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Variation of Earthquake Ground Motions with Focus on Site Amplification Factors

A Case Study

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Abstract—**In this paper, an evaluation of the variation of earthquake ground motions with a focus on site amplification factors based on spectral analysis is presented. By using strong motion record obtained at six sites in Japan, probability distributions of site amplification factors were shown. The relations between standard deviations of site amplification factors and distances between the sites were studied. The variations of representative values of earthquake ground motions based on the variations of site amplification factors were discussed by using probabilistic seismic hazard analysis with focus on Fourier amplitude and group delay time. The distributions of peak ground accelerations and peak ground velocities were shown. It is suggested that design earthquake ground motions considering the average site amplification factors may lead the engineering design on the dangerous side.**

Keywords-earthquake ground motion; site amplification factor; Fourier spectrum

I. INTRODUCTION

Loads to be considered in engineering practice have a randomness. Variations of design loads must be evaluated precisely because the probability of the violation of the limit states shall be smaller than the allowable one in the design. Concerning earthquake resistant design, it is needless to point out that earthquake ground motions have very large variations and proper evaluation of these variations is very important. Variation of earthquake ground motion also plays an important role in hazard and risk analysis. Earthquake ground motions can be evaluated by considering source, path and site amplification characteristics. Site amplification characteristic implies the amplification factor in the frequency domain due to the deep and shallow subsurface condition, namely the ground condition from the ground surface to the seismic bedrock at the site of interest. It is known that site amplification factors differ from site to site. As the site amplification factor is strongly affected by the 3-dimensional sedimentary environment of soil layers, it can only be evaluated precisely in an empirical manner by using strong motion records. Spectral inversion technique [1-3] that separates source and path characteristics from the observed record is used for the purpose and site amplification factors at many strong-motion observation sites have been shown [4, 5]. Although many studies have been conducted on the variations of the representative values of earthquake ground motions (e.g. peak ground acceleration and peak ground velocity) by using attenuation equations [6, 7], few studies have been conducted on the variations of site amplification factors [8, 9]. In this study, authors evaluated the variations of the site amplification factors by using strong motion records observed at many sites. In this paper, the effect of the variations of the site amplification factors on the representative values of strong motions such as peak ground velocity are discussed.

II. EVALUATION METHOD OF SITE AMPLIFICATION FACTORS

Let R denote a reference site where its site amplification factor is known and T denote a target site where its site amplification factor is to be obtained. Fourier amplitude spectra of the earthquake ground motions $O(f)$ can be expressed as multiplication of source spectra $S(f)$, path spectra $P(f)$ and site amplification spectra $G(f)$ as:

$$O_R(f) = S(f) \cdot P_R(f) \cdot G_R(f) \tag{1}$$

$$O_T(f) = S(f) \cdot P_T(f) \cdot G_T(f) \tag{2}$$

where f is the frequency. Path spectra are calculated by:

$$P_R(f) = \exp\left\{-\left(\pi f r_R\right) / \left(Q(f) V_S\right)\right\} / r_R \tag{3}$$

$$P_T(f) = \exp\left\{-\left(\pi f r_T\right) / \left(Q(f) V_S\right)\right\} / r_T \tag{4}$$

where r is the hypocentral distances, $Q(f)$ is the quality factor along the propagation path and V_S is the shear wave velocity along the propagation path. Quality factor is a parameter that expresses the attenuation characteristic of seismic waves with distance [10]. It is known to be frequency dependent and differs from region to region [11]. This study employs the quality factor estimated in [12] for subduction earthquakes in eastern Japan as:

$$Q(f) = 114 f^{0.92} \tag{5}$$

where $G_T(f)$ is the site amplification factor at site T obtained by (6):

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$$G_T(f) = G_R(f) \cdot \frac{O_T(f)}{O_R(f)} \cdot \frac{r_T}{r_R} \cdot \frac{\exp\{-(\pi f r_R)/(Q(f)Vs)\}}{\exp\{-(\pi f r_T)/(Q(f)Vs)\}} \qquad (6)$$

The current study uses site amplification factors at reference sites obtained by the spectral inversion [4].

III. VARIATION OF SITE AMPLIFICATION FACTORS

Five K-NET [13] and one KiK-net [14] earthquake ground motion observation stations in Fukushima and Ibaraki prefectures in Japan, were chosen for the study (Figure 1). Figure 2 indicates the site amplification factors obtained by the spectral inversion [4] for the six sites. Site amplification factors at FKS011, FKS012 and IBR002 show large amplitudes in the frequency band <1Hz. On the other hand, site amplification factors at other sites show small amplitudes in this frequency band and have predominant peaks at frequencies higher than 2.5Hz. The reason is that in the low frequency band, thick sedimentary layers resulted in large amplification factors and thin sedimentary layers resulted in small amplification factors. Figure 3 shows the relation between sediment thicknesses and average site amplification factors in the range of 0.2 to 1.0Hz. The sediment thickness is defined as the depth of the seismic bedrock whose shear wave velocity exceeds 3km/s. We referred to the J-SHIS database [15] for the evaluation of the sediment thickness. Figure 3 shows high correlation between sediment thicknesses and average site amplification factors in the low frequency band.

Fig. 1. Earthquake ground motion observation stations

IBR003 was set to be the target site. The variation of site amplification factors was calculated by (6). Data with good signal to noise ratio were chosen from the viewpoint of compatibility with ω^{-2} theory [16], where ω is the angular frequency ($=2\pi f$). The observed spectra were set to be the square roots of the sum of squares of the two horizontal components of waveforms in order to eliminate the effect of radiation patterns. The data set numbers used in this study were 194 for FKS011, 235 for FKS012, 173 for FKS013, 266 for IBR002 and 142 for IBRH13. The calculated site amplification factors for IBR003 are shown in Figure 4. Gray solid lines denote individual site amplification factors, blue solid lines denote average site amplification factors, blue dotted lines denote average ± standard deviation site amplification factors and red solid lines denote site amplification factors obtained by the spectral inversion [4].

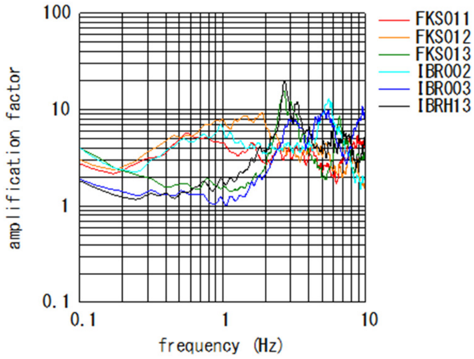


Fig. 2. Site amplification factors

The average site amplification factors were qualitatively consistent with those by the spectral inversion. Figure 5 shows the frequency characteristics of logarithmic standard deviations of the site amplification factors. Logarithmic standard deviations were large for cases where distances between the two sites are long (e.g. FKS011 and FKS013 as reference sites). By contrast, standard deviations were small in cases where the distances between the two sites are short (e.g. IBR002 and IBRH13 as reference sites). Standard deviations averaged from 0.19 to 0.25 in the range of 0.5 to 10.0Hz. Standard deviations obtained in this study were found to be consistent with those in the literature. For example, authors in [9] reported that the standard deviation was 0.25 for strong motion observation stations in the Miyagi prefecture in Japan. Figure 6 shows the relation between distances from the reference to target sites and average standard deviations of site amplification factors. Standard deviations of site amplification factors tend to increase as the distances between the reference and target sites increase. The reason is that the effect of the variation of the path characteristic on (6) increases when the distances between sites are long. Figure 7 shows examples of distributions of site amplification factors normalized by the average values at frequencies 1.0 and 3.0Hz. The distributions of standard deviations of site amplification factors were found to be lognormal.

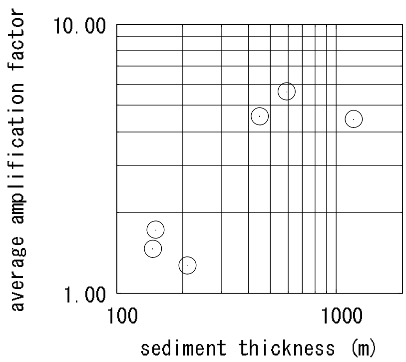


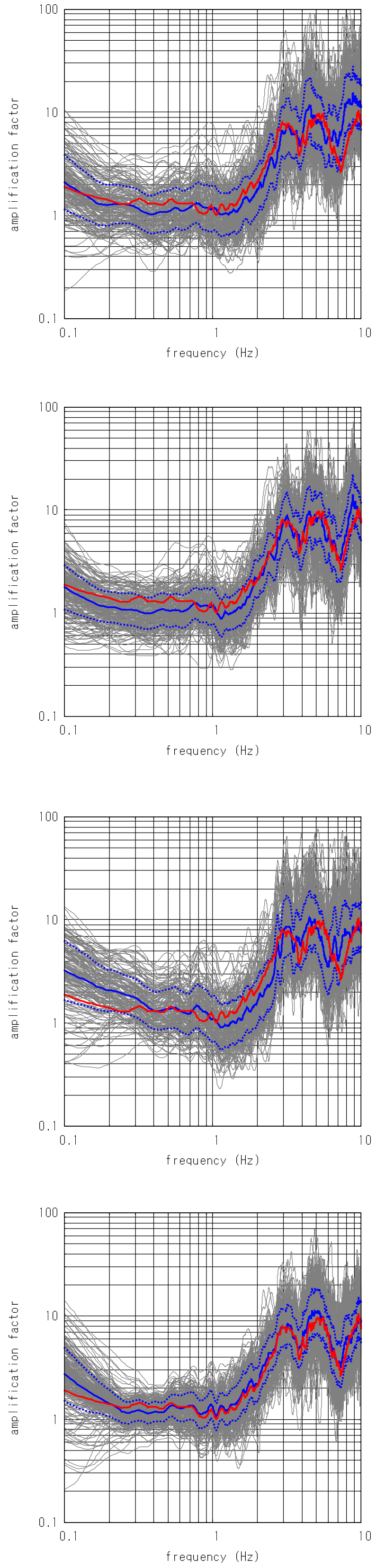
Fig. 3. Relation between sediment thickness and average site amplification factors

(a)

(b)

(c)

(d)



(e)

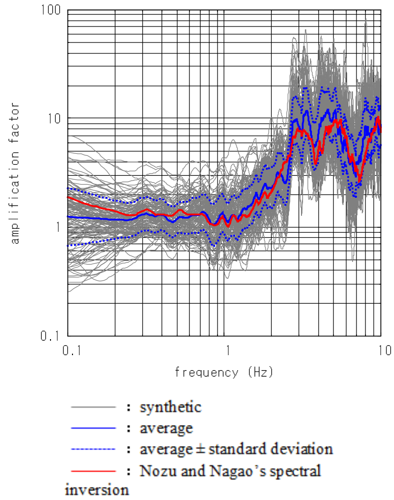


Fig. 4. The calculated site amplification factor of IBR003 (a) R: FKS011, (b) R: FKS012, (c) R: FKS013, (d) R: IBR002, (e) R: IBRH13

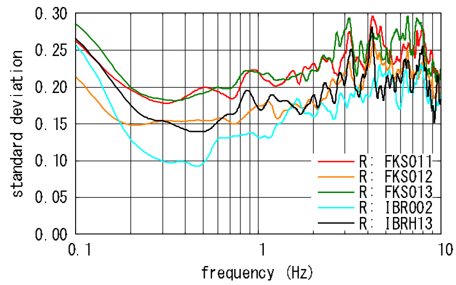


Fig. 5. Frequency characteristic of the standard deviations of the site amplification factors

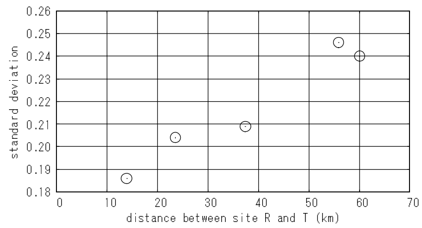


Fig. 6. Relation between the distance from the reference to target sites and the average standard deviation of site amplification factors

IV. VARIATION OF EARTHQUAKE GROUND MOTIONS CONSIDETING SITE AMPLIFICATION FACTORS VARIATION

In Japan, two-stage design earthquake ground motions for the earthquake-resistant design of public works have been introduced after the 1995 Kobe earthquake. One of the two-stage design earthquake ground motions is called the Level-one earthquake ground motion which presumably occurs with a certain degree of frequency during the design working period of infrastructures. The earthquake ground motion corresponds to the reference earthquake ground motion for evaluating serviceability of structures specified in ISO23469 [17]. The Level-one earthquake ground motions at the target site IBR003 were calculated considering the variations of the site amplification factors discussed so far.

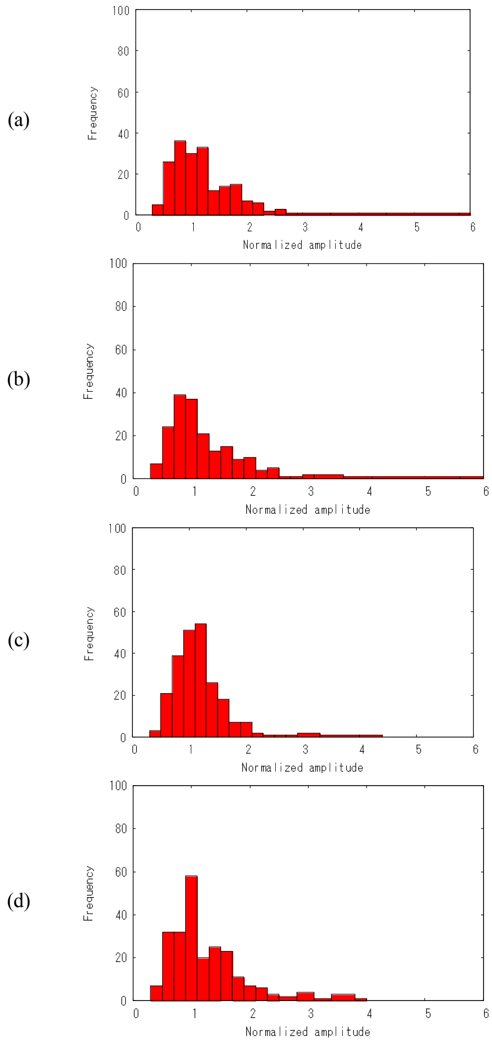


Fig. 7. Distribution of the standard deviation of the site amplification factors. R: FKS011: (a) 1.0Hz, (b) 3.0Hz. R: FKS012 (c) 1.0Hz, (d) 3.0Hz

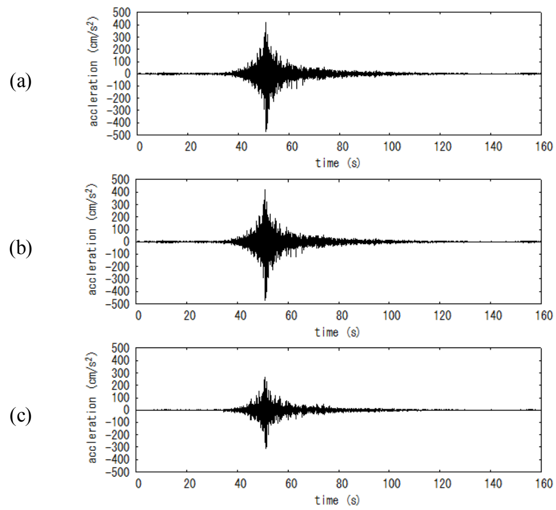


Fig. 8. Time history of the Level-one earthquake ground motions with the average site amplification factors: (a) referring FKS011, (b) referring IBR002, (c) by the spectral inversion.

Probabilistic seismic hazard analysis with focus on Fourier amplitude and group delay time proposed in [18] was used for the calculation of the earthquake ground motions. Figure 8 shows examples of time histories of calculated Level-one earthquake ground motions. Peak ground accelerations were 476.3cm/s^2 with FKS011 as reference site, 355.1cm/s^2 with IBR002 as reference site, and 316.6cm/s^2 with site amplification factors obtained by the spectral inversion.

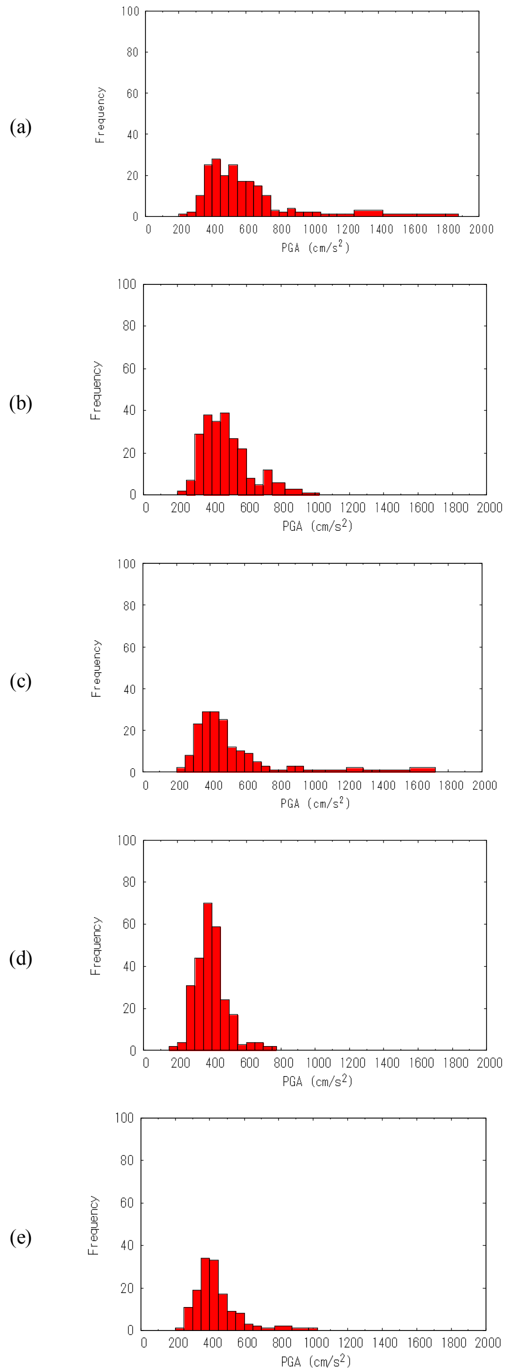


Fig. 9. Frequency distributions of peak ground accelerations. (a) R: FKS011, (b) R: FKS012, (c) R: FKS013, (d) IBR002, (e) R: IBRH13

There is a difference in the peak ground accelerations that cannot be ignored. The reason of the difference in the peak ground accelerations is the difference in the site amplification factors. Figures 9 and 10 show the frequency distributions of peak ground accelerations and peak ground velocities, respectively. Peak ground accelerations are often used in earthquake resistant design of infrastructures, however, it is well known that there is a strong correlation between peak ground velocities and structure damage level.

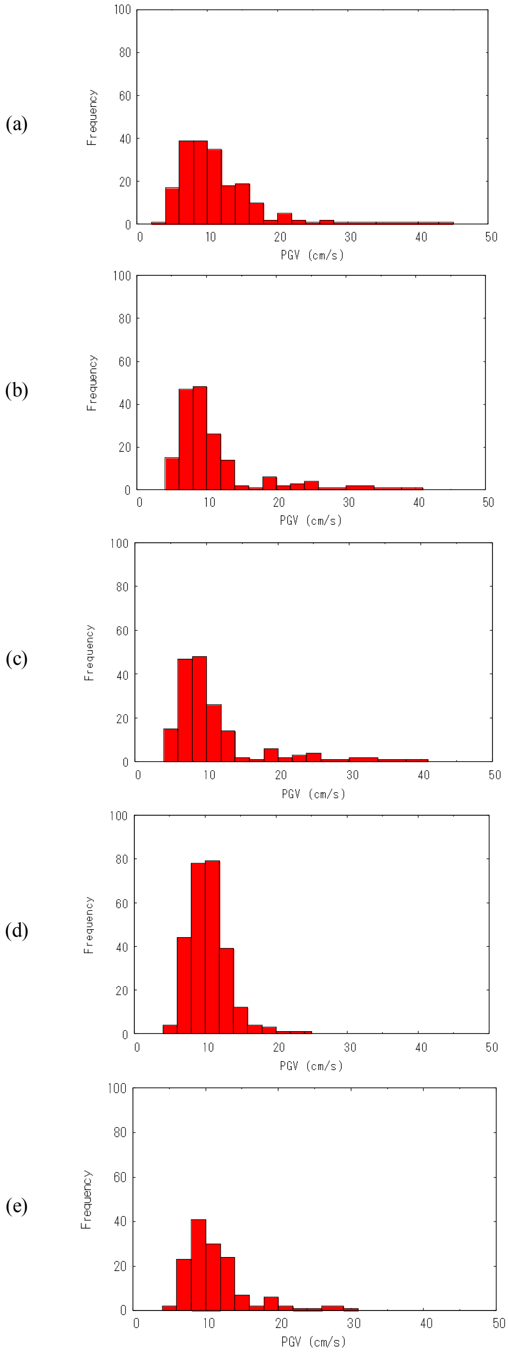


Fig. 10. Frequency distributions of peak ground velocities: (a) R: FKS011, (b) R: FKS012, (c) R: FKS013, (d) R: IBR002, (e) R: IBRH13

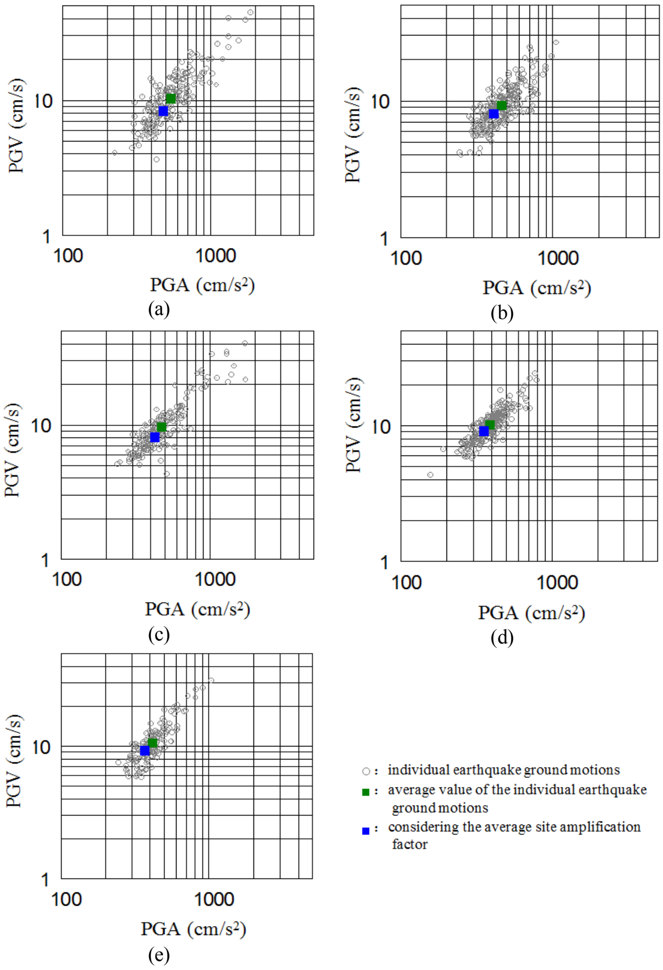


Fig. 11. Peak ground accelerations and peak ground velocities of the Level-one earthquake ground motions (a) R: FKS011, (b) R: FKS012, (c) R: FKS013), (d) R: IBR002, (e) R: IBRH13

Peak ground accelerations and peak ground velocities were found to follow lognormal distributions. Note that the nonlinear characteristic of the surface ground is not considered in this study. Peak ground accelerations and peak ground velocities of the earthquake ground motions considering the average site amplification factors were smaller than the average of those of the individual earthquake ground motions as shown in Figure 11. The reason is that distributions of peak ground accelerations and peak ground velocities followed lognormal distributions. Average ratios of the former to the latter were 0.90 for the peak ground acceleration and 0.86 for the peak ground velocity. From the above, it is suggested that utmost care is required for setting design earthquake ground motions because the evaluation of the earthquake ground motion with average site amplification factors may lead to earthquake resistant design on the dangerous side. Figure 12 shows the relation between the standard deviations of peak ground accelerations and peak ground velocities and those of the site amplification factors. Standard deviations of peak ground accelerations and peak ground velocities were large in cases where standard deviations of site amplification factors were large. The average ratios of the former to the latter were 0.59

for peak ground accelerations and 0.70 for peak ground velocities.

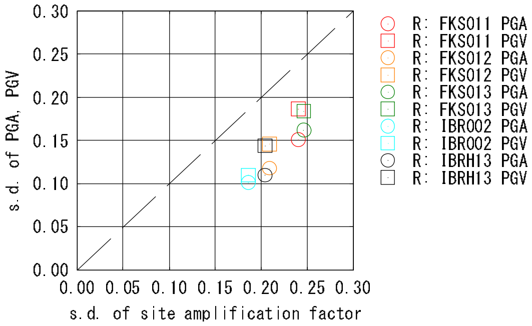


Fig. 12. Relation between the standard deviations of the site amplification factors and those of the peak ground acceleration and the peak ground velocity

V. CONCLUSION

This study discussed the variations of earthquake ground motions affecting earthquake resistance by utilizing the spectral analysis of the strong motion record obtained at plural sites. The variations of earthquake ground motions considering the variation of site amplification factors were evaluated and the effect of variations of site amplification factors on the representative values of earthquake ground motions were discussed. The following are derived from this study:

- Distributions of site amplification factors followed lognormal distributions. The longer the distance between the reference and the target site, the larger tended to be the variation of the site amplification factor. Distributions of peak ground accelerations and peak ground velocities also followed lognormal distributions.
- Both peak ground accelerations and peak ground velocities of earthquake ground motions considering average site amplification factors were smaller than the average of those of the individual earthquake ground motions.
- Utmost care is required for setting the design earthquake ground motions because the evaluation of earthquake ground motions with average site amplification factors can lead to the earthquake resistant design on the dangerous side.

These findings were derived from the strong motion records observed at six earthquake ground motion observation stations in Fukushima and Ibaraki prefectures in Japan. Further work on the applicability of these findings to other strong motion records is underway in order to discuss reasonable design earthquake ground motion setting method.

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