enough duration time to discuss large amplitude component around 6 seconds in Osaka bay area. At KiK-net OSKH04 site in mountain area, acceleration waveform with duration around 300 seconds is provided, and its characteristics are almost same with that at CHY site. The record is used afterward in this study.

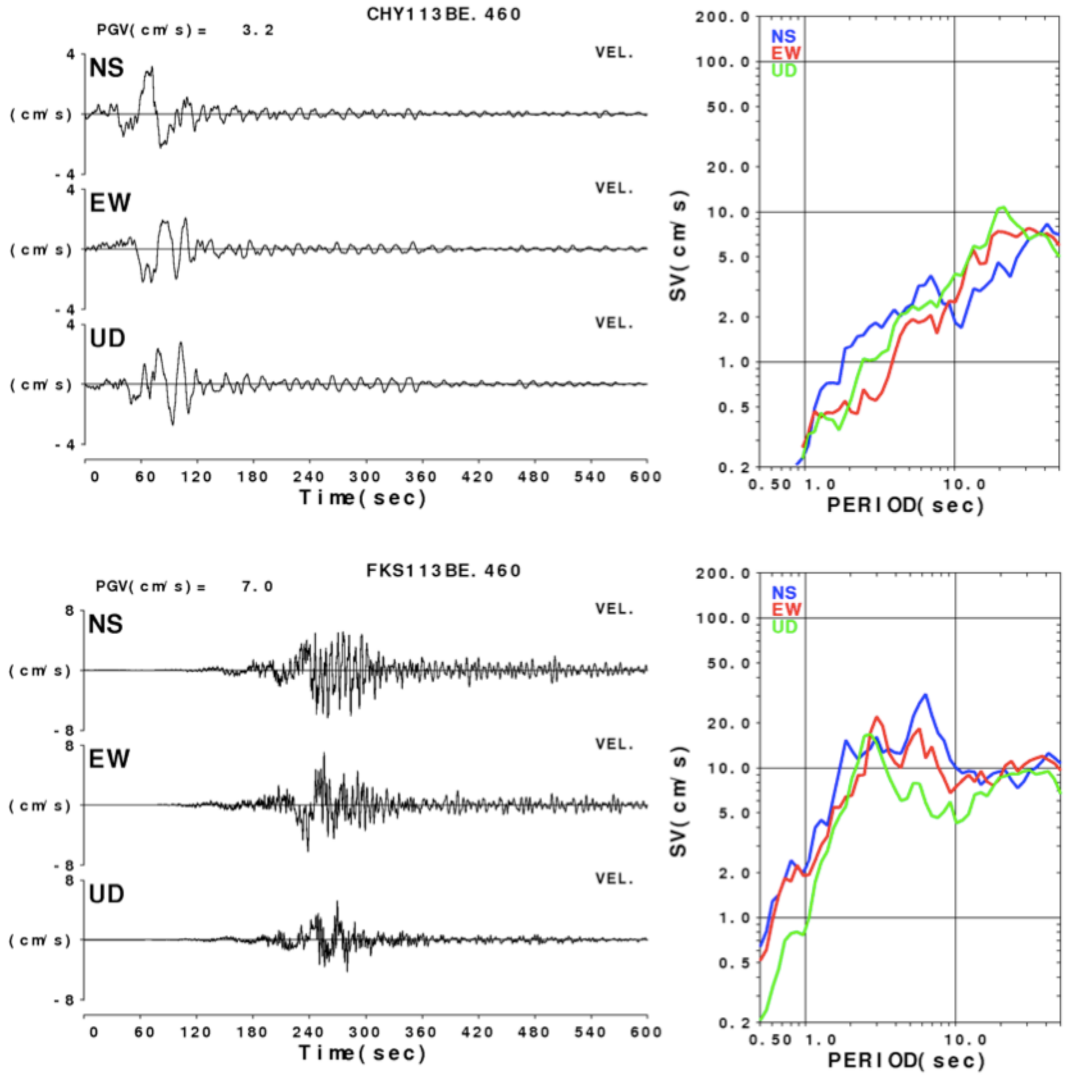

Fig.2 Velocity waveforms and relative velocity response spectrum with damping 0.05 at CHY (upper panel) and FKS (lower) sites

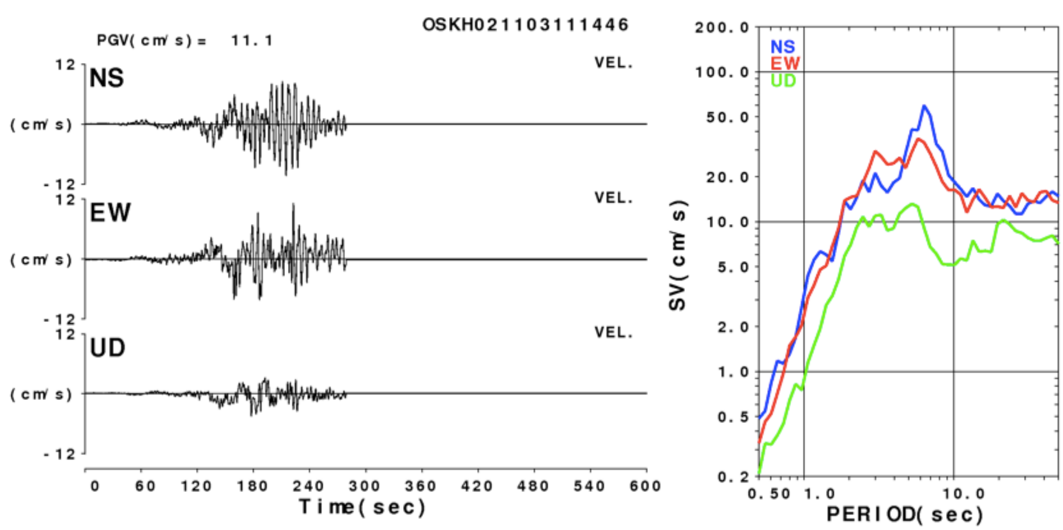

Fig.3 Same as Fig.2 but for KiK-net OSKH02 site

2.2 Spectral ratio between bedrock and surface at OSKH02 site

KiK-net sites have two accelerometers at ground surface and bottom in bedrock. OSKH02 site has bottom sensor at 2008 m depth. Spectral ratio between the two sensors through the 2011 off the Pacific coast of Tohoku earthquake is shown in Fig.4 in each horizontal component. Remarkable peaks around 6 seconds are detected in both components and its amplitudes are up to 50 times. Same phenomena are observed through other ground motions with reasonable amplitude in Osaka bay area. They are also indicated in Fig.4.

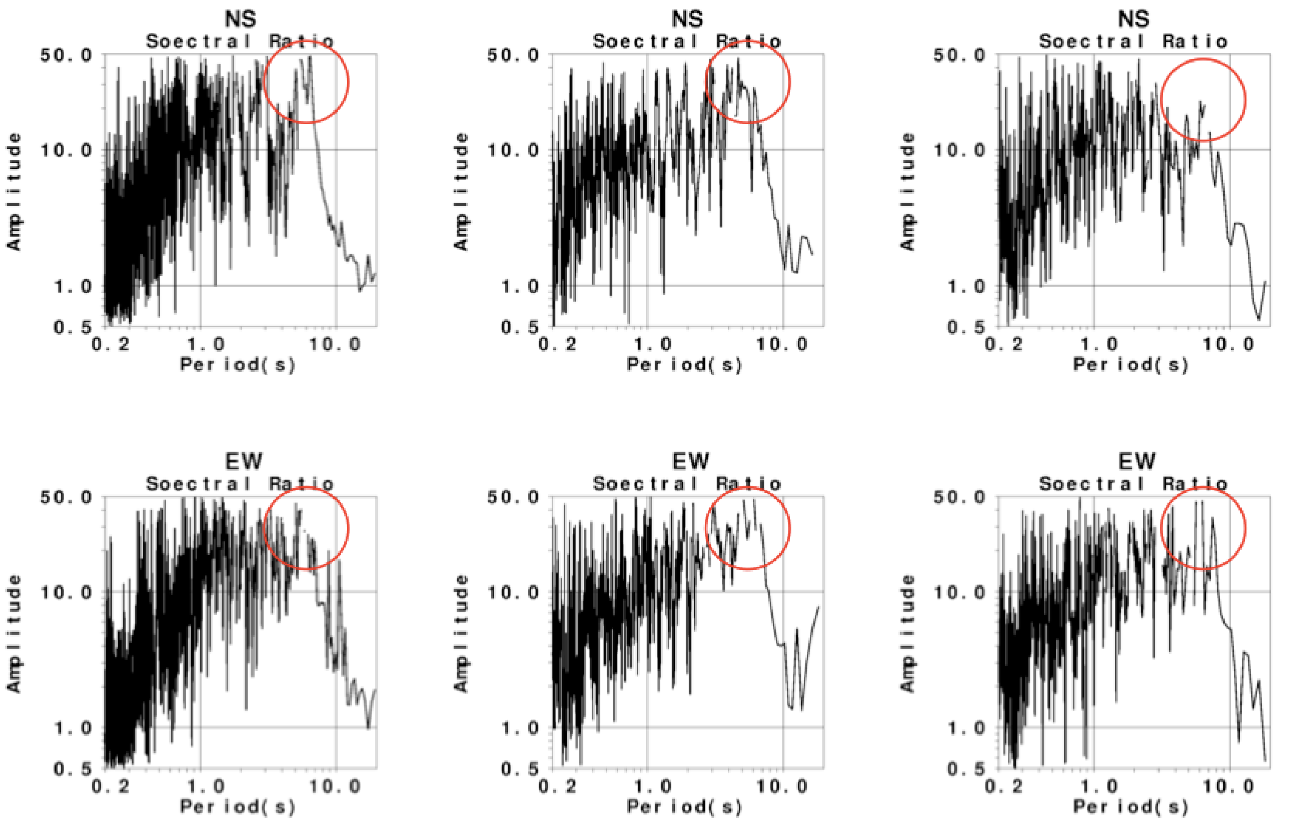

Fig.4 Spectral response between the two sensors, surface over bedrock in each horizontal component

Left: the 2011 off the Pacific coast of Tohoku earthquake, Mw9.0,
Center: the 2000 western Tottori earthquake, Mj7.3,
Right: the 2004 off the Kii peninsula earthquake, Mj7.4.

In the Osaka bay area, sedimentary structure models have been provided. Fig.5 shows granite bedrock depth distribution by one of those models (Kagawa et al. [1]). Bedrock depth 1550 m is estimated from the model at OSKH02 site. In the model, sedimentary deposits are divided into three layers ‘A’ to ‘C’ (Table 1), and depth of each boundary, $D_{A\text{-}B}$ and $D_{B\text{-}C}$ is assumed to be proposal to the bedrock depth, D_{BASE}. Proportional coefficients are estimated as 0.191 and 0.472 respectively for $D_{A\text{-}B}$ and $D_{B\text{-}C}$. Sediments are in alternate layers of sand and clay and their consolidation stages reflect velocity structure. In the table 1, shear wave velocities for layers ‘A’ and ‘B’ are slightly modified from original values (Kagawa et al. [1]) reflecting preliminary analysis for fitting observed site response at OSKH02 site.

From the velocity structure model above, site response between two sensors at ground surface and in bedrock, is estimated by multiple reflection theory in frequency domain (Thomson [7], Haskell [8]) as shown in left panel of Fig.6. Bottom seismometer of OSKH02 is installed at 2008 m depth inside bedrock since top of the bedrock is estimated as 1550 m. In the velocity model at OSKH02, two bedrock layers with same physical parameters are modeled, and the layer below 2008m is set as a half space. The response in the left panel of Fig.6 is calculated with vertical incidence plane SH wave as up-going wave (E) from half space. The amplification factor in the panel is calculated from ground surface response (2E) over input up-going wave only (2E). Maximum amplification factor from the theoretical estimation is around 5 times which is smaller than the observed one.

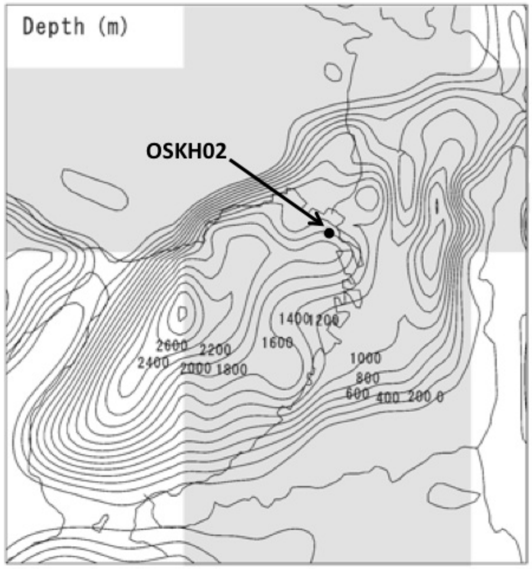

Fig.5 Bedrock depth distribution in Osaka sedimentary basin (Kagawa et al. [1])

Table 1 Velocity Structure model for each model layers (modified from Kagawa et al. [1])

	Top Depth(m)	Thickness(m)	Vs(m/s)	ρ (tf/m^3)	h (Q=vs/10)
A	0	298	400	1.6	0.013
B	298	434	700	1.8	0.007
C	732	818	1000	2.0	0.005
D	1550	458	3200	2.7	0.002
	2008	–	3200	2.7	0.002

3. An illustration of the large amplification between bedrock and surface

3.1 Effect of down going wave

Because the seismometer is installed in the bedrock, effect of down-going wave (F) should be considered. The right panel of Fig.6 is calculated considering both up-going and down-going wave (E+F). Maximum amplification factor becomes larger than that in the left panel and is around 20 times, however, it is not large enough comparing the observed amplification.

As for another approach, spectral ratio between ground surface records (2E/2E) at OSKH02 and rock site, OSKH04 in mountain area are estimated. The left panel of Fig.7 shows the result and average amplification factor around period 6 seconds is almost same as estimated from theoretical estimation of same wave propagating condition shown in the right panel of Fig.7 omitting a keen peak.

From the results above, considering down-going wave is necessary but is not enough for explaining amplification factors between surface and bottom seismometers at OSKH02.

3.2 Temporal change of the amplification

Previous discussions are based on body wave assumption that plane SH waves propagate vertically. Here more detailed examinations are applied. For next step, wave behavior on ground surface at OSKH02 is minutely examined. Fig.8 shows filtered displacement particle motions for every 30 seconds. Displacement waveforms after low pass filter are employed to emphasize long period component of propagating wave at the site. In the figure, large amplitude wave packets appear after 150 seconds of the record. And large amplitude portions dominate almost north-south direction as indicated by close ellipsoids. Also their up-down component is quite small. The waves are considered to propagate from east. It means that the dominated wave packets that are highly amplified at the surface of OSKH02 consist of Love waves. Love wave propagation in Osaka sedimentary basin has been observed and studied by previous research (e.g. Kagawa et al. [1], Iwata et al. [2], Sato et al. [3]) and they also support contribution of Love waves for long period waves propagate within the Osaka sedimentary basin.

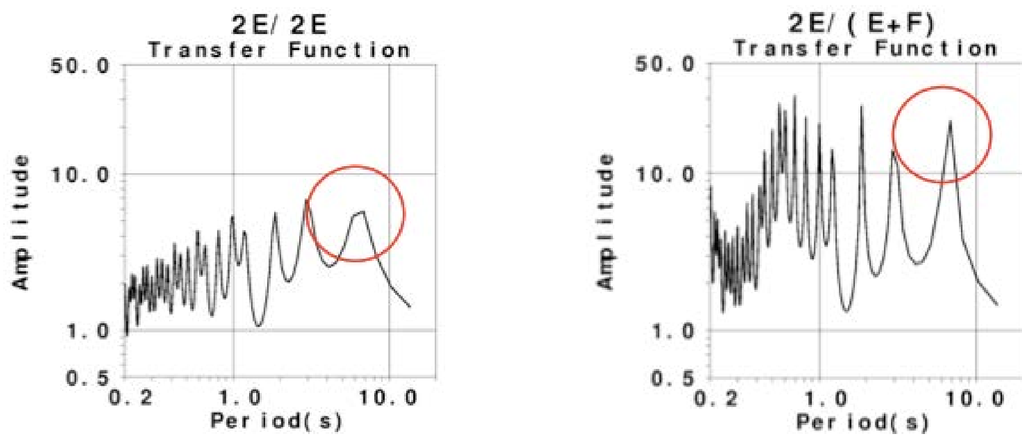

Fig.6 Theoretical site response between ground surface (2E) and at sensor location, 2008m at bottom sensor location, up-going wave (2E) is only considered (left panel), up-going and down-going waves (E+F) are considered (right panel).

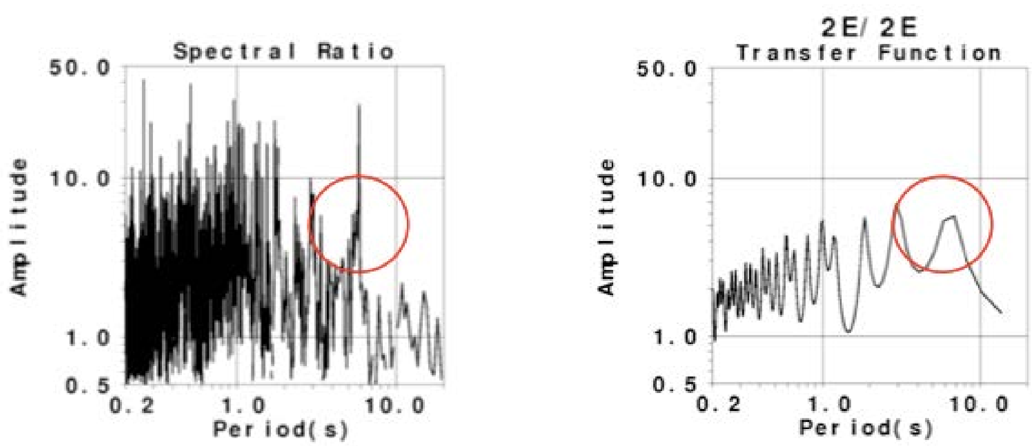

Fig.7 Spectral ratio of surface ground motions between OSKH02 and OSKH04 (left panel) and theoretical site response between ground surface (2E) and up-going wave (2E) at sensor location, 2008m (right panel)

Fig.9 shows moving spectral ratios between surface and bottom seismometers for each component. Fourier amplitude ratios from period 4 to 9 seconds are calculated every 2 seconds time interval using 20.48 seconds records. Plotted amplitude ratios are normalized within each component, and the darker the large amplitude is. From the figure, amplitude ratios in former 150 seconds before large Love wave arrival seems to be smaller than those after Love wave arrival. It is assumed that amplification between surface and bottom sensors at OSKH02 after Love wave arrival is affected by amplitude ratio of standing Love wave. On the other hand, it is assumed that body wave response is dominant before Love wave arrival.

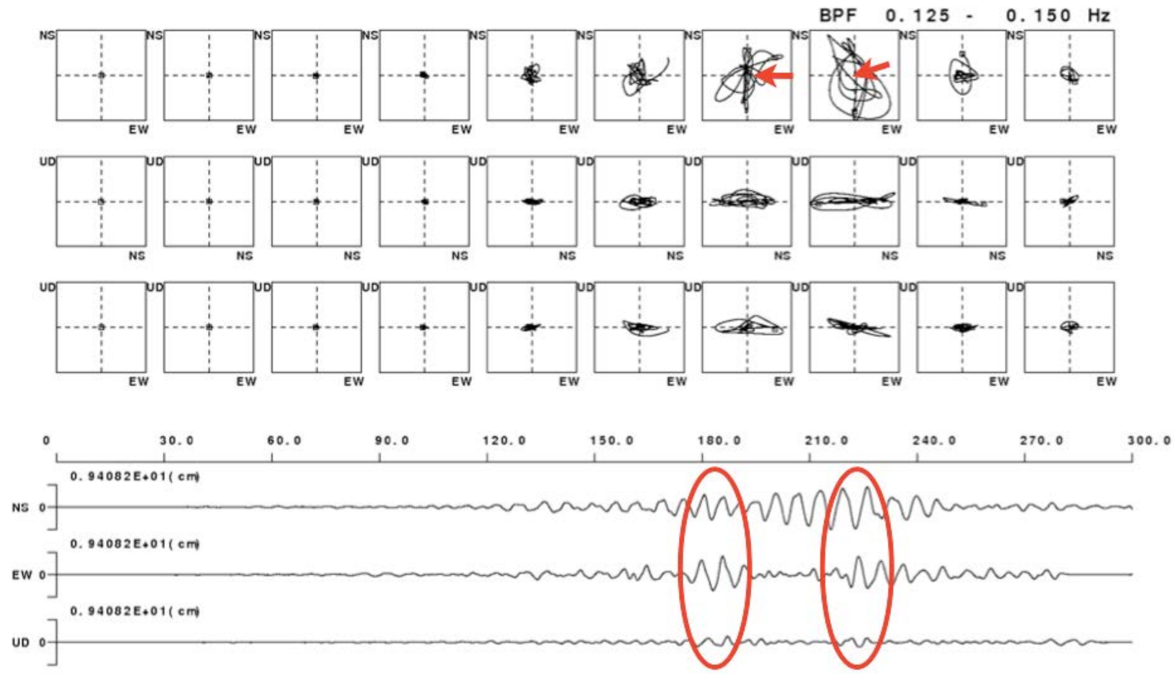

Fig.8 Particle motions of every 30 seconds from ground surface seismometer at OSKH02

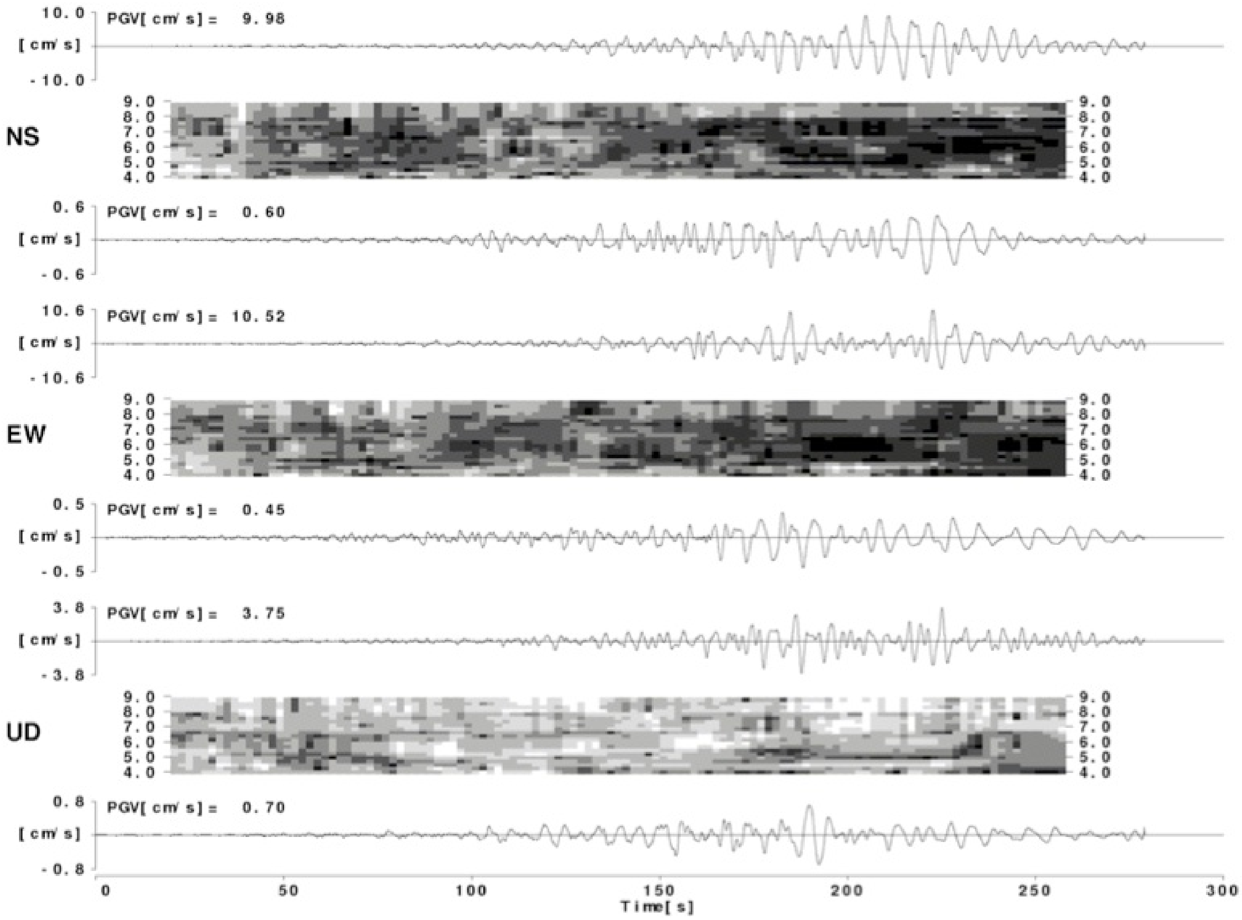

Fig.9 Moving amplification factors of every 2 seconds between surface and bottom seismometers at OSKH02

3.3 Amplification of standing Love wave

Fig.10 show spectral amplitude ratios between seismometer locations at surface and bottom for the portion before 150 seconds (before Love wave arrival) on left panel and for the portion after 150 seconds (after Love wave arrival) on right panel respectively. The predominant periods and amplitude levels before Love wave arrival are well explained by theoretical SH wave response as superimposed in the left panel, the response is same as the left panel of Fig.6. Spectral amplitude ratio after Love wave arrival is remarkably larger than that before Love wave arrival, and it is difficult to explain by body wave response.

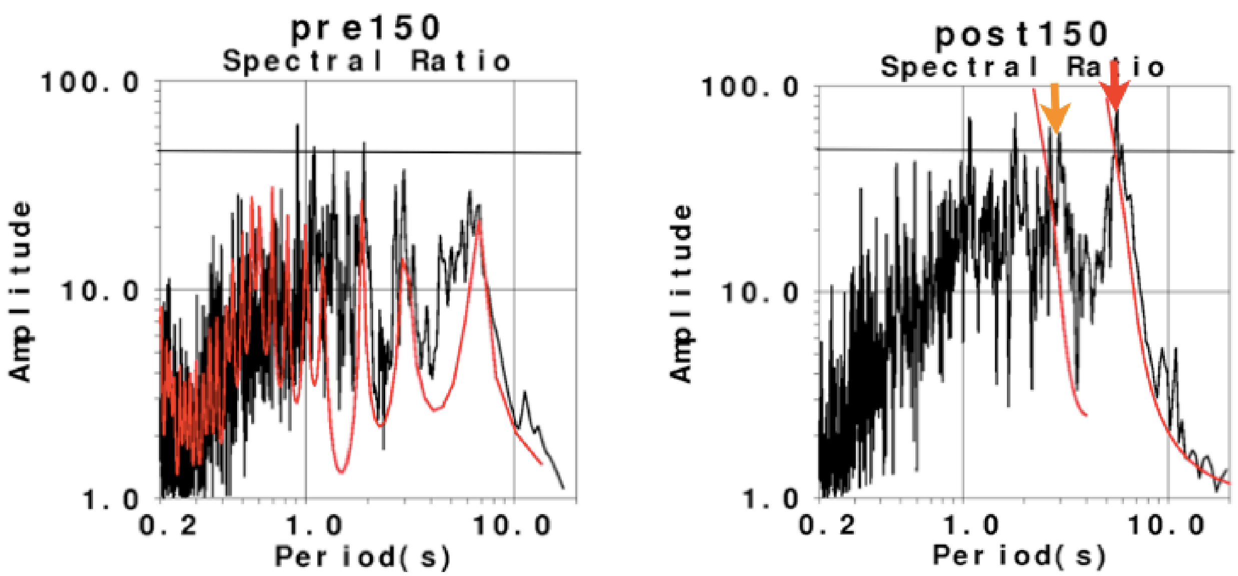

Fig.10 Amplifications of two different time portions and explaining theoretical responses with theoretical explanations

Left: Theoretical response by SH wave between two sensor locations (2E/E+F).

Right: Theoretical amplitude ratio of fundamental and first higher Love waves between two sensor locations, and tow arrows indicate airy phase periods of Love wave.

Fig.11 shows Love wave dispersion for fundamental and first higher modes. Solid lines indicate phase velocities and thin dash line shows group velocities. Thick dash lines are theoretical amplitude ratio of Love wave between seismometer locations at surface and bottom. The periods that give Airy phases for two Love modes are also indicated by vertical dash lines.

In the right panel of Fig.10, the theoretical amplitude ratios of Love wave in Fig.11 are superimposed. They agree well with observed amplification ratio despite that the amplification ratio over 50 times, and observed large amplifications are well examined by theoretical amplification of Love wave between surface and bottom seismometers in fundamental and first higher mode.

It suggest that vertical response of body wave, shear wave, is dominant in former portion of observed wave and it transmits to standing surface wave response after Love wave arrival. Observed amplification factor over 50 times between surface and bottom seismometers are well explained by the effect of standing Love waves.

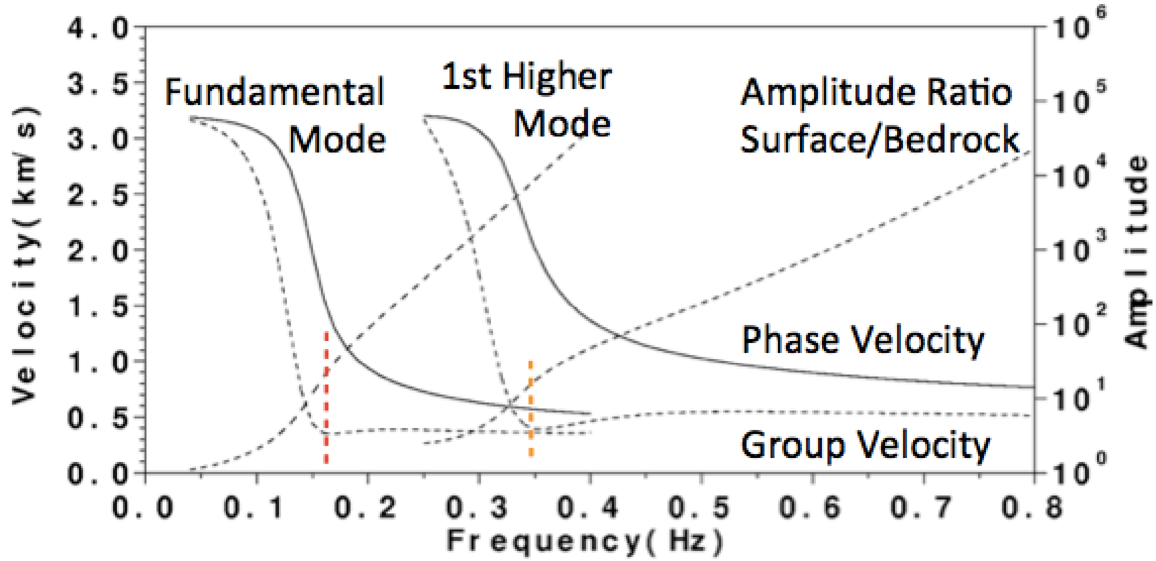

Fig.11 Phase and group velocities and amplitude ration between two sensor points at surface and bottom of fundamental and first higher Love waves

Airy phase periods for both modes are indicated by vertical dash lines.

4. Conclusion

Large amplification between seismometers between ground surface and bottom in bedrock have been observed in the Osaka bay area. Through the 2011 off the Pacific coast of Tohoku earthquake, large surface ground motion win period 6 to 7 seconds caused remarkable damage on high rise building in the area. Considering ground motions observed through the earthquake, the following results were obtained from this study.

1) It is difficult to explain the average amplification ratio about 50 times at predominate period from velocity structure model.

2) Amplification characteristics between ground surface and bedrock changed at the time when large amplitude surface wave arrived the site.

3) Site response before the surface wave arrival can be explained by body wave response by velocity structure at the site.

4) Amplification characteristics after the surface wave arrival agree well with the response of standing Love waves in fundamental and first higher mode in long period.

5) Amplification factor at predominant period over 50 times after surface wave arrival also can be explained by standing Love wave.

It is important to consider not only body wave response but also standing surface wave response for asesimic design of high-rise building with long natural period. And effect of deep sedimentary structure should be discussed before constructing structures with long natural period.

Acknowledgements

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