Importance of site-specific design ground motions and in-situ earthquake observation for design of infrastructures

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ABSTRACT

The earthquake resistant design of D-runway of Tokyo international airport was based on site-specific design ground motions, evaluated using records of small earthquakes obtained in-situ. Site-specific design ground motions are also required in the design standard for port facilities in Japan. The present article describes some important features of earthquake ground motions and explains how important it is to consider site-specific design ground motions in the design of infrastructures. The article also refers to the importance of in-situ earthquake observation for the quality control of design ground motions.

Key words: *earthquake observation, site effect, strong ground motion, earthquake resistant design, infrastructure*

1 INTRODUCTION

The earthquake resistant design of D-runway of Tokyo International Airport was based on site-specific design ground motions, evaluated using records of small earthquakes obtained in-situ. Site-specific design ground motions are also considered in the design standard for port facilities in Japan (OCDI, 2009). On the other hand, there are some design codes in Japan in which site-specific design ground motions are not required (e.g., Japan Road Association, 2002). The present article describes some important features of earthquake ground motions and explains how important it is to consider site-specific design ground motions in the design of infrastructures. The article also refers to the importance of in-situ earthquake observation for the quality control of design ground motions.

2 IMPORTANCE OF SITE EFFECTS

Generally speaking, strong ground motions are determined by three effects, namely, the source effect, the path effect and the site effect as shown in Figure 1. The source effect is defined as the effect of the rupture process of the earthquake. The path effect is defined as the effect of the materials along the propagation path from the source to the bedrock beneath the site. The site effect is defined as the effect of sediments below the site down to the bedrock. The bedrock here is defined as a layer with a shear wave velocity over 3000 m/s (OCDI, 2009), which corresponds to fresh granite in Japan.

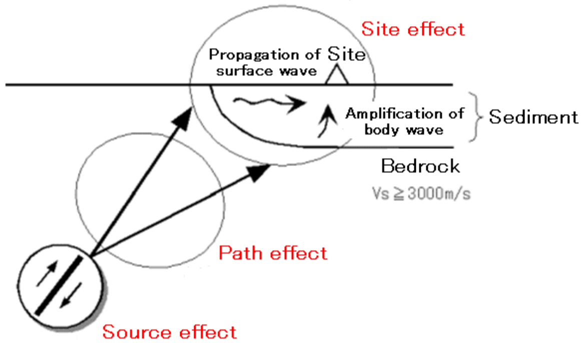

Figure 1 Source, path and site effects

The existence of sediments below the site has significant effects on the amplitude, the frequency content and the duration of strong ground motions. It is important to note here that the "sediments" involve not only shallow soil deposit with SPT *N* value less than 50 (shear wave velocity less than about 300 m/s) but also deeper firm ground with *N* value over 50 (shear wave velocity ranging from 300-3000m/s). Seismic waves are mainly amplified due to the contrast of shear wave velocity. Because the contrast of shear wave velocity between the surface and the bedrock is sometimes as large as 20 (=3000/150), seismic waves are significantly amplified by the existence of the sediments. At the same time, the frequency content of strong ground motions is closely related to the thickness of the sediments. If the sediments are thin enough, then only high-frequency component of strong

Figure 2 The topography around the port of Sakai, west Japan (left) and the velocity waveforms for the fault-normal component recorded around the port during the 2000 Tottori-ken Seibu earthquake (M_J7.3).

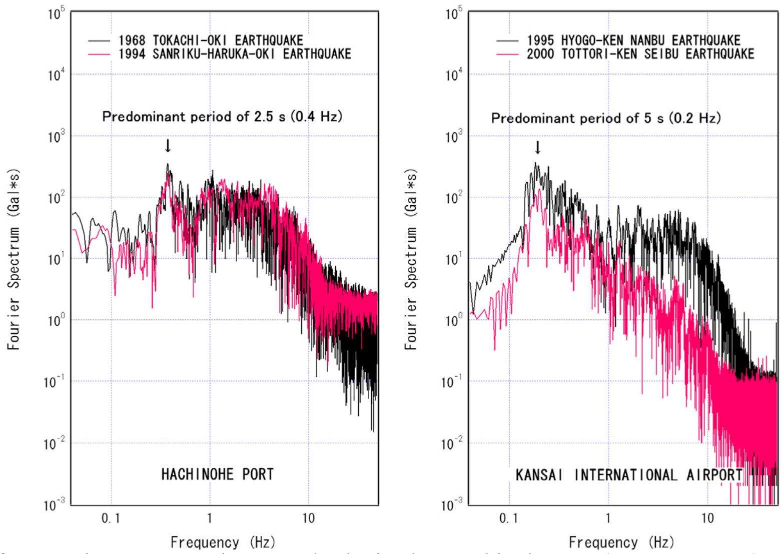

Figure 3 Fourier spectra of past major strong motion records obtained at Hachinohe Port (NS component) and Kansai International Airport (Runway-normal component)

ground motions will be amplified, which is a favourable condition for large-scale structures. But if the sediments are thicker, then frequency components closer to the natural frequency of large-scale structures may be amplified. In this case seismic design should be performed carefully.

It is important to recognize here that the characteristics of deeper firm ground, which is usually beyond the reach of geotechnical investigations including SPT, have significant effects on the amplification of seismic waves, because the contrast of shear wave velocity within deeper firm ground itself is as large as 10 (=3000/300).

Figure 2 shows an example of the importance of the site effect. The left panel shows the topography around the port of Sakai, west Japan. Two observation stations, namely, Sakaiminato-G (Strong Motion Earthquake Observation in Japanese Ports) and JMA (the Japan Meteorological Agency) are located in the plains of Yumigahama Peninsula in the left-hand side of the photo. Other two stations, namely, SMN001 of K-NET (Kinoshita, 1998) and SMNH10 of KiK-net (Aoi *et al.*, 2000) are located in mountainous Shimane Peninsula in the right-hand side of the photo. Observed peak ground velocities during the 2000 Tottori-ken Seibu earthquake (M_J7.3) were approximately four times larger for the plains of Yumigahama Peninsula than for mountainous Shimane Peninsula (the right panel of Figure 2). The difference can be attributed to the amplification of seismic waves due to the sediments in Yumigahama Peninsula. Thus, evaluation of the site effect is fundamentally important to predict strong ground motions from future large earthquakes and to determine design ground motions. If we neglect the site effect in the evaluation of design ground motions, it may lead to an overestimation or underestimation of seismic load sometimes by a factor of 4 or more.

Figure 3 shows an example of the effect of the sediments on the frequency content of strong ground motions. At Hachinohe Port, both of the Fourier spectra from the 1968 Tokachi-oki earthquake (M_J=7.9) and the 1994 Sanriku Haruka-oki earthquake (M_J=7.5) are characterized by a peak at the frequency of 0.4 Hz (the period of 2.5 seconds). The former record is famous as "Hachinohe wave" and was widely used for the design of port structures in Japan in the past. On the other hand, at Kansai International Airport, both of the Fourier spectra from the 1995 Hyogo-ken Nanbu earthquake (M_J=7.3) and the 2000 Tottori-ken Seibu earthquake (M_J=7.3) are characterized by a peak at the frequency of 0.2 Hz (the period of 5 seconds). The difference of predominant periods can be attributed to the thickness of sediments down to the bedrock at each observation station. These observations reveal how important it is to consider site-specific design ground motions, which is consistent with the site effects. If we use, for example, "Hachinohe wave" for the design of structures at Kansai International Airport, then earthquake response analysis of structures will wrongly tell us that the response of structures with natural period of 5 seconds are small, which is a misleading result because the structure will actually be exposed to a strong ground motion with predominant period of 5 seconds.

3 BRIEF INTRODUCTION TO STRONG MOTION EVALUATION

There are several methods to generate site-specific design ground motions. In this section, the method based on site-specific amplification and phase characteristics (Kowada *et al.*, 1998; Nozu and Sugano, 2008; Nozu *et al.,* 2008) is described.

First, a small earthquake is hypothesized, whose area is equal to the area of the asperity of the target earthquake divided by N^2 and whose final slip is equal to the final slip of the asperity divided by N. The ground motion from the small earthquake is called the "Green's function". The Fourier amplitude of the Green's function is evaluated as a product of the source spectrum S(f), the path effect P(f) and the site amplification factor G(f).

The source spectrum of the small event is assumed to follow the ω^{-2} model (Aki, 1967). According to the ω^{-2} model, the source spectrum (acceleration Fourier amplitude spectrum) can be expressed as follows.

$$S(f)=C\frac{M_0}{4\pi\rho V_S^3}\frac{(2\pi f)^2}{1+(f/f_c)^2}, \quad (1)$$

where
M_0: seismic moment of the small event
f_c: corner frequency of the small event
ρ : density in the bedrock
V_s: shear wave velocity in the bedrock
C: constant (OCDI, 2009)

The seismic moment is defined as follows (Aki, 1966).

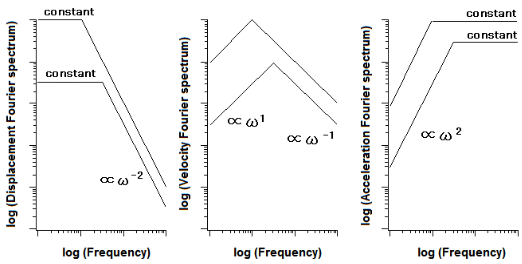

Figure 4 Source spectra which follow the ω^{-2} model.

$$M_0 = \mu A D_0, \quad (2)$$

where
μ : rigidity in the bedrock
A: area of the event
D_0: slip of the event

Figure 4 shows the displacement, velocity and acceleration source spectra following the ω^{-2} model.

As for the path effect, it is a common practice to take into account both the geometrical spreading and the inelastic damping as follows.

$$P(f)=\frac{1}{r}\exp(-\pi f r/QV_S) , \quad (3)$$

where
r: hypocentral distance
Q: Q value along the propagation path

As for the site amplification factor, those obtained from in-site earthquake observation should be used. The digital data of the site amplification factors at permanent earthquake observation stations in Japan evaluated by the Port and Airport Research Institute and the National Institute for Land and Infrastructure Management are available on a CD-ROM (Nozu and Nagao, 2005), but before using the data, it is necessary to make sure (by using microtremor observations) that the characteristics of ground motions do not differ significantly between the site of construction and the permanent observation station. If the characteristics of ground motions are found to be different between them, it is recommended to conduct a temporary in-situ earthquake observation at the site of construction to evaluate the site amplification factor (see chapter 4).

As for the Fourier phase of the Green's function, the Fourier phase of a record at the earthquake observation station can be used. If several records are available at the site, it is recommended to choose an event which has a similar incident angle and a similar backazimuth with the target asperity. The Green's function in the frequency domain can be written as follows.

$$S(f)*P(f)*G(f)*O_s(f)/|O_s(f)|_p, \quad (4)$$

where $O_s(f)$ is the Fourier transform of a record at the

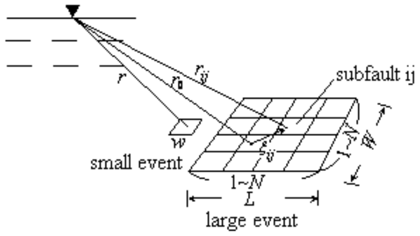

Figure 5 Superposition of Green's functions

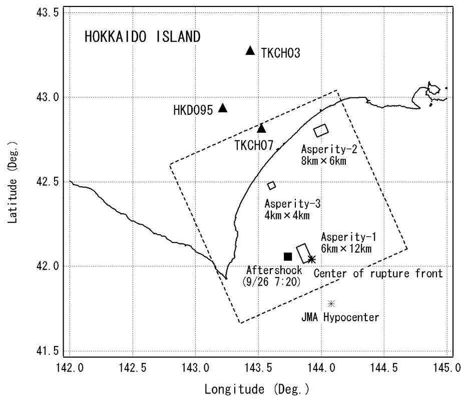

Figure 6 Simplified source model developed for the 2003 Tokachi-oki, Japan, earthquake (M_J8.0) composed of three asperities (open rectangles). Triangles indicate strong-motion sites. Closed rectangle indicates the small event whose phase characteristics are used in the simulation.

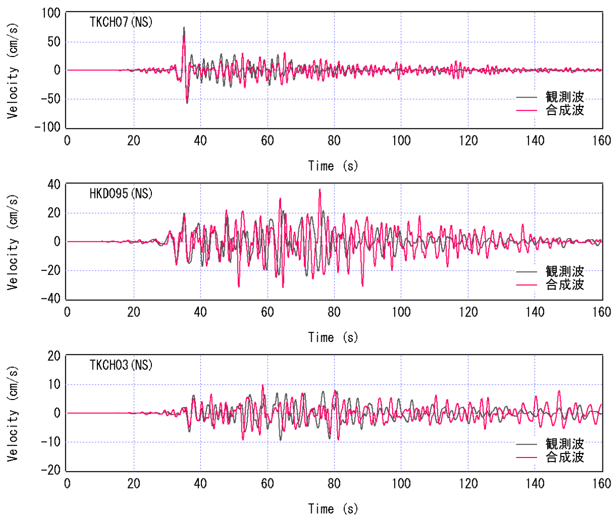

Figure 7 Observed and Synthetic velocity waveforms (0.2-1.0 Hz) at TKCH07, HKD095 and TKCH03 during the 2003 Tokachi-oki, Japan, earthquake (M_J8.0)

site and $|O_s(f)|_p$ is its Parzen-windowed amplitude (band width of 0.05 Hz is used). The time domain Green's function can be obtained as the inverse Fourier transform of the equation (4). Finally, the time domain Green's function can be superposed as follows (e.g., Miyake *et al.*, 1997) to obtain the ground motion from the asperity (Figure 5). When two or more asperities are considered, contribution from all the asperities should be superposed. A computer program to synthesize strong ground motions based on the method described above is open to public from the Port and Airport Research Institute (Nozu and Sugano, 2008). The source parameters for the simulation can be determined either following the guideline provided by OCDI (2009) or based on detailed investigation on the target earthquake.

The method has been applied to past damaging earthquakes in Japan. Figure 6 shows the simplified source model developed for the 2003 Tokachi-oki, Japan, earthquake (M_J8.0) composed of three asperities. In Figure 7, synthetic velocity waveforms (0.2-1.0 Hz) at three stations are compared with the observed ones. It should be noted that the observed waveforms show significant variability from site to site, from an impulsive waveform at TKCH07 to a long-tailed waveform at TKCH03. These characteristics are accurately reproduced in the simulation, because site-specific amplification and phase characteristics are considered in the simulation.

4 IMPORTANCE OF IN-SITU EARTHQUAKE OBSERVATION

In the evaluation of design ground motions using the techniques described above, the reliability of the result is obviously dependent on the quality of the evaluation of the site effects. To achieve the quality control of design ground motions, it is necessary to promote temporary in-site earthquake observation. Recall that the characteristics of deeper firm ground, which is usually beyond the reach of geotechnical investigations including SPT, have significant effects on the amplification of seismic waves. In-site earthquake observation is the most efficient, economical, and reliable tool for the evaluation of the site effects.

Because the site for construction of important infrastructures is often fixed years before its design procedure, an well-organized design program will allow us to conduct temporary observation of earthquake ground motions at the site for construction before the design procedure begins. The term for the temporary observation should be determined taking into account the seismicity of the area. Typically, in Japan's case, a term of 1-3 years would be required. The seismometers used for the observation should cover all the frequency range for which strong ground motions should be predicted. The trigger level should be chosen very carefully. In general, a very small trigger level should be chosen to obtain as many records as possible in a limited term. It might be useful to adopt a mechanism in which the seismometer is triggered when the velocity, instead of the acceleration, exceeds certain value. The location of the observation should also be determined carefully. When it is difficult to install the seismometer just at the construction site, then microtremor observation should be conducted in and around the construction site and the seismometer should be installed within an area in which the characteristics of microtremor can be regarded uniform.

Once earthquake records are obtained, the site amplification factor at the temporary station can be evaluated, based on the known site amplification factors at permanent stations, as follows. The first step is to find earthquakes which are recorded both at the temporary station and the surrounding permanent stations. Then, for these earthquakes, the source spectra should be determined so that the synthetic spectra at permanent stations are consistent with the observed ones. It is a common practice to assume that the source spectra follow the ω^{-2} model (the equation (1)). Finally, using the source spectra thus obtained and the observed spectra at the temporary station, the site amplification factor at the temporary station can be determined.

A simplified version of this analysis can be applied if the temporary station is close enough to a permanent station for which the site amplification factor is known. In this case, these stations share the same source effect and the same path effect. Therefore, the Fourier spectral ratio of the records from the same earthquake at these stations represents the ratio of the site amplification factors. Thus, the site amplification factor for the temporary station can be easily obtained as the spectral ratio multiplied by the site amplification factor at the permanent station.

Figure 8 shows an example of the result of temporary in-situ earthquake observation conducted by the Chugoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan, to reveal the site effects at the port of Iwakuni. The vertical axis shows the ratio of the observed Fourier amplitude at the temporary station at the port of Iwakuni with respect to a nearby permanent station (YMG016). The temporary observation was conducted for about six month in 2005. From the result, it can be recognized that the site amplification factor at the temporary station is larger by a factor of 10 around 1 Hz and smaller by a factor of 10 around 2 Hz than YMG016. Such a significant difference in site amplification factors should be interpreted as a consequence of the effects of whole sediments including deeper firm ground (with shear wave velocity ranging from 300-3000m/s), because the difference of shallow soil layers alone cannot explain such a significant difference. Therefore, this is an example in which the site effects, including the effects of deeper firm ground, which is beyond the reach of geotechnical investigations, were efficiently revealed by conducting temporary in-situ observation of earthquake ground motions.

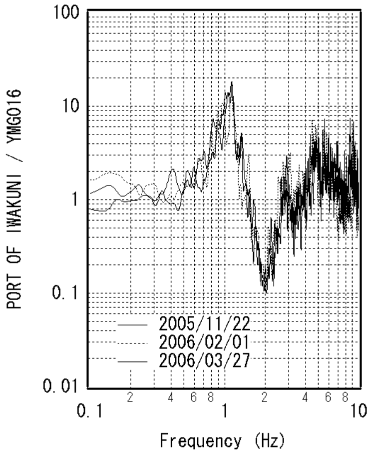

Figure 8 An example of the result of temporary in-situ earthquake observation conducted at the port of Iwakuni by the Chugoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan. The vertical axis shows the Fourier spectral ratio of the records at the port of Iwakuni with respect to YMG016.

4 SUMMARY

The main points of the present article can be summarized as follows.

1. Site-specific design ground motions are required for the rational seismic design of infrastructures, because the existence of sediments below the site has significant effects on the amplitude, the frequency content and the duration of strong ground motions.
2. To achieve the quality control of design ground motions, it is necessary to promote temporary in-site earthquake observation at the site for construction.

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