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PREDOMINANT PERIOD AND NON-LINEAR RESPONSE OF SOIL LAYERS FROM MULTIPLE-SITE RECORDS

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ABSTRACT

The non-linear characteristics of site effects due to the seismic motion are investigated. A combined mean-site-effect-spectrum of network recordings is introduced as a reference spectrum. The site-to-mean spectral ratios obtained by comparing recording spectra with the reference spectrum, show the non-linear behavior of soil deposits very clearly. The results indicate that non-linear characteristics that exist commonly, can be very large, and make the site response complex. Due to the different seismic motions, not only the predominant period shifts, the modal contributions change also. The results show that using weak motion records, predominant period fit the horizontal to vertical spectral ratio of microtremor and transfer function of shear-wave well. The proposed method gives a stable predominant period and amplitude of the site-to-mean spectral ratio under different strong ground motions due to the recent earthquakes.

KEYWORDS

Site-to-mean spectral ratio; site effects; non-linear effect; strong ground motion; multiple-site records; microtremor.

INTRODUCTION

The effects of local soil conditions are of particular significance in the prediction of earthquake ground motion and is an important factor for the earthquake damage estimation. To investigate such effects of surface geology on seismic motion, 1) transfer function from analytical models (Ansary *et al*, 1995), 2) site effects of seismic recordings through the resolution of an inverse problem (Kato *et al*, 1994), and 3) a horizontal to vertical spectral ratio of microtremors (Nakamura, 1989) are generally used. However, these methods can not give reliable results for some cases, and they are significantly impaired by their a priori linear assumption. During strong motion earthquakes, a linear numerical model of soil or a spectral ratio of microtremor can not predict the behavior of soil deposits correctly. The traditional inverse resolution method with linear assumption, can not give us a good estimate of response at strong motion site either. Recent earthquakes, like the 1994 Northridge Earthquake and the 1995 Hyogoken-Nanbu Earthquake, provided many near source recordings, these clearly demonstrate the consideration of non-linear effects at the sites.

The authors developed a new method, called the site-to-mean spectral ratio (SMSR) (Tong and Yamazaki, 1995a), to investigate the predominant period of the soil deposit from multiple-site records. This method does not include a priori linear assumption. The site effects at the same station given by the new method, are not the same for the different events. The differences are mainly due to different intensity of ground motions, and partially dependent on the source characteristics of the earthquake events. In this method, for the weak motions, the peak locations match the results given by the horizontal to vertical spectral ratio of microtremor and the transfer function of shear-wave very well, and for the strong motions, predominant periods of surface layers becomes longer when the ground motion becomes stronger. Site amplification characteristics of the proposed method are not only dominated by the first mode of ground vibration but also higher modes.

THE SMSR METHOD

The method proposed here, is based on removing the source effects and path effects from the recordings. Basically, for any one recording , which is obtained at the j station, due to the k event, can be described in the frequency domain as follows:

$$F_{kj}(f) = S_k(f)\cdot T_{kj}(r_{kj}, f)\cdot G_{kj}(f) \qquad (1)$$

where $F_{kj}(f)$ is the Fourier spectrum of each record, $S_k(f)$ is the source spectrum of event k, $T_{kj}(r_{kj}, f)$ is the path effect term, and the last term $G_{kj}(f)$ is the site effect in station j.

In the traditional inverse method, $G_{kj}(f)$ is estimated from the logarithmic form of equation (1), by the least square weighted inversion on linear equations. To resolve this problem, two assumptions are introduced. The assumptions are as follows: instead of the real path term $T_{kj}(r_{kj},f)$, an a priori frequency dependency law is used, and $G_{kj}(f)$ is assumed to be independent of the intensity of ground motion. The second assumption means that the non-linear characteristics is removed before resolving. At a real station j, if the seismic motion intensity are different during the event k and the event $k+1$, considering the non-linear properties of site j, it will be difficult to accept the assumption: $G_{kj}(f) = G_{k,j+1}(f) = G_j(f)$. However, excluding the site linear assumption, traditional inverse method can not be performed. Apparently, some new techniques are required .

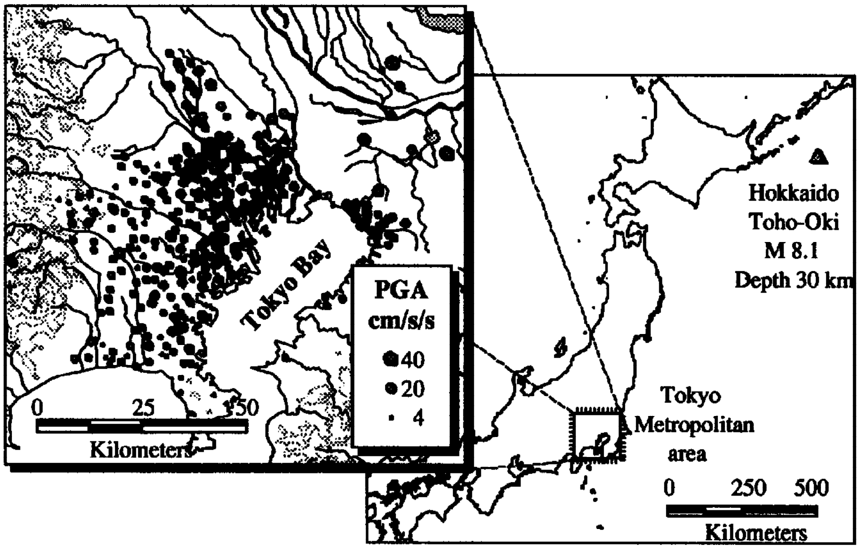


Fig. 1. In Tokyo Metropolitan area, 31 two horizontal component accelerographs have been installed by Tokyo Gas Company (Yoshikawa *et al.*,1995). This figure shows the distribution of PGA in cm/s/s from these stations and more than 300 *SI* sensors during the Hokkaido-Toho-Oki earthquake (Japan, Oct. 4, 1994, M_{JMA} = 8.1, Depth = 30km)

Figure 1 shows a particular recorded data set. Within this particular regional network, the maximum of site-to-site distances is 100 km, and the average of site-to-source distances is 1,100 km. In this case, since the site-to-source distance is large, the source term, $S_k(f)$, and the path term, $T_{kj}(r_{kj}, f)$, are almost same for the recording stations. Differences between the recording spectra, $F_{kj}(f)$, are due to the site effects, $G_{kj}(f)$, only. If a site is selected as the reference of these stations in the network, each relative site effect can be estimated through the spectral ratio given by $F_{kj}(f)/F_{k,ref}(f)$. However, an ideal reference site, free from any site effect, is not available. Here, the mean-site-effect-spectra (MSES) is defined as

$$R_k(f) = \frac{1}{n}\sum_{j=1}^{n}\frac{F_{kj}(f)}{\overline{F}_{kj}} \tag{2}$$

where, $F_{kj}(f)$ is the Fourier spectrum at the station j recorded during the event k, $\overline{F}_{kj}$ is the average amplitude of $F_{kj}(f)$ in the range of 0.5 Hz to 25 Hz, and n is the number of the recording sites used. In equation (2), each site Fourier spectrum is normalized by $\overline{F}_{kj}$, that makes the influence of each station to the $R_k(f)$ equal, for all sites including very sensitive sites as well as insensitive sites. If the site effect in each stations is comparatively different, Eq. (2) will average the frequency dependency of the site effects. This means that in an ordinary case, using $R_k(f)$ as a reference site is much better than using any real recording. By introducing the normalized reference site spectrum, a spectral ratio can be given by

$$U_{kj}(f) = \frac{F_{kj}(f)}{R_k(f)} \tag{3}$$

for all the recording sites and considering two horizontal components, the following two methods can be considered as methods to combine the effects of the two components:

$$C(f) = \sqrt{U_{kj}^{x}(f)U_{kj}^{y}(f)} \tag{4}$$

or

$$C^{*}(f) = \sqrt{U_{kj}^{x}(f)^2 + U_{kj}^{y}(f)^2} \tag{5}$$

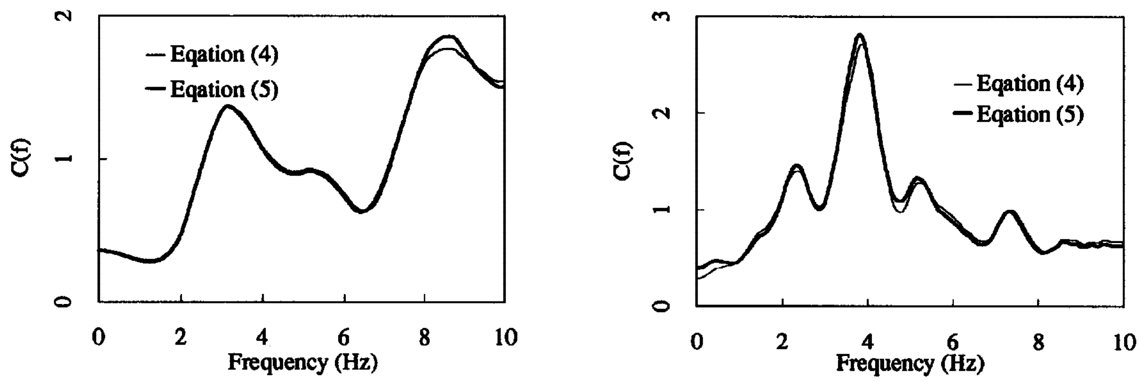


Fig.2. Comparison of equations (4) and (5). Left figure is from the Meguro station in the Network shown in Fig. 1 and the right one is Tokyo station of JMA-87 wide range network.

Here, equation (4) shows the common site effects in two directions, and equation (5) reflects tendencies of two directions. As shown in Fig. 2, the differences caused by the two kind of synthesis methods are very small, but the curve given by Eq. (5) shows the peak more clearly. In this study, Eq. (5) is used for analysis. Finally, since the $C_{kj}(f)$ is taken from a spectra to a normalized spectrum, that will change the amplitude largely depending on the intensity of seismic motion, the SMSR (site-to-mean spectrum ratio) is normalized by the amplitude average $\overline{C}_{kj}$ (between 0.5-25 Hz) of the combined ratio defined as

$$g_{kj}(f) = \frac{C_{kj}(f)}{\overline{C}_{kj}} \qquad (6)$$

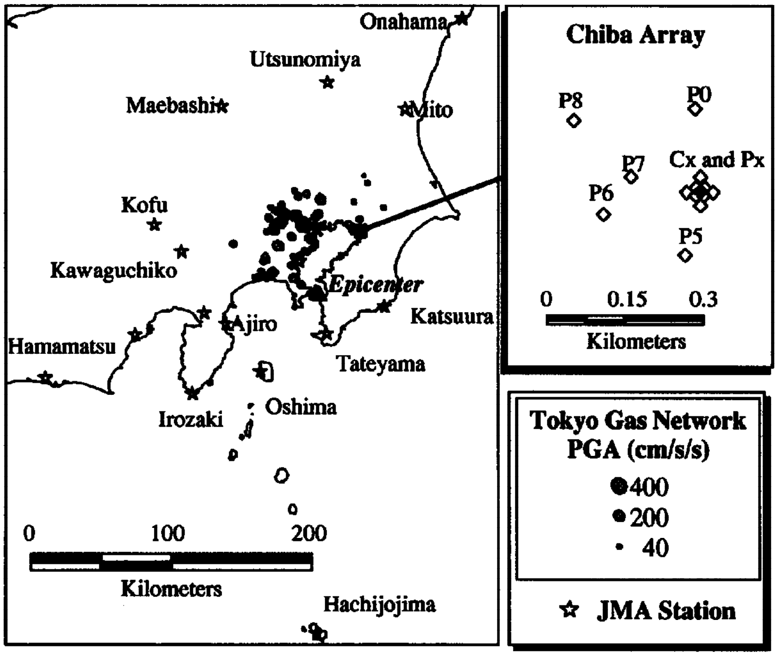


Fig.3. Comparison of three different scale networks. The circle marks show the distribution of PGA due to the Tokyo Bay Earthquake (Feb. 2, 1992, M_{JMA} = 5.9, Depth = 93 km) recorded at the regional network (Tokyo Gas). The star marks show the stations in wide range network (JMA, 1991), and the diamonds are points at Chiba Array.

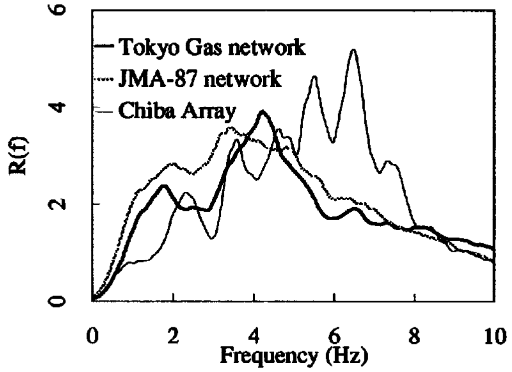


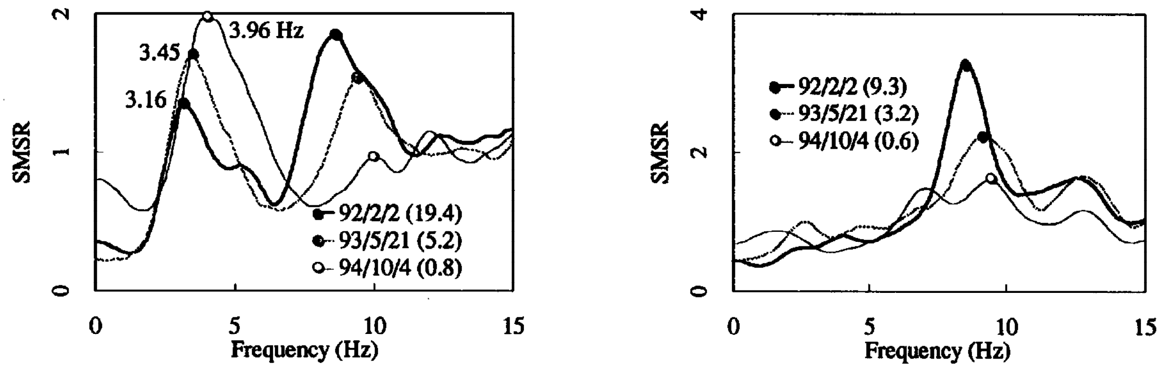
Fig.4. Comparison of three mean-site-effect-spectra given by different scale network for the same event (Fig. 3).

In the far-field recording (such as Fig. 1), the application is ideal, but for near-field recordings, the path and the source terms in Eq. (1) can not be assumed to be the same. For an array stations around an earthquake fault, even the source term in Eq. (1) is not the same during the same event. Figure 3 shows three different observation network, and the distribution of Peak Ground Acceleration (PGA) recorded from one of these networks due to the Tokyo Bay Earthquake. Figure 4 shows the comparison of mean-site-effect-spectra given by the three different scale networks. The largest observation network of JMA (excluding the very weak motion recordings), for recording stations the maximum site-to-site distance is 440 km, and the minimum, average and maximum of site-to-source distance are 26, 113 and 237 km, respectively. The middle scale network of Tokyo Gas, the maximum site-to-site distance is 100 km, and the minimum, average and maximum of site-to-source distance are 12, 50 and 87 km, respectively. Finally, the smallest network is a very dense array at Chiba (Katayama *et. al*, 1991), the maximum site-to-site distance is 0.3 km, the average of site-to-source distance is 51 km. As shown in the Fig. 4, the mean-site-effect-spectrum is very similar for the largest and the middle array networks, but it is different for the smallest array network. This comparison shows that, large networks with different path effects, like the site effects as mentioned earlier, Eq. (2) will average the frequency dependency of the path effect. On the other hand, if a network is too small although with many components, all the recordings will have the same site effect. This only noises are cancel out by applying Eq. (2). It is obvious that the method proposed here has some limitation. It can not be used in the cases where all the records are obtained by closely spaced stations.

In this study, using the different recorded data sets, including the recordings in the Kobe area during the Hyogoken-Nanbu Earthquake, the difference from the source and path terms still allow the application of the above approach. This results can be interpreted by the fact the frequency dependency of the path effect is less sensitive compare to the source and site effects.

THE NON-LINEAR EFFECT BY THE SMSR

The earthquake observation stations in the Tokyo Gas network shown in Fig. 1 have recorded many recent earthquakes including near-field and far-field recordings. These provide seismic motion with different intensity. From these recordings, the SMSRs of different events at each site are calculated.



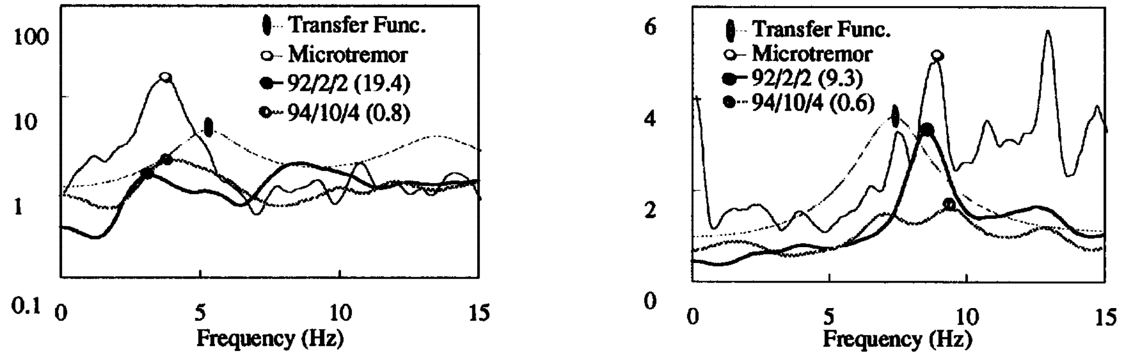
(a) Meguro station of Tokyo Gas network

(b) Hoya station of Tokyo Gas network

Fig. 5. Shift of predominant peaks of site-to-mean spectrum ratio with different earthquake events discriminate by the date in the legend . As an index of intensity of records, the values in parentheses are average amplitude of Fourier spectrum in cm/s.

Figure 5 (a) shows three SMSR at Meguro station, a relative sensitive site. During most of the recorded events, the PGAs at Meguro are larger than the other stations around it. The non-linear characteristics in site amplification in the different level of seismic motion are clearly shown. The values in parentheses is the average amplitude of Fourier spectrum of each recording, that is an index of seismic motion intensity. As shown in the figure, the fundamental resonance frequency shifts from high to low values, and the second mode becomes more dominant as the ground motion changes from weak to strong motion. The peak location's difference, between the strongest (PGA is 363 cm/s/s) and the weakest (PGA is 19 cm/s/s) motions is 3.96-3.16 = 0.8 Hz, almost one-fifth of the fundamental resonance frequency. Figure 5 (b) shows Hoya station, in the same network (Fig. 1), which has rather ordinary shaking intensity. This station has a quite high fundamental resonance frequency about 9 Hz, but the non-linear effect of site amplification still exist, although the seismic motion is not so strong (PGA$_{\text{strong}}$ = 172 cm/s/s, PGA$_{\text{weak}}$ = 11 cm/s/s)

To check these results given by the proposed method, the peak location of SMSR for 31 sites are compared with microtremor measurements and the transfer function of the shear-wave propagation (Ansary *et. al.*, 1995). Fig. 6 shows two instances of the comparison between the SMSR, microtremor method and shear-wave transfer function. For the calculation of transfer function of shear-wave, a damping ratio of 2% has been used, assuming input motion at the outcrop. From the comparisons shown in Fig. 6, it can be concluded that generally, the position of fundamental period from the three different methods fit well for weak motions, but for strong motions only SMSR can be used. In the case when the curves show different results, the SMSR gives most stable result for all the sites and for all the events. Under more than one strong motions recorded at the same station as shown in Fig. 7 (a) and (c), the proposed method gives stable predominant period and amplitude. To investigate the complex site effects using weak and strong ground motions together, the SMSR is very useful, especially in estimating the predominant period of site, and their non-linear characteristics.



(a) Meguro station of Tokyo Gas network

(b) Hoya station of Tokyo Gas network

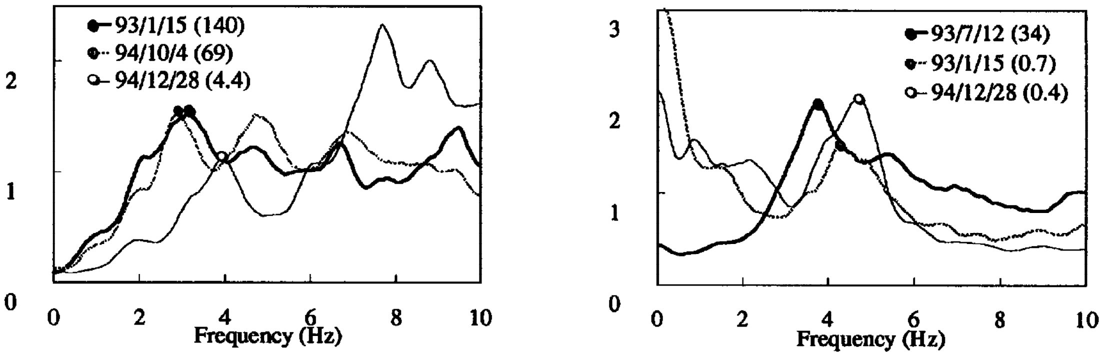
Fig. 6. Comparison between the SMSR, microtremor method and shear-wave transfer function. The SMSR of the strongest and the weakest motions are plotted.

THE NON-LINEAR RESPONSE AT THE DAMAGING SITE

From January 1993, five damaging earthquakes occurred in Japan, and all of them provided strong seismic recordings (Tong and Yamazaki, 1995b; Yamazaki *et al.*, 1995). Table 1 summarizes the five events together with the strongest JMA-87 recordings. Figure 7 shows the results of SMSR for four stations of JMA-87 observation network, where the largest PGA are recorded during the five events (two recordings were at JMA Kushiro station). It is believed that the non-linear site effects play a key role in the ground motion at the four sites during the five events. Applying the SMSR method quantitative estimates of non-linear site effect is possible as can be seen from Fig. 7. Comparing the weak ground motion recording at the same stations, all of strong motions (the bold lines) change the fundamental resonance frequency greatly. At the case where two strong motions were recorded, the two resonance frequencies are quite stable (Kushiro (a) and Hachinohe (c)). It can be concluded that, the predominant periods obtained by the SMSR for strong motion recordings are quite stable, and at these four sites, any estimate of strong motion without consideration of non-linear site effect will not be reliable.

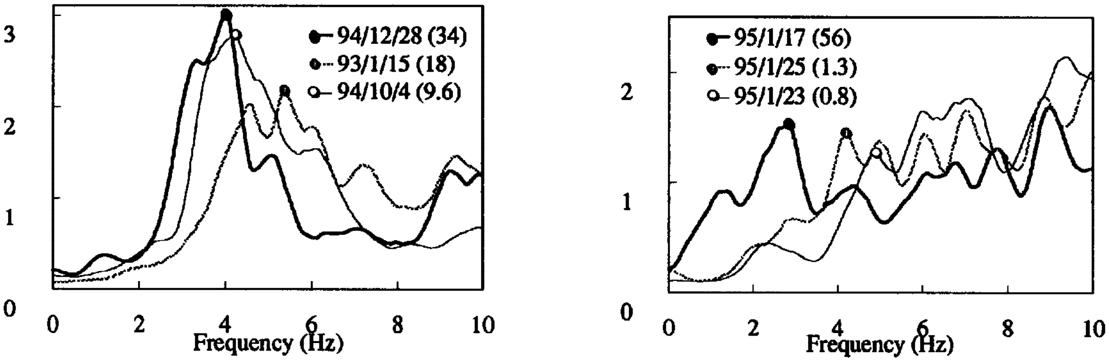
Table 1. Summary of five large earthquakes in Japan and strong motion records

Earthquake	Kushiro-Oki	Hokkaido-Nansei-Oki	Hokkaido-Toho-Oki	Sanriku-Haruka-Oki	Hyogoken-Nanbu
Data	Jan. 15, 93	July 12, 93	Oct. 4, 94	Dec. 28, 94	Jan. 17, 95
Epicenter	42° 51' N 144° 23' E	42° 47' N 139° 12' E	43° 22' N 147° 40' E	40° 27' N 143° 43' E	34° 36' N 135° 02' E
M_{JMA}	7.8	7.8	8.1	7.5	7.2
Depth (km)	110	34	30	Very shallow	14
JMA station	Kushiro	Suttsu	Kushiro	Hachinohe	Kobe
PGA. (cm/s/s)	919	216	474	602	818
Epicentral Distance (km)	14	84	270	185	17
SMSR (in Fig. 7)	a	b	a	c	d



(a) JMA Kushiro station

(b) JMA Suttsu station



(c) JMA Hachinohe station

(d) JMA Kobe station

Fig. 7. Comparison of SMSR between the strong motions and weak motions at four JMA stations. The bold lines show the recording with the largest PGA at each station. As an index of intensity of recording, the values in parentheses are average amplitude of Fourier spectrum in cm/s.

CONCLUSIONS

The site-to-mean spectral ratio (SMSR) of different intensity recordings shows that the predominant period becomes larger as ground motion becomes stronger. The results of this study show the complexity of site effects, that the response of site can not be determined only by the first mode, sometimes the higher mode become dominant. This tendency of the ratio could be attributed to the non-linear ground characteristics and frequency contents of the seismic waves. The procedure stated here can be applied to the data sets recorded on local to wide range observation networks but to the exclusion of very small arrays with the same site effects. Generally, the predominant period obtained by the proposed method using weak motion record, fit transfer function of shear-wave well, but in some cases when the different methods show different results, the new method is more reliable than the transfer function. For weak motion, the SMSR matches microtremor results quite well. But some sites, that do not have a strong contrast in the impedance ratio near the ground surface, there no clear peak exists by using the microtremor. In this case, if there exist seismic recordings, the proposed method is useful. For strong ground motion, the proposed method gives a stable predominant period and amplitude under different strong ground motions. On the other hand, the proposed method is based on multiple-site records. hence it can not be directly applied to the sites without earthquake observation. Some relationships between the SMSR and soil parameters might be required. To extend the use of the SMSR, some additional research is required. The SMSR provides only the frequency dependency but not site amplification, so next step of this research will be to supplement SMSR by combining the inversion methods and the SMSR to obtain the amplification factor.

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