EVALUATION OF EARTHQUAKE RESPONSE SPECTRA CONSIDERING DEPTH OF SEISMIC BEDROCK

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ABSTRACT :

The design earthquake motions are often defined by the response spectra. For example, in the seismic design standard for the Japanese Railway facilities (1999) there are two types of design spectra for the Level-1 earthquake and the Level-2 earthquake. The Level-1 earthquake is the earthquake, which has an occurrence probability of a few times during the service life of the structures. The Level-2 earthquake motions have high intensity, which are defined by taking into account earthquake activities in the inter-plate regions (Spectrum-I) and defined by considering the near source earthquake motions characteristics caused by intra-plate earthquakes (Spectrum-II). The Spectrum-II for the Level-2 earthquake has been evaluated by chiefly using the records observed in the 1995 Hyogo-ken Nambu earthquake. These records have been observed at the site where the strong motions were largely amplified due to the influence of the deep seismic bedrock. However, the ground motions were not so much amplified at the site with the shallow bedrock. Therefore, we propose the response spectra for the Level-2 earthquake considering the depth of the seismic bedrock. In the area with shallow bedrock, we can make the designed spectra approximately 30 percent less than those in the deep area at the longer period. Using these proposed spectra, the seismic design become more rational for the structures built in mountain areas with shallow bedrock.

KEYWORDS: engineering bedrock, seismic bedrock, response spectra for the Level-2 earthquake

1. INTRODUCTION

In the Japanese seismic design standards for highway or railway facilities, two types of design earthquake ground motions are considered; an earthquake to secure the serviceability of structures (the Level-1 earthquake motion), and an earthquake to secure the safety (the Level-2 earthquake motion) [Japan Road Association, 2002] [RTRI, 1999]. The Level 1 earthquake is the earthquake, which has an occurrence probability of a few times during the service life of the structures. The Level-2 earthquake motions have high intensity, which are defined by taking into account earthquake activities in the inter-plate regions (Spectrum-I) and defined by considering the near source earthquake motions characteristics caused by intra-plate earthquakes (Spectrum-II). These design earthquake motions have been decided based on the records of observed earthquake ground motions. Among these design earthquake motions, the Level-2 earthquake motion has mainly been evaluated by using the records observed in the 1995 Hyogo-ken Nambu earthquake. These records were observed at the site with the deep seismic bedrock, where the strong motions were largely amplified by the site effect. A ground motion observed at a site on the stiff ground, however, is not so much amplified because the depth of bedrock is shallow. It is uneconomic, therefore, to build the structure using current designed earthquake motions. It is considered that structures can be designed more rational considering the difference of the ground structure in case of revising the design earthquake motion. In this paper, we examine the level of the earthquake response spectra near faults by considering the effects due to the depth of the seismic bedrock.

2. DATA USED FOR INVESTIGATION

2.1. Data Sets of Observed Earthquake Motions

In this paper, we investigate the characteristics of near-fault earthquake response spectra at the engineering bedrock, and select earthquake motions that satisfy the following conditions.

1) The observation points are located on the stiff ground, where the depth from the ground level to the engineering bedrock (whose shear velocity is more than 400m/s) is within 10m.
2) The magnitude of the earthquake is approximately Mw7.0.
3) The distance between the fault and observation point is less than 100 (km)
4) Only the earthquake data obtained from inland near source are used.
6) The data are not influenced by the nonlinearity of site.

Table 1 shows the earthquake data used in this study. Figure 1 shows the epicenters of the selected earthquakes.

2.2. Adjustment of Response Spectra Using Attenuation Relation

The scattering of original response spectra for observed earthquakes is very large. This scattering originates from uncertainty of 1) source mechanism, 2) transmitting path, 3) local soil condition. To reduce scattering, the level of original response spectra are corrected by the earthquake magnitude and hypocentral distance. Moreover, the effects of local soil conditions are stripped off.

Table 1 Near-source seismic records of recent earthquakes in Japan

No.	Earthquake	Date Time	M_{JMA}	Mw	Number of record
1	Hyogo-ken Nambu	1995/1/17 5:46	7.2	6.9	10
2	Western Tottori	2000/10/06 13:30	7.3	6.8	34
3	Mid Niigata Prefecture (main shock)	2004/10/23 17:56	6.8	6.7	22
4	Mid Niigata Prefecture (after shock)	2004/10/23 18:34	6.5	6.4	24
5	West Off Fukuoka Prefecture	2005/3/20 10:53	7.0	6.7	30
6	Noto Hanto	2007/3/25 9:42	6.9	6.7	10
7	Niigataken Chuetsu-oki	2007/7/16 10:13	6.8	6.6	22
				Total	152

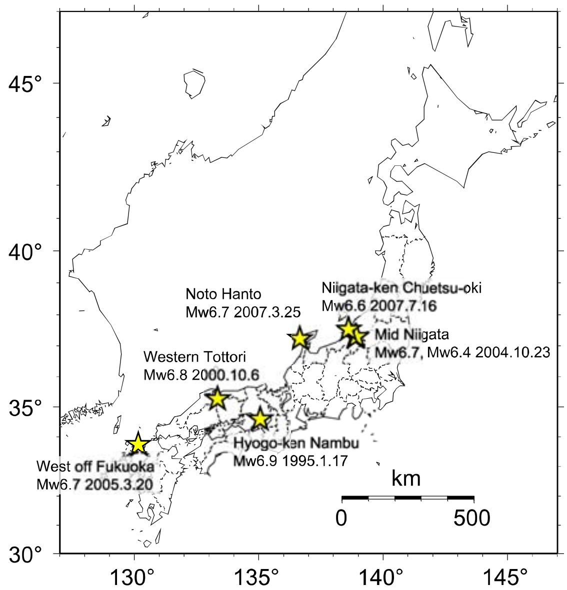


Figure 1 Location of epicenter

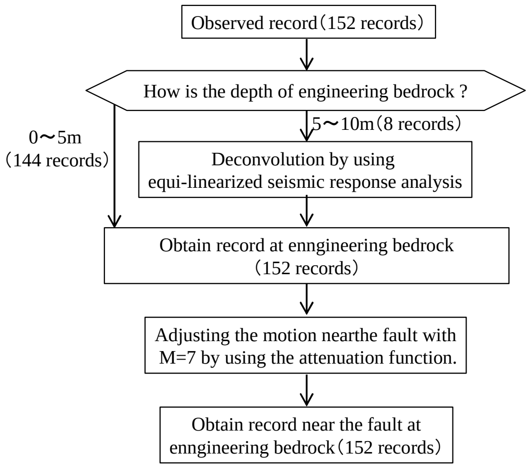


Figure 2 The flowchart of adjustment method

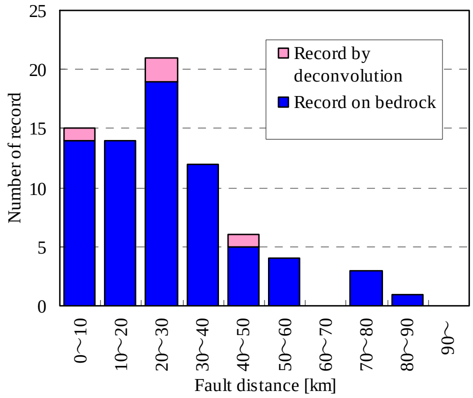


Figure 3 Distribution of the shortest fault distance

To grasp the characteristics of response spectra of earthquake motions just above the earthquake fault with Mw7.0, the response spectra calculated from observed earthquake motions are adjusted to those at the shortest fault distance of 3km by using the attenuation function. Figure 2 shows the flowchart of adjustment method. There are several attenuation relationships of acceleration response spectrum taking into account the earthquake source extent. The attenuation relationship proposed by Uchiyama and Midorikawa [Uchiyama and Midorikawa, 2006] is used in this paper. The attenuation equation uses the shortest fault distance to the earthquake fault. The shortest fault distances, therefore, are calculated for the collected earthquake data shown in Table 1. Figure 3 shows the distribution of calculated shortest fault distance. It is said that the seismic fault cannot exist within the depth of 0~2 km from the surface [Takemura, 1998]. Therefore, the observed response spectra are corrected to the response spectra at the point whose shortest fault distance to fault is 3km.

The ground motions are also influenced by the condition of soil deposit. To remove the effects of local soil condition, the earthquake motions observed at ground surface are decomposed to those at the engineering bedrock by using the inverse analysis based on multi-wave-reflection theory. The nonlinearity of soil is taken into account by using equivalent linear analysis proposed by Sugito *et al.* (FDEL [Sugito *et al.*, 1994]).

3. RESPONSE SPECTRA CONSIDERING DEPTH OF SEISMIC BEDROCK

3.1. Comparison between observed response spectra and Japanese design response spectra

Figure 4 shows the observed response spectra at engineering bedrock adjusted by the method mentioned in Section 2.2. It is evident that the spectra become smaller as the period becomes longer. The design spectra for highway bridges and railway facilities in Japan are also depicted in Figure 4. The design spectra exceed the adjusted spectra in the period longer than 0.5sec. However, the design spectra underestimate the adjusted spectra in the period shorter than 0.5sec. In order to investigate this inconsistency, the response spectra of the 1995 Hyogo-ken Nambu Earthquake and the 2000 Western Tottori Earthquake are compared as shown in Figure 5. It should be noted that Hyogo-ken Nambu records have a single large velocity pulse caused by the site effect [Kawase and Hayashi, 1996]. Since the current design spectra are mainly evaluated by records in the Hyogo-ken Nambu earthquakes, the shape of design spectra is similar to that of Hyogo earthquake. On the other hand, a ground motion observed in Tottori earthquake is not so much amplified, because the depth of bedrock is shallow. The predominant period of the response spectrum is shorter than that in Hyogo earthquake. As a result, the spectra in Tottori earthquake are larger than the design spectra in the short period and smaller in the long period. Moreover, the severe damage ratios in Tottori earthquake are less than those in Hyogo earthquake [Hayashi *et al*., 2001].

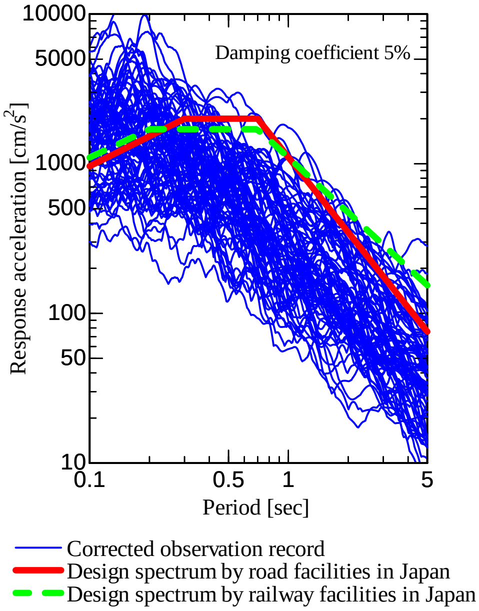
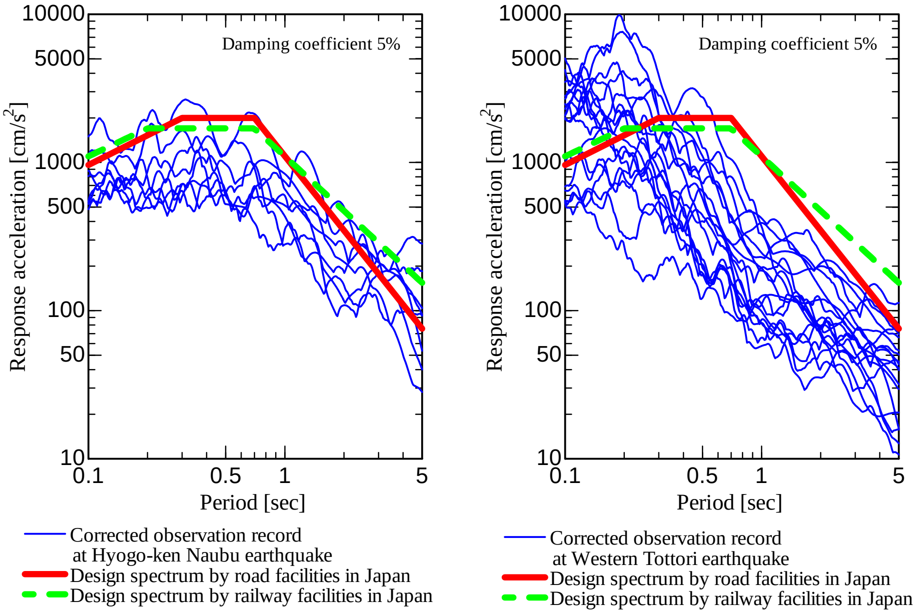


Figure 4 Response spectra adjusted to the shortest fault distance of 3km



(a) Hyogo-ken Nambu earthquake (b) Western Tottori earthquake

Figure 5 Comparison of selected spectra and the design spectra

3.2. Evaluation of the design spectra considering the effects of seismic bedrock

The current design spectrum used in Japanese Railway facilities has been evaluated stochastically by the use of response spectra calculated from observed inland near source earthquake motions. The level of the current design spectrum is defined so that the non-exceedance probability is 90%, assuming that the nature of stochastic characteristic of calculated response spectra can be characterized by the normal distribution at each period. The effect of the subsurface structure, however, is not considered in the spectra as mentioned in Section 3.1. We define the design spectrum in the same manner, without considering the effects of the subsurface structure, the new design spectrum becomes much larger than the present design spectrum in the range of short period as shown in Figure 4. The predominant period of the strong motion becomes shorter at the area where the depth of seismic bedrock is shallow, and longer at the area with deep bedrock. As a result, it is not economical to design structure by using such design spectra. In order to overcome such absurdity, the effect of the subsurface should be considered for composing new design spectra. First, the observed data (see Table 1) are classified into two groups according to the depth of the bedrock. Next, corresponding response spectra for these groups are calculated. Based on the characteristics of the spectra, the appropriate designed spectrum is proposed.

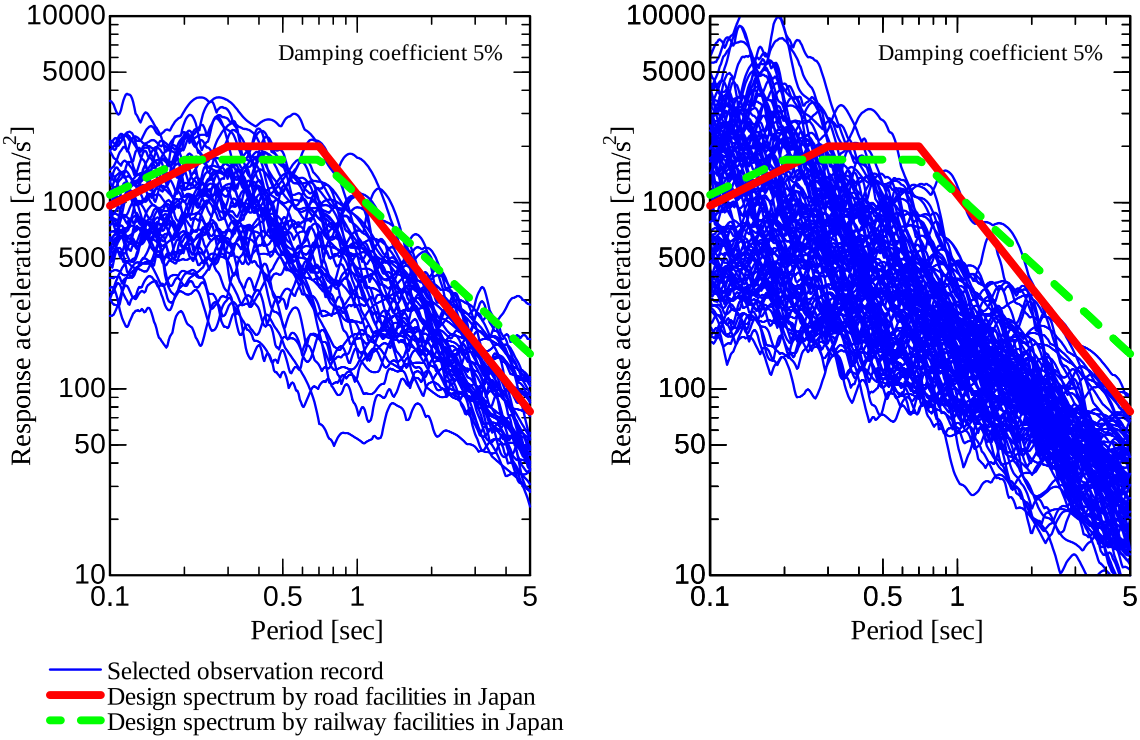
The depth of the seismic bedrock at each observed point is estimated by referring the boring data or a subsurface structure model of the whole Japan proposed by Fujiwara *et al* [Fujiwara *et al*., 2006]. However, it should be noted that the estimated depth of bedrock is not obtained in a good accuracy. These observed data are, therefore, roughly divided into two groups; one is the bunch of the site where the depth of the seismic bedrock is less than 500m, and the other one is the site at the depth of the bedrock of more than 500m. Figure 6 compares the observed response spectra at deep bedrock site with those at shallow bedrock site. This figure indicates that the characteristics of spectra are classified clearly by means of the depth of the bedrock. The present design spectra in Japanese highway bridge and railway facilities are same level as the observed spectra at deep bedrock site or more. In addition, these observed response accelerations are almost equal in the range from 0.1sec to 0.5sec. On the contrary, these observed data at shallow bedrock site are conversely greater than the design spectra at short period.

Based on these classifications, the new design spectra considering the depth of the seismic bedrock is proposed. In Japanese seismic design standard, the level of design earthquake motion to secure the safety of structure is defined as maximum ground motion at the location of construction. Here, 90% of the non-exceedance probability is used to define the new design acceleration spectrum based of the past research [Sato *et al*., 2001]. The earthquake motion observed far from hypocenter contains much error when the record is corrected using the method proposed in chapter 2. Therefore, the weighting factor $W_n(t)$ is used defined by equation (3.1).

$$W_n(t) = \frac{1}{SA(t)[R = r_n, M, D] \big/ SA(t)[R = 3.0, 7.0, D]} \tag{3.1}$$

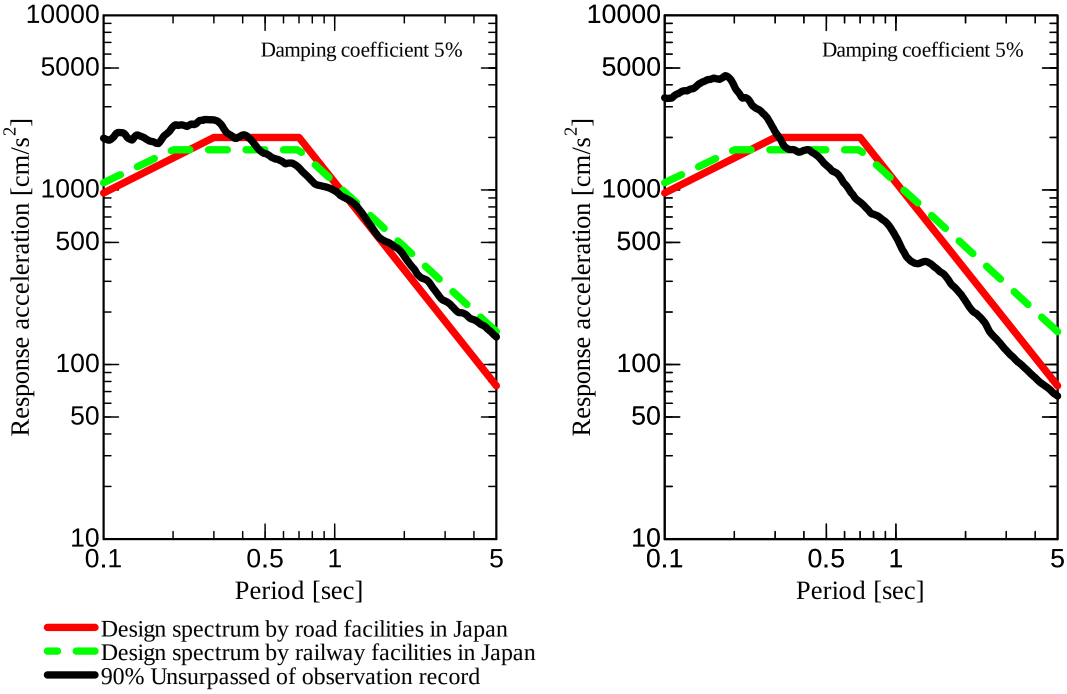
Where, r_n [km] expresses the distance from hypocenter to the observed point, n is the observation number, t [sec] is a period, M is a magnitude, D [km] is a depth of hypocenter and SA [cm/s2] is a simulated response acceleration obtained by the attenuation relationship.

Figure 7 compares the present designed spectra and the calculated spectra by using the method proposed preceding paragraph. The calculated spectrum at the deep bedrock site agrees well with the present design spectra in Japanese highway bridges and railway facilities. Therefore, it is appropriate to use the current design spectra when the structures are designed at deep bedrock site. At shallow bedrock site, on the other hand, it can be economical to use the proposed spectrum shown in Figure 7 (b).



(a) Records at site depth of the seismic bedrock > 500m (b) Records at site below 500m

Figure 6 Comparison of the observed response spectra at deep bedrock site and those at shallow bedrock site



(a) Records at site depth of the seismic bedrock > 500m (b) Records at site below 500m

Figure 7 Comparison the present designed spectra and the calculated spectra by using the proposed method

4. CONCLUSION

In this paper, the effect of the subsurface structure on response spectra is clarified. The characteristics of spectrum near the fault are examined by following procedure.

1) The strong ground motion records, which are observed at the site close to the fault, are collected.
2) The influences of seismic amplitude caused by the surface ground condition are removed by selecting records observed on the stiff ground.
3) The observed original response spectra of ground motion with various magnitudes and with the shortest distances to fault are corrected to the response spectra with M=7 and with shortest fault distance of 3 km, by using the attenuation function.
4) The corrected spectra are classified roughly into two categories, the record observed at deep bedrock site (the depth of seismic bedrock is deeper than about 200-500m) and the record observed at shallow bedrock site.
5) The envelope curve of these selected response spectrum is proposed for each group.

As a result, in the area with shallow bedrock, designed seismic spectrum can be reduced about 30 percent compared to spectrum in the deep bedrock at the range of longer period. Using these proposed spectra, structures can be built more rational on the stiff ground such as in the mountain region.
However, it should be noted that the proposed spectra are obtained from the limited number of observed data. Therefore, further researches such as numerical simulations are needed to improve the accuracy.

ACKNOWLEDGMENT

We used the strong-motion records supplied by the National Institute for Earth Science and Disaster Prevention (NIED; K-NET, KiK-net). GMT (Wessel and Smith, 1991) was used for making several figures.

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