RISKY HIGH-RISE BUILDINGS RESONATING WITH THE LONG-PERIOD STRONG GROUND MOTIONS IN THE OSAKA BASIN, JAPAN

K. Miyakoshi[1] and M. Horike[2]

[1] *Earthquake Engineering Group, Geo-Research Institute, Osaka, Japan*
[2] *Professor, Faculty of Engineering, Osaka Institute of Technology , Osaka, Japan*
Email:ken@geor.or.jp

ABSTRACT :

The Osaka Basin, western Japan, is a typical sedimentary basin. It is composed of thick soft sediments with the maximum thickness of the sediments 3 km in the sea zone and 1.8 km in the plain zone. This geologic circumstance results in the prevalence of long-period (above 1sec) strong ground motions with long-lasting duration of several minutes in earthquake motions inside the basin. To mitigate earthquake damage to long natural-period structures due to the next M8 class interplate earthquakes, Nankai and Tonankai earthquake, we make the map of the predominant period of surface waves in the Osaka Plain by using the three-dimensional basin model. This map enables us to pick up high-rise buildings that may be resonant with the long-period strong ground motions, and to give a warning to reinforce them. We draw the conclusion that high-rise buildings in the height range between 150 and 300m are risky in the Osaka City, and the number of them was 16 in 256 buildings (about 6%).

KEYWORDS: Long-period strong ground motion, The Osaka Basin, Surface wave, Predominant period, High-rise buildings

1. INTRODUCTION

The Osaka Basin, western Japan, is a typical sedimentary basin, being surrounded all around by low mountains: Hokusetsu mountains in the north, Ikoma mountains in the east, Izumi mountains in the south, and the Awaji island in the west (Fig. 1). It is composed of the sea zone of the Osaka Bay in the west side and the land zone of the Osaka Plain in the east side and is elliptical in shape with the maximum axis-length of about 100 km and the minimum axis-length of about 50 km. Thick soft sediments cover all over the basin and the maximum thicknesses of the sediments are 3 km in the sea zone and 1.8 km in the plain zone.

Besides the geological feature of the Osaka Basin mentioned above, considering that Lg waves and the Love waves effectively propagate in the crust of the western Japan for relatively shallow earthquake events outside the basin (Furumura and Kennett, 2001), and because three-dimensional (3D) soft sedimentary basins such as the Osaka Basin effectively induces and transmits Love waves (Bard and Bouchon, 1980 and Horike et. al., 1990), long-period (above 1sec) ground motions prevail in horizontal earthquake motions with long-lasting duration of several minutes inside the basin (e.g., Hatayama et al, 1995).

Typical examples of large earthquake events, which generate long-period earthquake motions, are the interplate earthquakes of the 1944 Tohnankai earthquakes (M7.9) and the 1946 Nankai (M8.0). Historical literatures over about 1500 years reveal that these interplate earthquakes occurred repeatedly with the recurrence time of about 100 years. This allows predicting the next Nankai and the next Tonankai earthquakes with the probabilities of 50 % and 60 % over 30-year time span by the Headquarters for Earthquake Research Promotion. Meanwhile, because the whole plain is urbanized with huge populations of 13 million and there are a large number of high-rise buildings and reservoir tanks, the mitigation of earthquake disaster due to these earthquakes is a key issue to the national government as well as municipal government.

In general, it is possible to predict the damage level of an individual building from the dynamic analysis using simulated strong motions. Thus far, many attempts have been made to simulate long-period strong ground motions in the Osaka Basin for the next Nankai earthquake (e.g., Tsurugi et al, 2005, Kawabe and Kamae, 2005). However, for insufficient knowledge of the propagation-path and the earthquake source, it is difficult to compute reliable earthquake motions. Therefore, we undertake another approach to mitigate earthquake damage to long natural-period buildings due to the next interplate earthquakes.

Miyakoshi et al.(1999) or Yamada and Horike (2007) have already constructed the 3D subsurface structure model of the Osaka Basin. This allows computation of the predominant periods for Love waves everywhere in the basin, resulting in selecting risky high-rise buildings that may be resonant with long-period strong motions. Thus, the aim of this paper is to give a warning to high-rise buildings in the basin to strengthen them based on the judgment of the possibility of the resonance.

We first derive a common site-specific predominant period irrespective to the azimuth and the magnitude from recordings radiated from six earthquakes over the size of M5 which are located at the positions enclosing the basin. Then, we show that these predominant period are well fitted with computed peak periods (or Airy phase) of Love wave, using the 3D basin model. Finally, we pick out risky high-rise buildings resonant with long-period strong motions by comparing the natural periods of them with the predominant-period map of the Osaka Basin.

2. PREDOMINANT PERIOD OF LONG-PERIOD GROUND MOTION

We determined the predominant period of long-period ground motion observed at strong ground motion observation sites maintained by CEORKA (abbreviation of Committee of Earthquake Observation and Research in the Kansai Area) in the Osaka Plain. As velocity type seismometers are installed at CEORKA sites, long-period earthquake recordings longer than 5sec is reliable for spectral analysis. The epicenter, magnitude and focal mechanism of the earthquakes used in this study are shown in Fig.2. We selected six earthquakes over the size of M5, which surround the Osaka Basin, to show that azimuth produces little effect on the predominant period of surface waves.

The triangles show the CEORKA sites and contour lines show the bedrock (Vs=3.2km/s) depth (km) of the Osaka Bain model (Miyakoshi et al., 1999) in Fig.1. Example of velocity recordings for EQ.3 (see Fig.2) at site ABN is shown in Fig.3. Horizontal spectra for the six events at site ABN are shown in Fig.4. They were obtained by taking the root mean of the Fourier spectra for NS and EW components. The reverse triangles show the peak period of horizontal spectra in the period range from 1 to 10sec. We assumed that this peak period is a predominant period for each earthquake. We next show that the predominant period is possible to regard as the one inherent to a site.

As can be seen in Fig.4, the predominant periods for the six events are concentrated in narrow period range for 4 – 6sec, despite a wide range of the azimuth. Furthermore, we can see that they are not related to the magnitude. These features indicate that the predominant period is primarily controlled by the basin structure. Similarly, at the other CEORKA sites, the predominant period were determined irrespective of the azimuth and the magnitude. Thus, the above discussion indicates that the predominant period of long-period ground motions for earthquakes occurred outside the Osaka Basin is primarily controlled by the basin structure and is determined site-specifically.

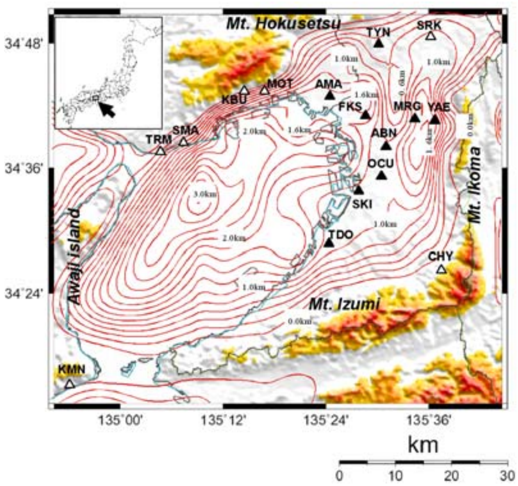

Figure 1 The Osaka basin, western Japan, model (Miyakoshi et al., 1999). Triangles showing locations of the strong ground motion observation stations maintained by CEORKA. Filled triangles denote CEORKA sites used in this study.

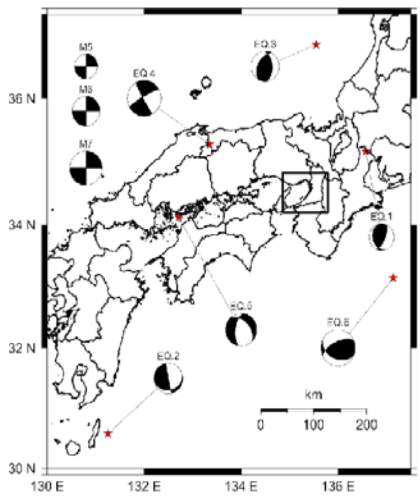

Figure 2 Map of epicenters (stars) of earthquakes used in this study (M_J > 5). Rectangle indicates study area for the Osaka basin.

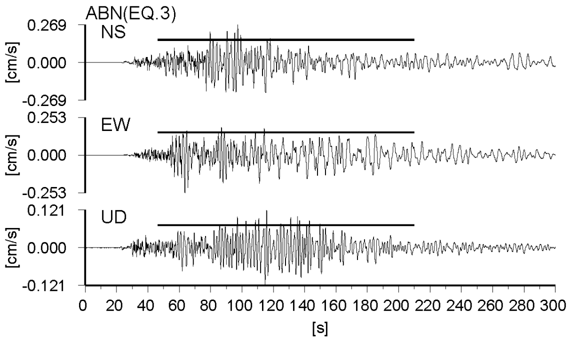

Figure 3 Example of the velocity seismogram recorded at site ABN for EQ.3. The records are band-pass filtered from 0.1 to 3Hz. Solid lines indicate the segment of the record (163.64 s) used for the spectral analysis.

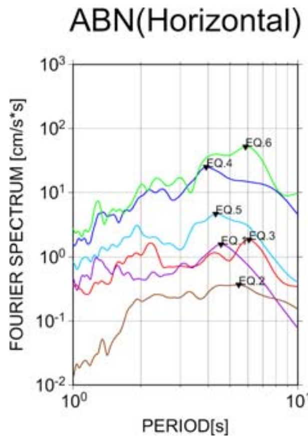

Figure 4 Fourier spectra of horizontal component for earthquakes observed at site ABN. Reverse-triangles indicate the predominant period for each earthquake.

3. MAP OF PREDONINANT PERIOD FOR LOVE WAVE

As mentioned previously, it is expected that the long-period ground motions are mainly composed of Love waves, generated by the incident Lg waves and Love waves in the Osaka sedimentary basin. Spectral amplitude of the Love wave is dominant at period where the group velocity becomes a minimum (Airy phase; e.g., Lay and Wallace, 1995). This indicates that the predominant period is determined from the dispersion curve of the Love waves. This idea is confirmed from well fitting of the period of the minimum group velocity with the peak period of the medium response (Harkrider and Anderson, 1966) at site ABN as shown in Fig.5. The computation of the dispersion curve and the medium response of the fundamental-mode of the Love wave were performed using the one-dimensional (1D) at site ABN derived from the 3D basin model (Miyakoshi et al., 1999). We used the same physical properties such as P- and S-wave velocities and densities for the four sedimentary layers in Osaka Basin as obtained by Kagawa et al. (2004).

To make a map of the predominant period for Love wave, we first divide the Osaka Plain into meshes with the size of about 1km×1km. Then, computing the dispersion curve for every mesh using 1D model, the predominant period is derived from the period of the minimum group velocity of Love wave at each mesh site. Finally calculated predominant period is spatially smoothed (arithmetic mean) using mesh points over a radius of the wavelength of Love wave in the area where the basement rock depth is deeper than 1.3km. Fig. 6 shows comparison of the smoothed predominant periods of Love wave (Cal.) with observed ones (Obs.) at CEORKA sites. Since we have confirmed that the calculated predominant period agrees with the observed one, we will draw the map of the predominant period of the Osaka Plain (Fig. 7).

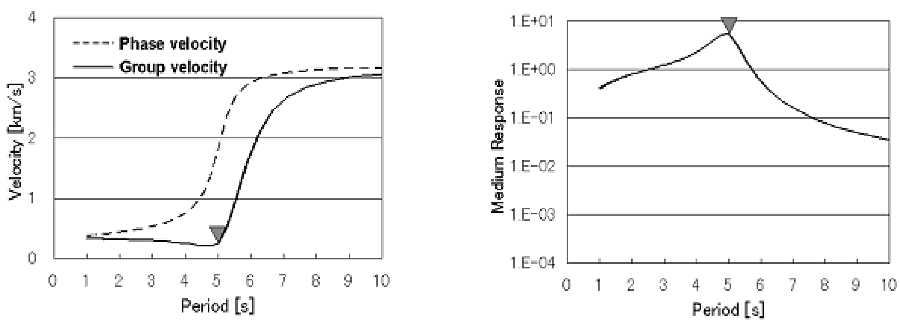

Figure 5 Examples of the theoretical dispersion curves (left) and the medium response (right) of the fundamental mode of Love wave, calculated for 1-D velocity model at site ABN extracted from the Osaka basin model (Miyakoshi et al., 1999). The theoretical dispersion curves are shown for the phase velocity (broken line) and the group velocity (solid line). Reverse-triangle denotes the period of the Airy phase (the minimum group velocity).

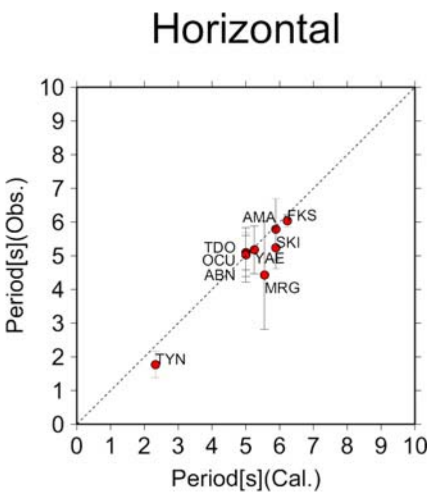

Figure 6 Comparison of the predominant periods of Love waves calculated for the 1-D velocity model at CEORKA sites (Cal.), with the observed ones (Obs.) for the horizontal component of the seismograms. Vertical bars denote the range of the standard deviation.

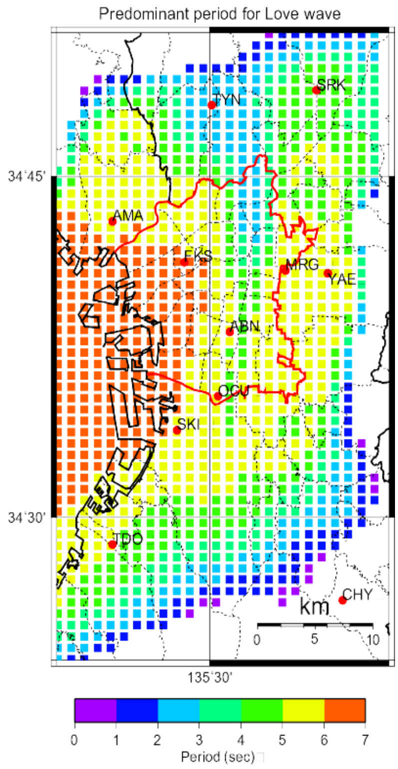

Figure 7 Map of the distribution of the predominant periods for Love waves in the Osaka plain. Red solid circles denote the strong ground motion observation stations maintained by CEORKA. Red solid line shows Osaka city boundary.

4. RISKY HIGH-RISE BUILGINGS IN THE OSAKA PLAIN

Map on Figure 7 provides useful information for repairing of existing high-rise buildings as well as for earthquake resistant design of new high-rise buildings. We attempted to pick up risky existing high-rise buildings, which may resonate with the long-period strong ground motion, using the map of predominant period of Love wave in the Osaka Plain. We made the database of existing high-rise buildings having the natural period of the fundamental-mode over 1sec in the Osaka Plain, compiling data from the Journal of the building letter published from 1995 to 2005. As the natural periods in the journal are given for two directions of minor and major axis of building, or NS and EW components, we choose the maximum value of the natural period within two directions.

The number of the buildings sums up to 256. The frequency distribution of high-rise buildings with natural period over 1sec is shown in Fig.8. The high-rise buildings with the natural period in period range for 1 – 3sec are over about 80%. The relationship between the natural period of high-rise building and building height is shown in Fig.9. The relationship between the natural periods in sec and building height in meter is almost linear, and its proportion coefficient is about 0.023. Though there are earthquake-resistant structures or response controlled (base-isolated or vibration controlled) structures in Fig.9, we have not distinguished both structures in this study.

The distribution of the natural period of high-rise buildings, on the map of the predominant period for Love wave in the Osaka Plain, is shown in Fig.10. The high-rise buildings are mainly concentrated in Osaka City area. Next we compared the natural period of the high-rise buildings with the predominant period of Love wave.

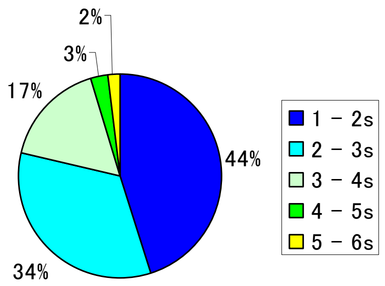

Figure 8 Frequency distribution of high-rise buildings having natural period over 1sec. Total number of the buildings is 256, picked up from the Journal of the building letter published from 1995 to 2005.

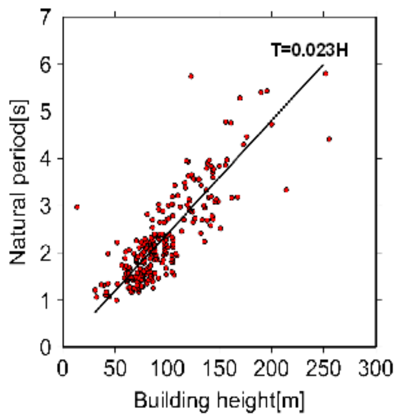

Figure 9 Relationship between the natural period of high-rise building (T) and building height (H) in the Osaka plain. Linear relationship with proportionality coefficient of 0.023 fit the data well.

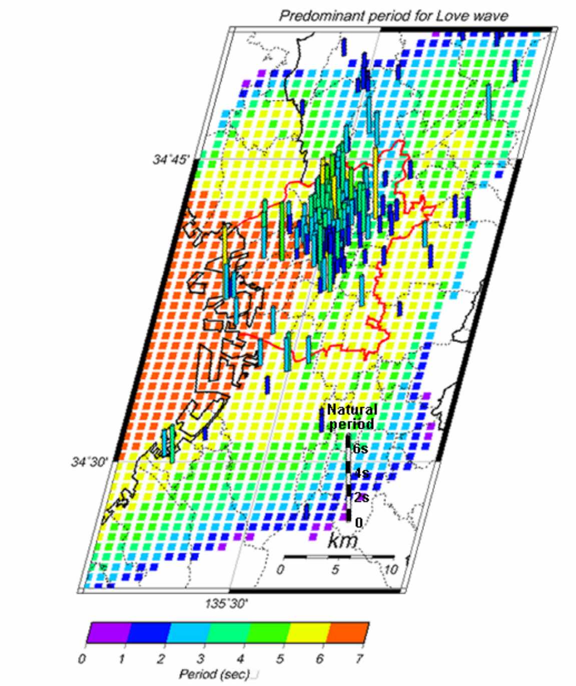

Figure 10 Distribution of the natural period of high-rise buildings on the map of the predominant period for Love wave. Red solid line shows Osaka City boundary.

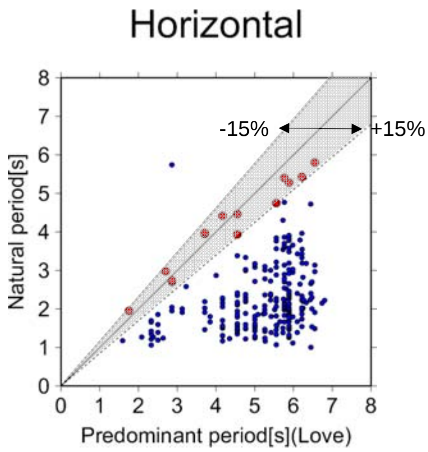

Figure 11 Relationship between the natural periods of high-rise building and the predominant period of Love wave. The high-rise buildings with the natural period almost equal to the predominant period of Love wave (the shaded zone; ±15%) are considered as the risky ones.

5. DISCUSION

The relationship between the natural period of the high-rise buildings and the predominant period of Love wave is shown in Fig.11. Most of natural periods of the high-rise buildings are shorter than predominant period of Love wave. Because the average of standard deviation for the observed predominant period of the long-period ground motion in this study is about 15%, we considered the high-rise buildings with the natural period within ±15% of standard deviation for the predominant period of Love wave (shaded zone in Fig. 11) as the risky ones. These buildings have possibility of the resonating of the swinging with the long-period strong ground motion. The number of the risky high-rise buildings was 16 in 256 buildings, and it is about 6%. The risky high-rise buildings have mainly been built around JR Osaka station, where the predominant period of Love wave lies in the range for 4 – 7sec. Referring to the relationship between the natural period and building height (see Fig.9), it is expected that the range of the height for the risky high-rise building is 150 – 300m, corresponding with the range of the predominant period for 4 – 7sec. These high-rise buildings may resonate with long-period strong ground motion excited by the damage earthquake of M7 – 8 classes.

6. RESULT

We determined the average predominant period of seismograms observed at the strong-motion observation stations, maintained by CEORKA (Committee of Earthquake Observation Research in the Kansai Area), in the Osaka Basin for six earthquakes over the size of M5, which occurred in western Japan. We also derived the predominant period of fundamental-mode Love wave from dispersion curves, calculated for 1-D velocity structure models extracted from the 3-D Osaka Basin model. The observed predominant periods show good agreement with calculated predominant periods smoothed by spatial window with radii of a wavelength for Love wave. Based on this result, we made a map of the predominant period of Love wave in the Osaka Plain.

Using the map of the predominant period for Love wave, we will attempt to pick up the risky high-rise buildings in the Osaka Plain, which have possibility of the resonating of the swinging with the long-period strong ground motion. The number of the risky high-rise buildings was 16 in 256 buildings in the Osaka Plain. The risky high-rise buildings have mainly been built in the Osaka City, where the range of the predominant period of Love wave is 4 – 7sec. Referring to the relationship between the natural periods of high-rise building and building height (proportion coefficient is about 0.023s/m), the range of the height for the risky high-rise building is 150 – 300m in Osaka City. Seismic strengthening is required for these high-rise buildings in Osaka City to resist the next M8 class interplate earthquakes, Nankai and Tonankai earthquake.

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