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# ESTIMATION OF EMPIRICAL SITE AMPLIFICATION EFFECTS USING OBSERVED RECORDS

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## SUMMARY

A new approach to estimate site amplification effects using observed ground motion records is proposed. First, we calculate the “bed rock spectra”, adopting the omega-squared source model, frequency-dependent Q-factor, and free-surface effect. The source spectrum is given from seismic moment and corner frequency for each event, using observed records at rock site. The Q-factor is obtained from spectral inversion analysis. The site amplification, then, is defined as the ratio of observed seismic spectra to the “bed rock spectra” at each site. We apply this method to evaluate site amplification effects in Kansai area, Japan. The result are in good agreement with those obtained from the spectral inversion analysis so far done, as long as relative site amplification effects from both methods are compared. The spectral inversion method gives only site amplifications relative to a reference rock site. This method here proposed, instead, gives overall amplifications due to sedimentary layers overlying bed rock, even the site amplification effects caused by weathered layers on a rock site.

## INTRODUCTION

It is very important to estimate site amplification effects to predict strong ground motions at target sites. So far, site amplification effects have been evaluated by observational and theoretical approaches. For the observational approaches, there have been developed the spectral inversion method [Iwata and Irikura, 1988] using S-wave data of the observed ground motions from earthquakes and the H/V method, the spectral ratio of the horizontal components to the vertical component obtained from microtremor observation. For the theoretical approaches, the 1-D multiple reflection theory, the 2-D and 3-D finite element method and so on have been applied. However, there are some weak points in every method. For example, the spectral inversion method in the former approach gives only site amplifications relative to a reference site, and detailed soil layer parameters have been rarely obtained.

So, a new approach to estimate site amplification effects is proposed. In this method, the effects are evaluated by removing source and propagation path characteristics from observed spectra. This method is applied to estimate site amplification effects at earthquake observation sites. We compared with results from other method to confirm the applicability of the proposed method.

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## METHOD

### Site Amplification Effects

The site amplification is defined as the ratio of observed seismic spectrum to the "bed rock spectrum" at each site in this study (See Figure 1). The vectorial summation of two horizontal components is used as observed spectrum.

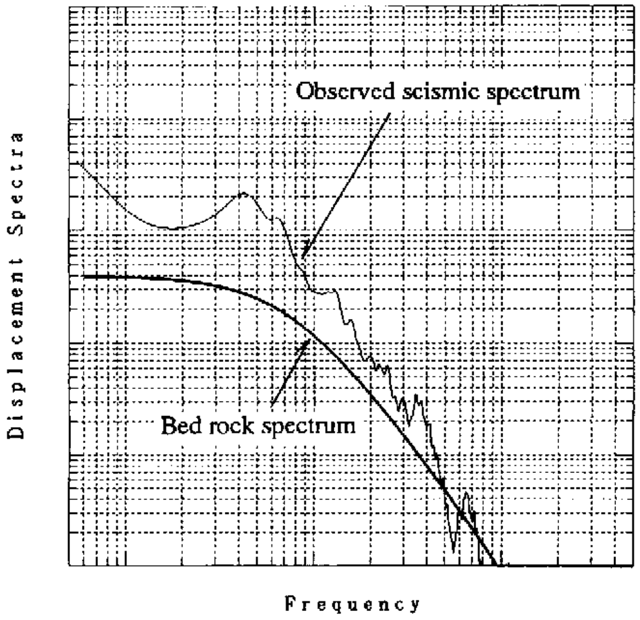

**Fig.1** Schematic illustration for calculating site amplification effects. Site amplification effects is defined as the ratio of observed seismic spectrum (thin line) to the "bed rock spectrum" (thick line) in the present study.

### Bed Rock Spectra

We calculate the "bed rock spectrum", considering source characteristics with the omega-squared model, propagation path effect with frequency-dependent Q-factor, and free-surface effect. The acceleration Fourier spectrum $A(f)$ (cm/s/s s) is expressed as

$$A(f) = CM_0 S(f) P(f) X^{-1} \exp \frac{-\pi f X}{Q(f)\beta}\ , \tag{1}$$

following [BOORE, 1986], where $f$, $M_0$, $X$, $Q(f)$, and $\beta$ are the frequency (Hz), the seismic moment (dyne cm), the hypocentral distance (cm), the frequency-dependent Q-factor, and the S-wave velocity (cm/s). The Q-factor is obtained from the spectral inversion method [IWATA and IRIKURA, 1988]. We used an S-wave velocity of 3.6(km/s) in this study. $S(f)$ is the source characteristics with the omega-squared model expressed as

$$S(f) = \frac{(2\pi f)^2}{1+(f/f_c)^2}\ , \tag{2}$$

where $f_c$ is the corner frequency (Hz). $P(f)$ is the high-cut filter that accounts for the observation that acceleration spectrum often shows a sharp decrease with increasing frequency above cut-off frequency, $f_{\max}$. $P(f)$ is expressed as

$$P(f) = \frac{1}{1+(f/f_{\max})}\ , \tag{3}$$

following [FACCIOLI, 1986]. $C$ is a constant given as

$$C = \frac{R_{\theta\phi} \times FS \times PRTITN}{4\pi\rho\beta^3}, \tag{4}$$

where $R_{\theta\phi}$, $FS$, $PRTITN$, and $\rho$ are the radiation pattern coefficient of S-wave, the amplification due to the free-surface effect, the reduction factor that amounts for the partitioning of energy into two horizontal components, and the density. We used the radiation pattern coefficient of 0.63 as the average value [BOORE and BOATWRIGHT, 1984], free surface effect of 2.0, and a density of 2.7 (g/cm$^3$). Since the vectorial summation of two horizontal components is used as observed spectrum, the reduction factor $PRTITN$ is taken as 1.0.

### Seismic Moment and Corner Frequency

Based on BRUNE's model [BRUNE, 1970], a seismic moment of an earthquake can be derived from the flat level of a displacement Fourier spectrum in low frequency range as

$$M_0 = \frac{4\pi\rho\beta^3}{R_{\theta\phi}} \times \Omega_0, \tag{5}$$

where $\Omega_0$ is the flat level of the corrected displacement spectrum in low frequency range at a unit distance from a source centroid. The flat level of the corrected displacement spectrum at low frequencies and the corner frequency are determined by the automated objective method [ANDREWS, 1986] using observed spectrum at rock site.

### Cut-off Frequency

If a seismic spectrum follows the omega-squared model, a shape of acceleration spectrum is flat above a corner frequency. Actually, the observed acceleration spectrum shows decaying with increasing frequency above a certain frequency called cut-off frequency, $f_{\max}$. The physical interpretation of $f_{\max}$ is still controversial, local site effect [HANKS, 1982] or source-controlled factor. If $f_{\max}$ is a property of local site condition, it should be a part of site effect i.e. $P(f)$ =1.0. If $f_{\max}$ is taken as source property, it should be given as a function of $M_0$ like

$$f_{\max} = 7.31 \times 10^3 \times M_0^{-0.12}, \tag{6}$$

following [FACCIOLI, 1986]. In this study, so, the site amplification effects are calculated by two ways.

Case1 : The $f_{\max}$ is not considered, i.e. $P(f)$ =1.0 in equation (1).

Case2 : The $f_{\max}$ obtained from equation (6) is considered.

## DATA

We applied this method to evaluate site amplification effects at 10 sites in Kansai area, Japan, which belonging to CEORKA (Committee of Earthquake Observation and Research in the Kansai Area). The observation has been doing by velocity-type strong-motion seismometers. The locations of the stations and the epicenters decided by Japan Meteorological Agency (JMA) are shown in Figure 2. In these stations, Amagasaki (AMA), Fukushima (FKS), Morigawachi (MRG), and Yae (YAE) are located on the alluvium in the center area of the Osaka basin. Kobe-Motoyama (MOT), Toyonaka (TYN), Sakai (SKI), and Tadaoka (TDO) are located on the diluvium. Two stations, Kobe University (KBU) and Chihaya (CHY) are located on the rock site. Table 1 shows the list of the events used in this study. The seismic moments and the corner frequencies of analyzed events estimated from observed spectra at KBU station are shown in Table 1. The following Q-factor that is obtained from the spectral inversion analysis in Kansai area [TAI *et al.*, 1995] is used.

$$Q(f) = 37.0 \times f^{0.84} \tag{7}$$

## RESULT

### Site Amplification Effects

Figure 3 show obtained site amplification effects at target stations. The bed rock spectra are calculated without considering $f_{\max}$ i.e. Case1. The thick lines represent mean value and the thin lines represent the standard deviation. The amplification factors at KBU and CHY located on the rock site are close to unity at low frequencies

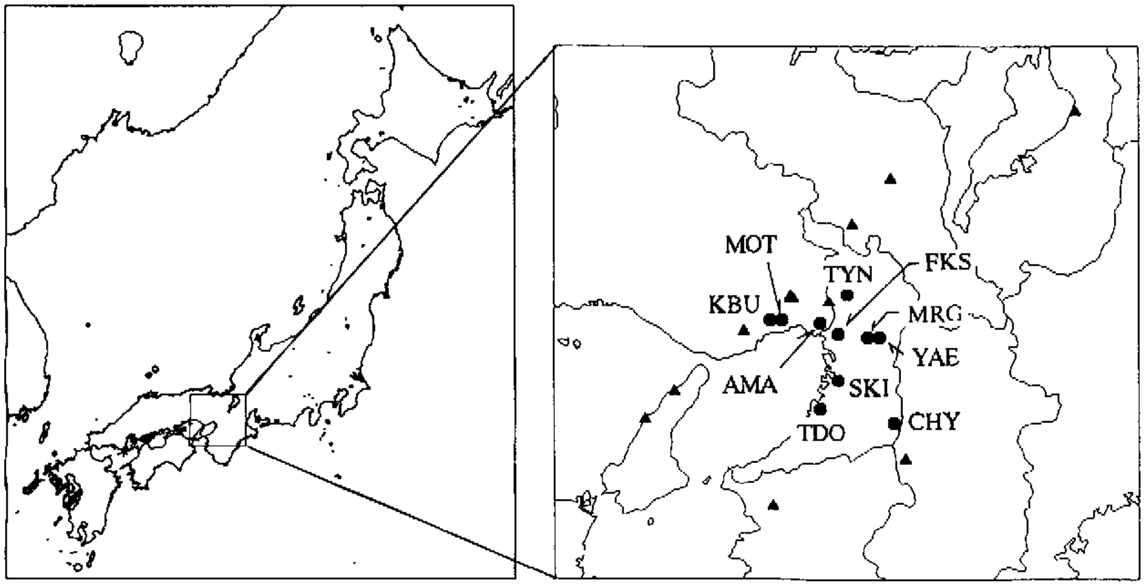

**Fig.2 Locations of the target sites(●) and the epicenters(▲) analyzed.**

**Table 1 List of events for estimating site amplification effects. Earthquake parameters are given by Japan Meteorological Agency (JMA). The seismic moments and corner frequencies of analyzed events are estimated from observed spectra at KBU station.**

| No. | Origin time | Latitude | Longitude | Region name of epicenter | Depth (km) | M | Moment (dyne cm) | $f_c$ (Hz) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1994.05.28 17:04:32.3 | N35°19.0' | E136°17.0' | NW Shiga Pref. | 44.0 | 5.2 | $5.042\times10^{24}$ | 0.70 |
| 2 | 1994.06.28 13:08:41.6 | N35°08.0' | E135°39.0' | Mid Kyoto Pref. | 15.0 | 4.6 | $2.118\times10^{23}$ | 1.20 |
| 3 | 1994.10.16 08:21:06.6 | N34°12.8' | E135°14.7' | NW Wakayama Pref. | 10.7 | 4.5 | $1.702\times10^{23}$ | 1.20 |
| 4 | 1994.10.24 11:51:05.5 | N35°00.0' | E135°31.0' | Kyoto Osaka Border Reg. | 15.0 | 4.3 | $1.070\times10^{23}$ | 1.51 |
| 5 | 1994.11.08 23:48:07.7 | N34°20.3' | E135°42.2' | Southern Nara Pref. | 74.7 | 4.3 | $4.574\times10^{23}$ | 1.25 |
| 6 | 1995.01.17 07:38:36.3 | N34°46.9' | E135°26.2' | SE Hyogo Pref. | 11.0 | 4.9 | $2.519\times10^{23}$ | 1.97 |
| 7 | 1995.01.23 06:02:28.4 | N34°31.8' | E134°54.4' | Awajishima Island Reg. | 15.4 | 4.5 | $1.177\times10^{23}$ | 1.95 |
| 8 | 1995.01.23 21:44:15.5 | N34°47.6' | E135°19.1' | SE Hyogo Pref. | 16.0 | 4.3 | $7.336\times10^{22}$ | 2.79 |
| 9 | 1995.01.25 23:15:57.2 | N34°47.4' | E135°18.8' | SE Hyogo Pref. | 16.7 | 4.7 | $2.445\times10^{23}$ | 2.12 |
| 10 | 1995.02.02 16:19:28.0 | N34°41.7' | E135°09.0' | Awajishima Island Reg. | 17.9 | 4.2 | $6.430\times10^{23}$ | 2.00 |
| 11 | 1995.02.18 21:37:33.9 | N34°26.7' | E134°48.4' | Awajishima Island Reg. | 12.6 | 4.9 | $6.483\times10^{23}$ | 1.29 |
| 12 | 1995.04.06 10:50:48.4 | N34°47.2' | E135°19.4' | SE Hyogo Pref. | 12.9 | 4.1 | $3.596\times10^{22}$ | 1.59 |

M: Magnitude in Japan Meteorological Agency(JMA) scale
$f_c$ : Corner Frequency

less than 2Hz. However, they increase up to about 2 around 4-5Hz, then decrease quickly at higher frequencies. The amplification factors around 4-5Hz are considered due to effects caused by weathered layers on a rock site.

On the other hand, AMA, FKS, YAE, and MRG on alluvium have larger amplification factors at low frequencies up to 2-3Hz, then smaller factors at higher frequencies because of low Q-factor in a soil layer. MOT, TYN, SKI, and TDO on diluvium have not common features in amplifications, varying from rock to alluvium.

Figure 4 shows comparison between the mean value of site amplification effects without considering $f_{\max}$ i.e. Case1 and with considering $f_{\max}$ i.e. Case2. The thin lines represent the amplification effects of Case1 and the thick lines represent those of Case2. The site amplification effects of Case2 are larger than those of Case1 at high frequencies, because the "bed rock spectra" are smaller beyond $f_{\max}$.

### Comparison of Site Amplification Effects Obtained from The Other Method

The spectral inversion analysis was applied to the target stations [TAI *et al.*, 1995]. To confirm the applicability of the proposed method, we compared the site amplification effects by this method with those by the spectral inversion analysis.

The site amplification effects obtained from the spectral inversion analysis [TAI *et al.*, 1995] are evaluated as relative value to the reference rock site, CHY. Then, the relative site amplifications are estimated by taking the ratios of the site effects at 9 stations to those at CHY as shown in Figure 5. The relative amplifications obtained here are compared with those by the spectral inversion analysis. The solid lines represent those by the represent method and the broken lines represent those by the spectral inversion analysis. At KBU station, the site amplification effect was not obtained by the spectral inversion analysis.

The results obtained here are in good agreement with those by the spectral inversion analysis except high frequency range. So, it is concluded that the proposed method is applicable to estimate site amplification effects.

## CONCLUSION

A new approach to estimate site amplification effects empirically is proposed in this study. The site amplification effects are evaluated by removing source and propagation path effects from observed record. The following conclusion is obtained.

1) The spectral inversion method gives only site amplifications relative to a reference rock site. This method here proposed, instead, gives overall amplifications due to sedimentary layers overlying a bed rock, even the site amplification effects caused by weathered layers on a rock site.

2) The site amplification factors at rock site are close to unity at low frequencies. However, they increase up to about 2 around 4-5Hz, then decrease quickly at higher frequencies. On the other hand, the site amplification factors on alluvium are large at low frequencies up to 2-3Hz, then smaller at higher frequencies. The site amplification effects on diluvium have not common features.

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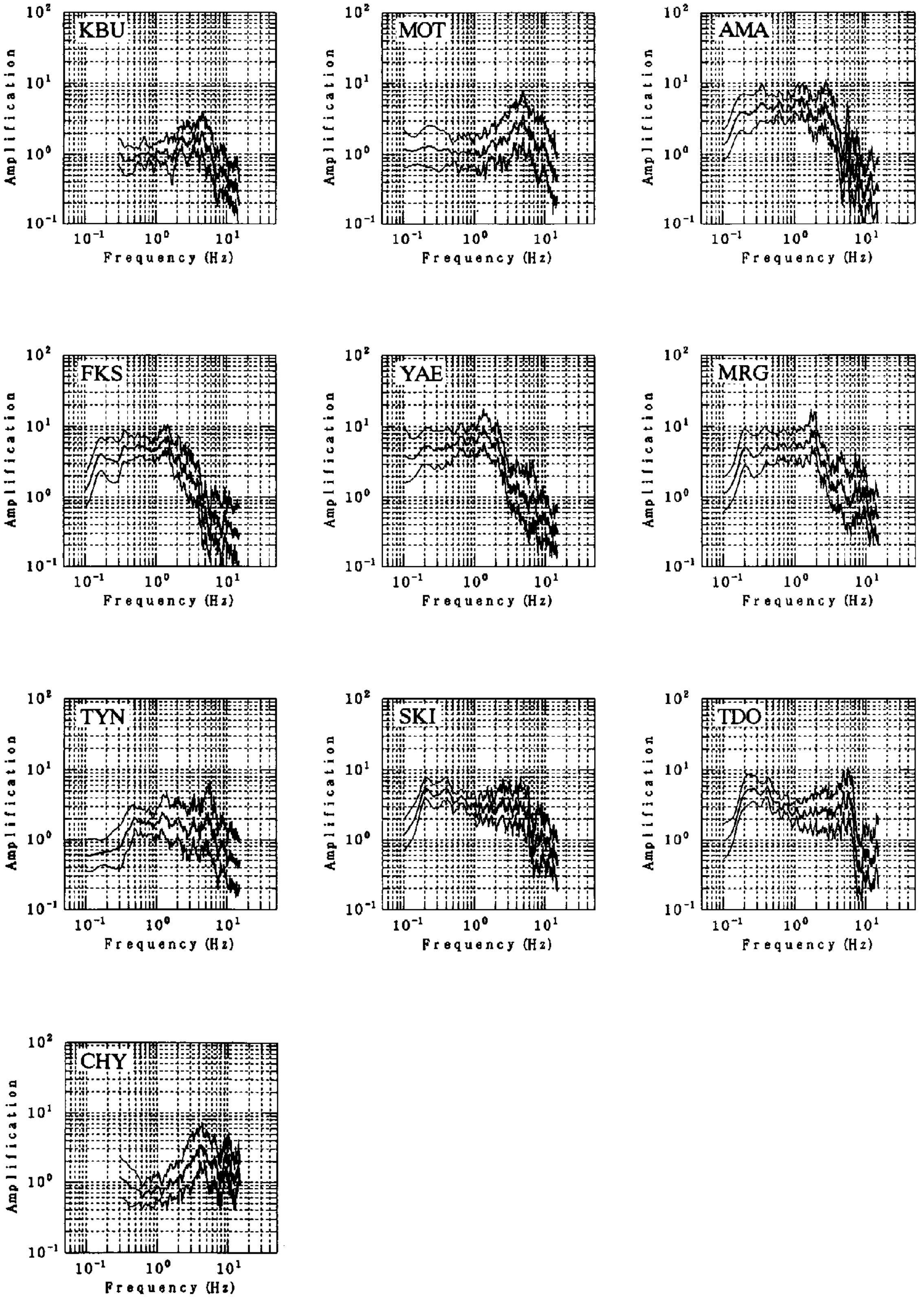

Fig.3 Site amplification effects. The bed rock spectra are calculated without considering $f_{max}$ i.e. Case1. Thick lines represent mean values. Thin lines represent the standard deviations.

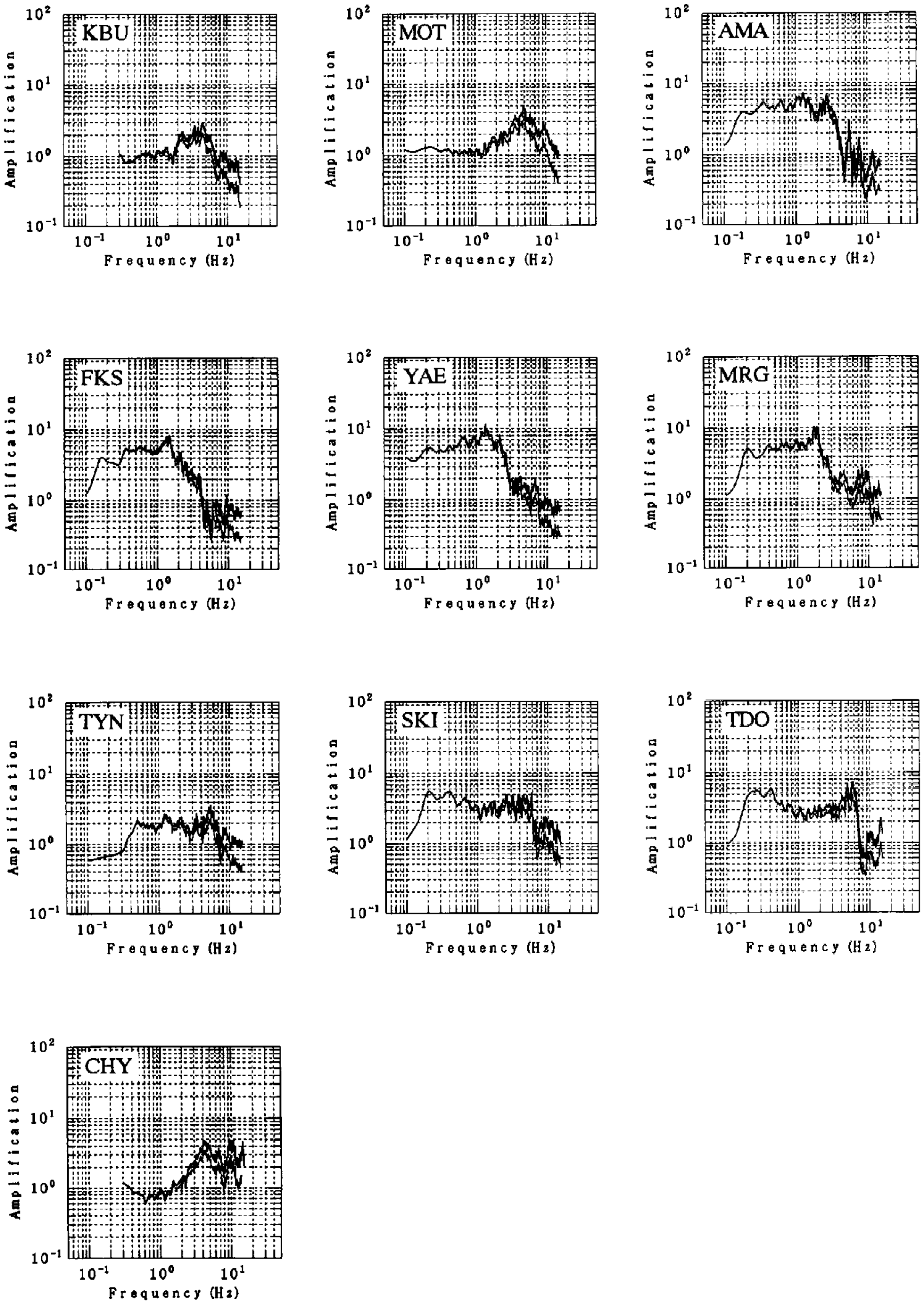

**Fig.4 Comparison between the site amplification effects with considering $f_{max}$ i.e. Case2 (thick line) and without considering $f_{max}$ i.e. Case1 (thin line).**

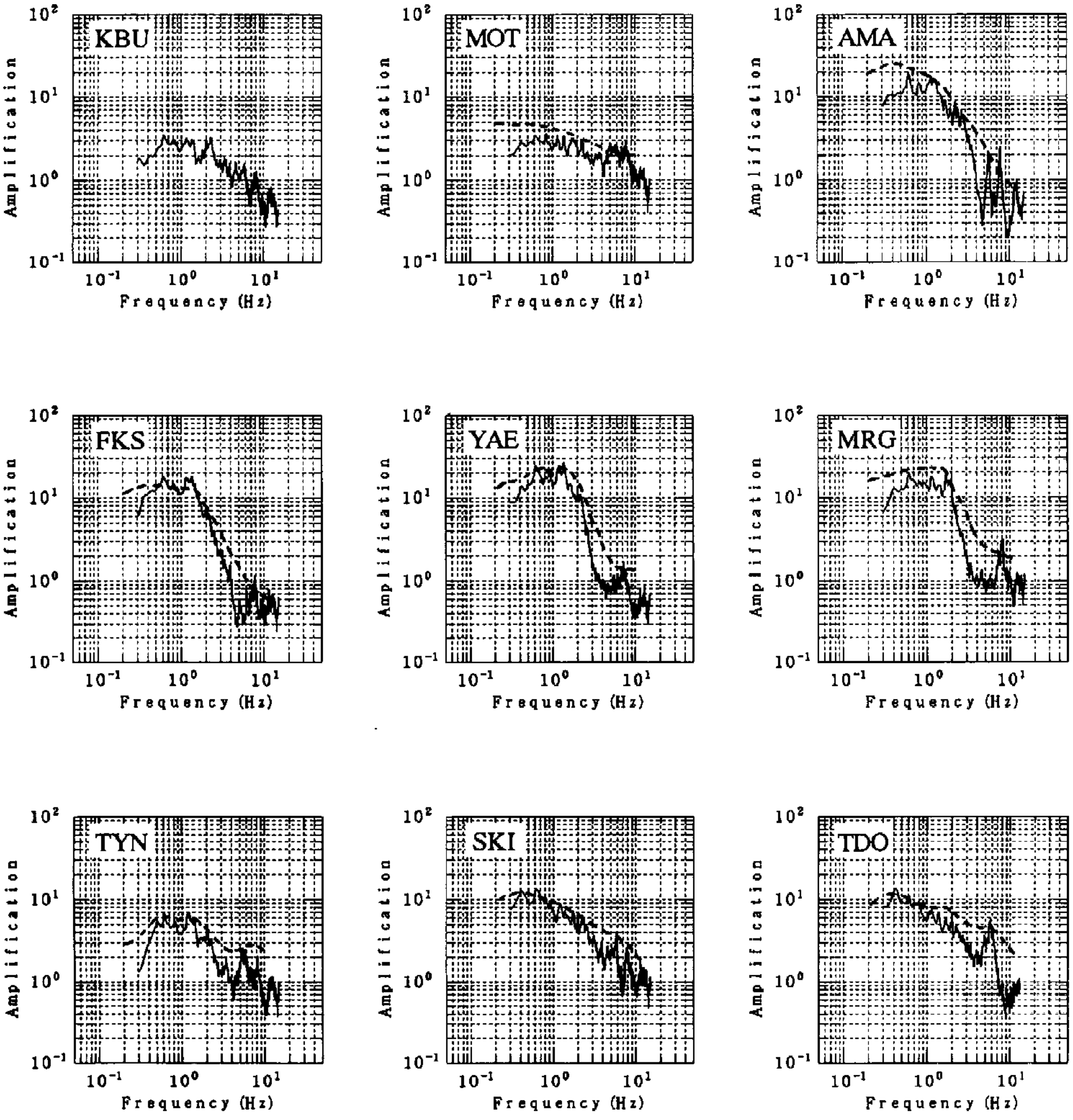

Fig.5 Comparison between the site amplification effects calculated by the present method (solid line) and those by TAI *et al.* (1995) (broken line).