13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 825

MODELING OF THE SPECTRAL AMPLIFICATION CHARACTERISTICS AT THE STRONG MOTION OBSERVATION SITES IN THE OSAKA BASIN, JAPAN

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SUMMARY

We have compared theoretical site-amplifications with empirical ones at sites in the Osaka basin, Japan, to validate an approach in modeling subsurface structures, where a subsurface structure model is made by combining simplified-deep and detailed-shallow models. The "deep model" is defined as a subsurface structure model covering a depth range from an engineering bedrock to the seismic bedrock, while the "shallow model" is defined as a subsurface structure model covering a depth range from surface to the engineering bedrock. A Pleistocene layer is regarded as the engineering bedrock in this study. The theoretical site amplifications are evaluated using this model with 1-D linear S-wave propagation theory. Empirical site amplifications are evaluated by using S-wave portion of observed waveforms. It is found that the theoretical site amplifications evaluated with 1-D theory using the above model gives fairly good approximations to the empirical ones at sites apart from basin edges.

INTRODUCTION

Accurate evaluation of site amplifications is needed to increase the accuracy in strong-motion predictions. Empirical evaluations by using observed waveforms of earthquakes (e.g., Iwata [1]; Phillips [2]; Tsurugi [3]) provide plausible results, but they provide the site amplifications only at the corresponding seismic stations. On the other hand, subsurface structure models (e.g., Horikawa [4]; Kagawa [5, 6]; Koketsu [7]) that are constructed by geophysical approaches are useful to evaluate site amplifications in the target area, but they have been used in frequency ranges up to or lower than 1Hz, because of the simplified model (e.g., Gil-Zepeda [8]; Horikawa [4]; Zhao [9]).

The aim of this study is to propose an approach in modeling subsurface structure for theoretical evaluations of site amplifications in wide-frequency ranges. Our target frequency range is 0.2 to 10Hz to include the natural frequency of most of structures. We address the Osaka basin, Japan, which has large amounts of strong-motion data and information on subsurface structure. Firstly, we estimate empirical site amplifications in wide-frequency range by using strong-motion waveforms observed at seismic sites. Secondly, we introduce an approach for constructing a subsurface structure model to evaluate site amplifications in the corresponding

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frequency range at those sites. Finally, we examine the effectivity of our approach in modeling subsurface structure, by comparing the theoretical site amplification factors with the empirical ones.

ESTIMATION OF EMPIRICAL SITE-AMPLIFICATION CHARACTERISTICS

We adopt a method proposed by Tsurugi [3] to evaluate empirical site amplifications. In their method, a seismic-bedrock spectrum is calculated by considering the omega-squared source spectrum and attenuation factor with body-wave geometrical spreading and frequency-dependent Q factor. The source spectrum is given from the seismic moment and the corner frequency for each event, which are estimated from observed records at a rock site. The Q factor is derived from spectral inversion analyses. A spectral ratio of observed seismic spectrum to the seismic-bedrock spectrum is taken for each event. Observed seismic spectrum is obtained by taking a root mean square of smoothed Fourier spectra of two horizontal components. Event-averaged spectral ratio is regarded to the empirical site amplifications.

Tsurugi [10] evaluated site-amplifications at sites in and around the Osaka basin, Japan by means of the above procedure. The target sites were seismic stations of the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) and those of K-NET deployed by National Research Institute for Earth Science and Disaster Prevention. They analyzed records of small earthquakes (Mw3.6-4.8) at hypocentral distances within 100km. Analysis frequency ranges were 0.2-10Hz for CEORKA data and 0.4-10Hz for K-NET from S/N ratio estimations.

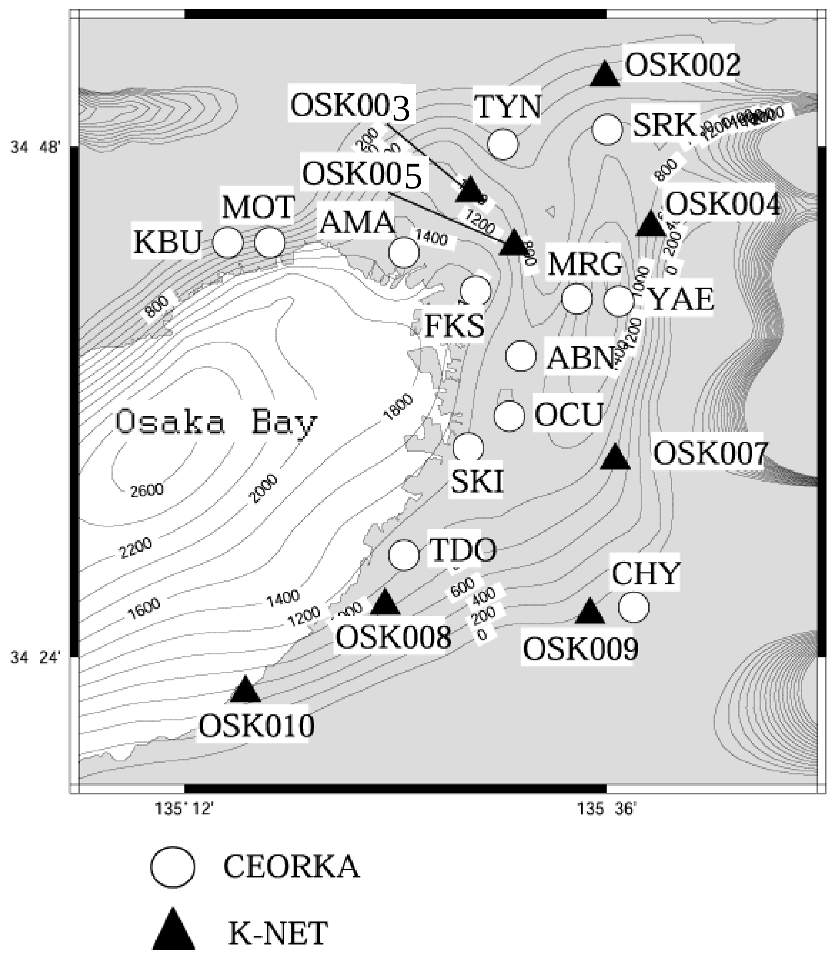


Fig. 1 Site map. Contours indicate the top depth [m] of seismic bedrock (Miyakoshi [11]).

In this study, 21 sites in the Osaka basin are selected from those of Tsurugi [2] (Fig. 1) and the empirical site amplifications are re-examined. The analyzing parameter sets used here are same as those of Tsurugi [10] except data duration. Tsurugi [10] used data length of 40.96 s from S-wave onset. In this study we use 7.00 s of S-wave portion in order to suppress effects of later phases. We analyze three to nine earthquake records per one station.

Fig. 2 compares the resulting site amplifications at site MRG with the original ones of Tsurugi [10], as an example. We can get the smaller amplification factor in the frequency range bellow 2Hz. As illustrated in the figure, remarkable decreases in amplification factor are seen at all sites, especially in the low frequency ranges, indicating that the effects of later phases are successfully suppressed.

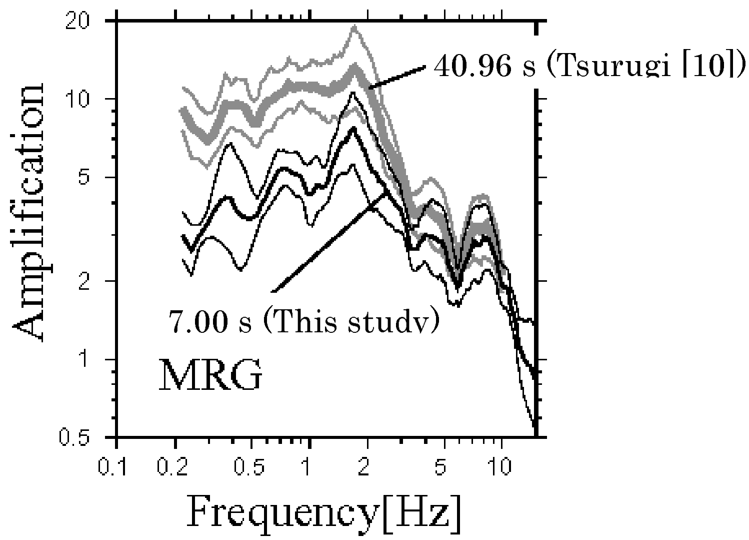


Fig. 2 Effects of analysis period for the empirical site amplifications at site MRG. Tsurugi [10] used analysis period of 40.96 s from S-wave onset whereas we used 7.00s of S-wave portion. Thick and thin lines correspond to the average and standard deviation, respectively.

THEORETICAL SITE-AMPLIFICATION CHARACTERISTICS

To construct a sedimentary-layer model adequately detailed over the whole-depth range from the surface to the seismic bedrock is not practical, especially for regions having thick sedimentary layers. Therefore we propose and examine a subsurface structure model that can be constructed by using limited amount of information, but that can reflect well the site-amplification characteristics of the sedimentary-layer structure. For this purpose, we divide the subsurface structure into deep and shallow parts defined as bellow: the "deep model" means a simplified 1-D subsurface structure model that represents sedimentary layers in a depth range from an engineering bedrock to the seismic bedrock; the "shallow model" means a detailed 1-D subsurface structure model from surface to the engineering bedrock. In this study the theoretical site-amplification factors are evaluated by the 1-D linear S-wave propagation theory with a subsurface structure model made by combining these models (combined model).

As the deep model, we adopt a three-dimensional model of the sedimentary basin structure proposed by Kagawa's group (Kagawa [5, 12], Miyakoshi [11]). They constructed the model based on substructural information obtained through geophysical explorations. In their model the sedimentary basin structure consists of three layers with the seismic bedrock (Table 1). The corresponding geologies for the first layer is regarded as from the depth of diluvial layers to Ma8, corresponding to layers from middle to late Pleistocene, according to Kagawa [12]. Alluvial layers, corresponding to Holocene layers, are excluded from this model. Because the interface topography of their model is represented by cubic B-spline functions, we can obtain the layer thickness beneath a site at arbitrary position.

To construct the shallow model, we use PS logging data at or neighbor (< 2 km) the site. We assume the interface between the Holocene and Pleistocene layers as the top of engineering bedrock, of which S-wave velocity is about 0.35km/s. The S-wave velocities of all PS logging data used in this study reach or approximately reach this value. There are no PS logging data nearby four sites of the CEORKA (OCU, TDO, TYN, YAE). Therefore theoretical site amplifications at these sites are evaluated by using only the deep models.

Table 1 Model parameters of the deep model.

Layer	Vp [km/s]	Vs [km/s]	Density [tf/m^3]	Corresponding geology
A	1.60	0.35	1.7	from diluvial layers to the top of Ma8
B	1.80	0.55	1.8	from the top of Ma8 to the lower part of Osaka group
C	2.50	1.00	2.1	from the lower to the lowermost parts of Osaka group
D	5.40	3.20	2.7	Seismic bedrock

Kagawa's model did not give attenuation characteristics as listed in Table 1. Adding to this, we do not have attenuation data to be used for the shallow models at all sites except MRG and MOT, where the attenuation coefficients are known from cyclic loading tests. Therefore, we observe attenuation effects on the theoretical site amplifications and estimate the attenuation factor of the subsurface structure model by comparing theoretical and empirical site amplifications.

In Fig. 3, we evaluated theoretical site amplifications for deep and shallow models separately by the 1-D theory, assuming h=0%, 1%, and 3% of attenuation coefficients in all layers. We can see from Fig. 3 (a) that the attenuation of the deep model affects significantly the spectral trends appearing in high frequency range. However, the spectral trend is not obvious up to 10Hz for the shallow model, as shown in Fig.3 (b). These are general tendencies at all sites in this study. Thus, we can expect that we could estimate the attenuation factor of the deep model from the spectral trend in the target frequency range.

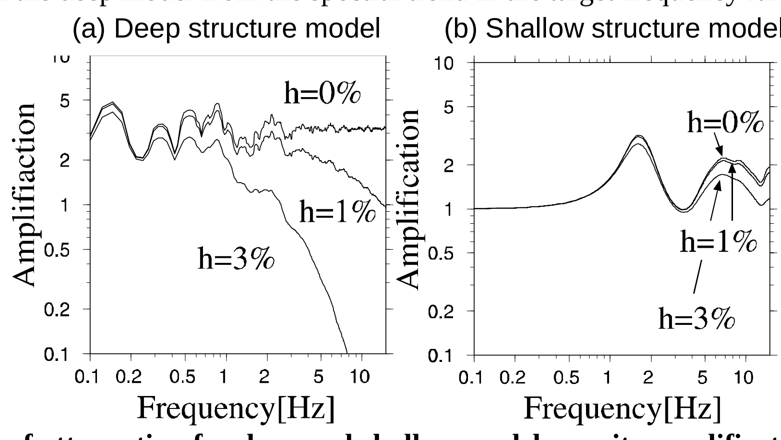


Fig. 3 Effects of attenuation for deep and shallow models on site-amplification evaluation (site MRG).

We determine attenuation coefficients by a forward modeling of spectral amplifications at site MRG. In a depth range from 4.5 to 21.0 m at site MRG, the attenuation coefficients h range from about 1% to 3% (for shear strain from 10^{-5} to 10^{-4}), according to tri-axial tests. Therefore, we use these values a priori for the shallow model. We take an ad hock procedure to determine the attenuation coefficients of the deep model, observing the agreement between theoretical and empirical site amplifications. When we use uniform values for all layers, h about 1% is found to be preferable for the deep model. Since it is expected that the attenuations decrease with depth, we finally assume the attenuation coefficients h of Layer A, B, and C as to be frequency independently 1.0%, 0.5% and 0.5%, respectively.

Fig. 4 compares the theoretical amplification factors of deep, shallow and combined models at site MRG with the empirical ones. The attenuation coefficients for the deep model are set to the above values, while those for the shallow model were set to the existing values. The 1-D theory is adopted for the evaluation. We can see from the figure that the resulting theoretical evaluation for the combined model explains the empirical site amplification factors fairly well.

We apply the above attenuation coefficients to the deep model also for the evaluation of site amplifications at the other sites in the following section. As the attenuation coefficients for the shallow models, we adopt uniformly 2% for all layers at every site except MRG and MOT, at which we use the existing values obtained from situ tests.

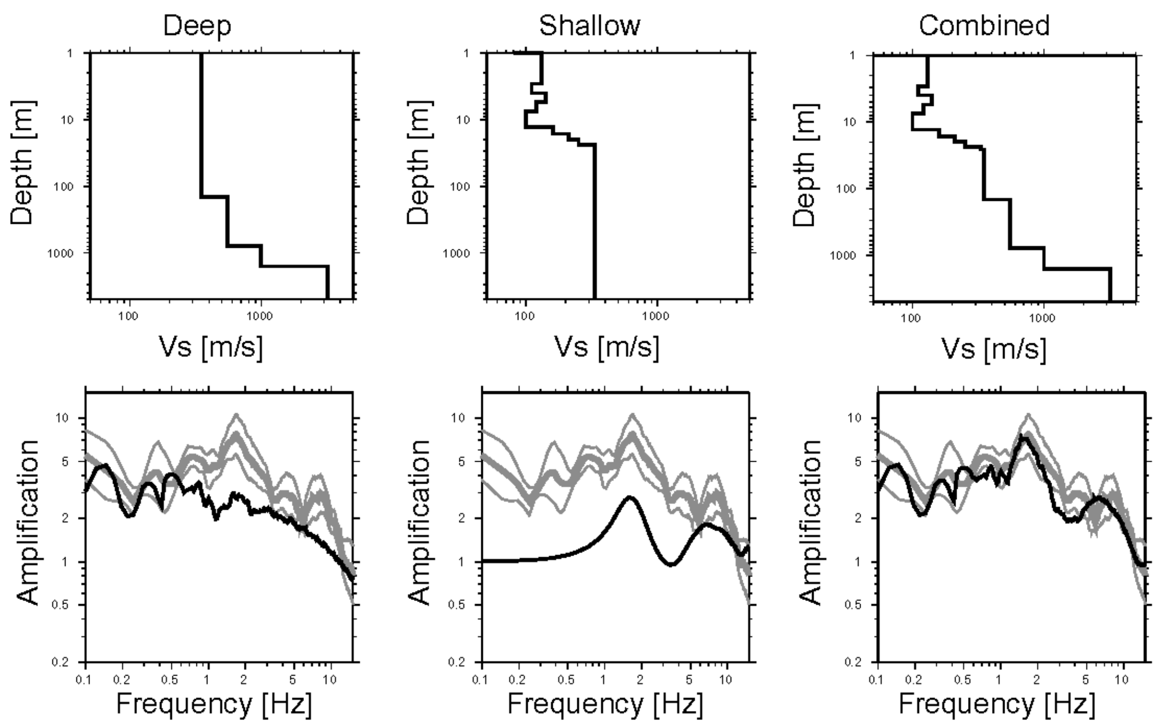


Fig. 4 Deep, shallow and combined models at site MRG (upper panels) and the corresponding theoretical site amplifications (solid lines in the lower panels), which are compared with empirical ones (shaded lines; thick and thin lines indicate the average and standard deviation, respectively).

COMPARISON BETWEEN THEORETICAL AND EMPIRICAL AMPLIFICATIONS

Fig. 5 shows the deep, shallow and combined models, and Figs. 6 and 7 compare the theoretical site amplification factors with the empirical ones. The 1-D theory is adopted for the evaluations. The theoretical evaluations due to the combined models mostly fall in the range between half and twice of empirical averages. Looking over the frequency range from 0.2 to 10Hz for CEORKA sites and from 0.4 to 10Hz for K-NET sites, both site amplifications in the lower frequency range fits better than those in the higher frequency range at most sites.

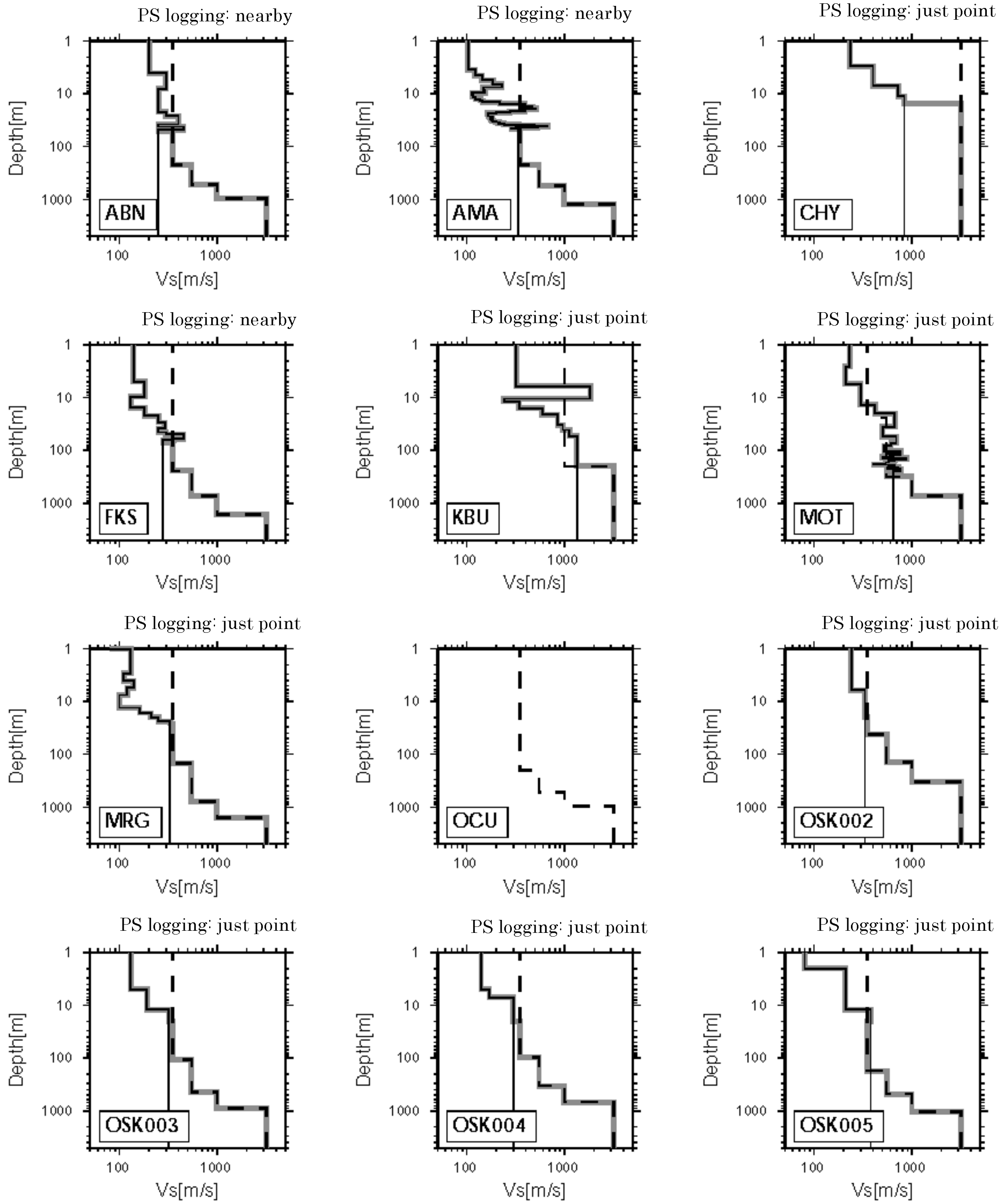


Fig. 5 S-wave velocity structure models. Solid, dashed, and thick lines indicate shallow, deep and combined velocity structure models, respectively. Log-log scale is used.

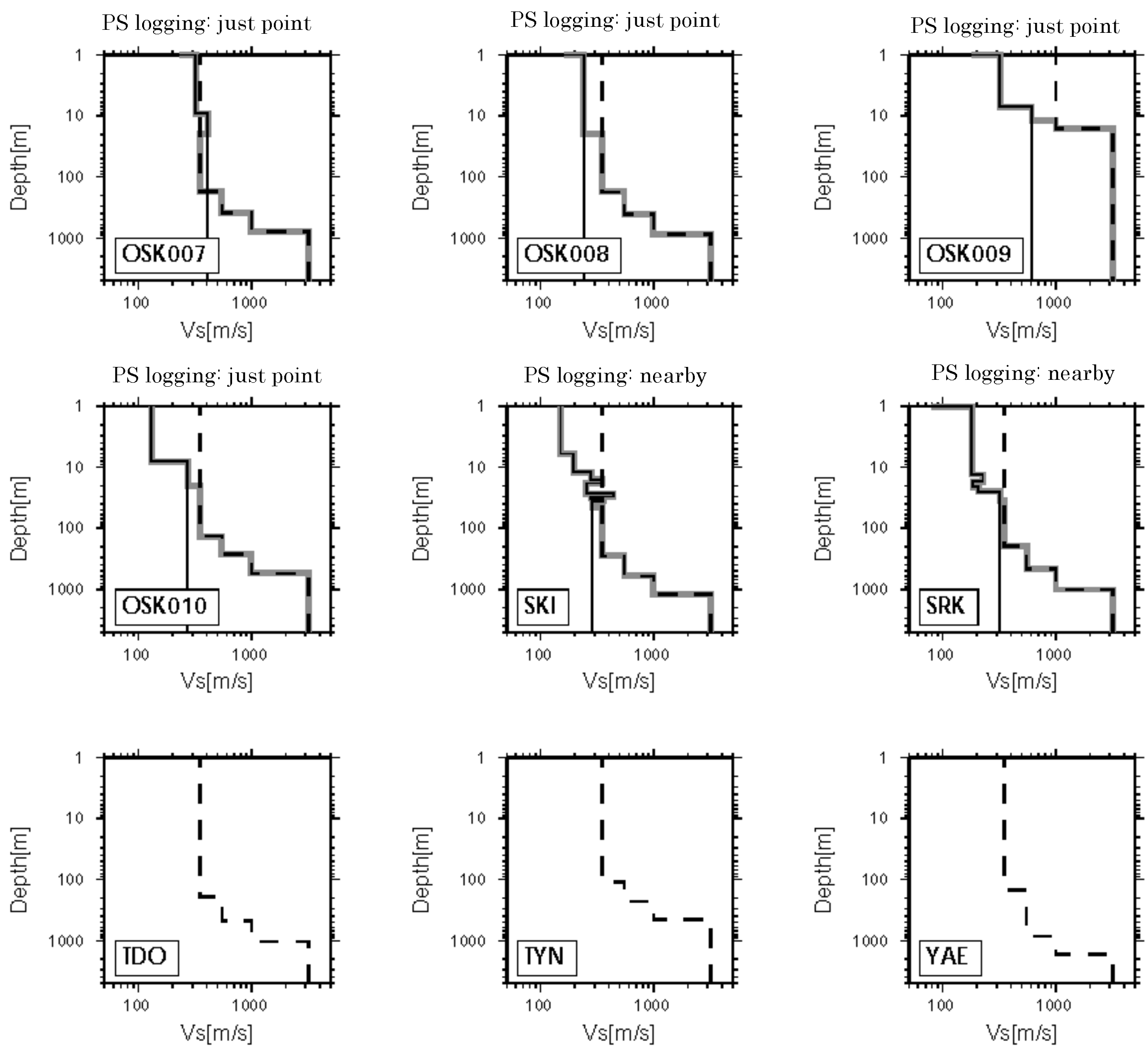


Fig. 5 Continued. We have only deep models at sites TDO, TYN and YAE.

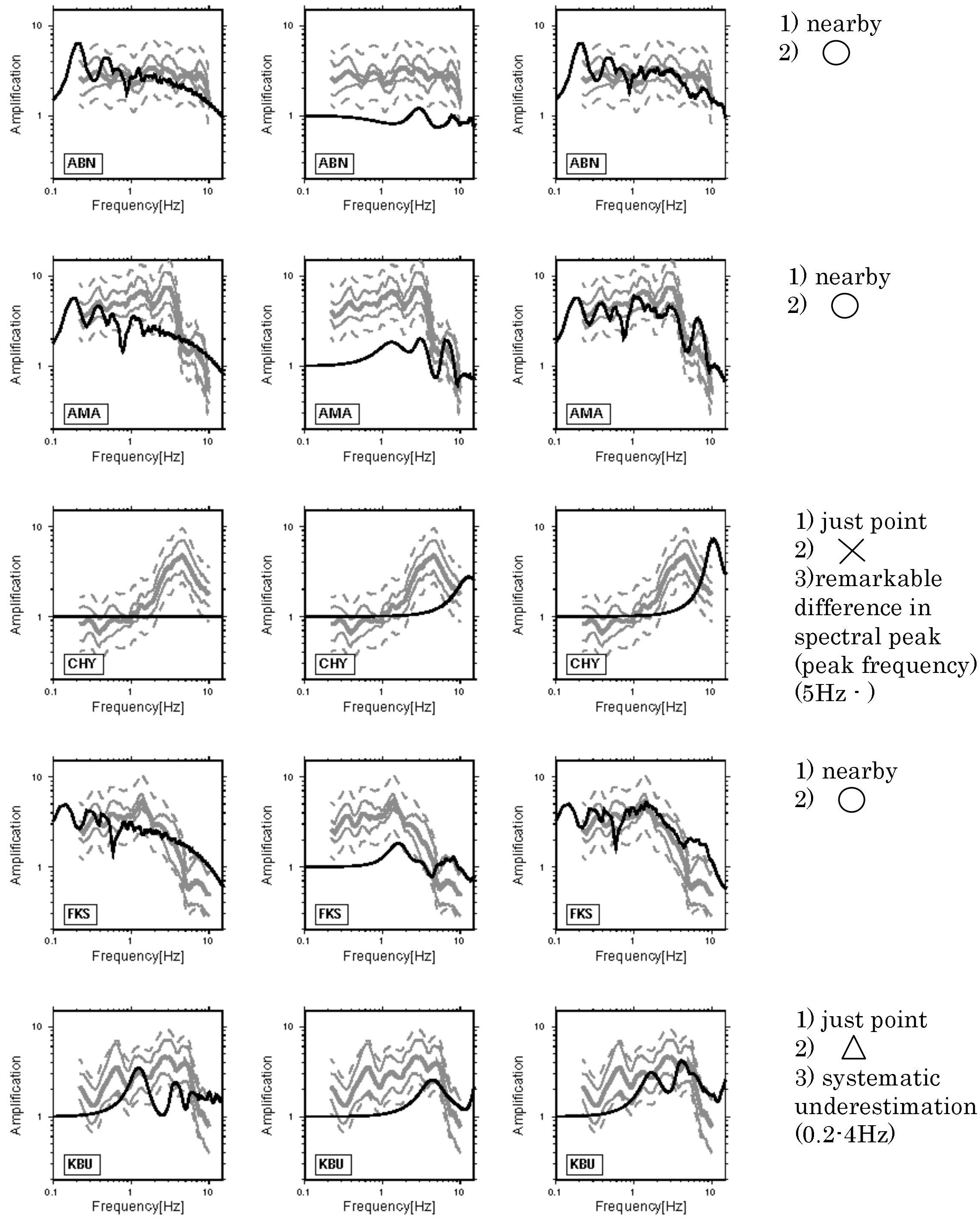
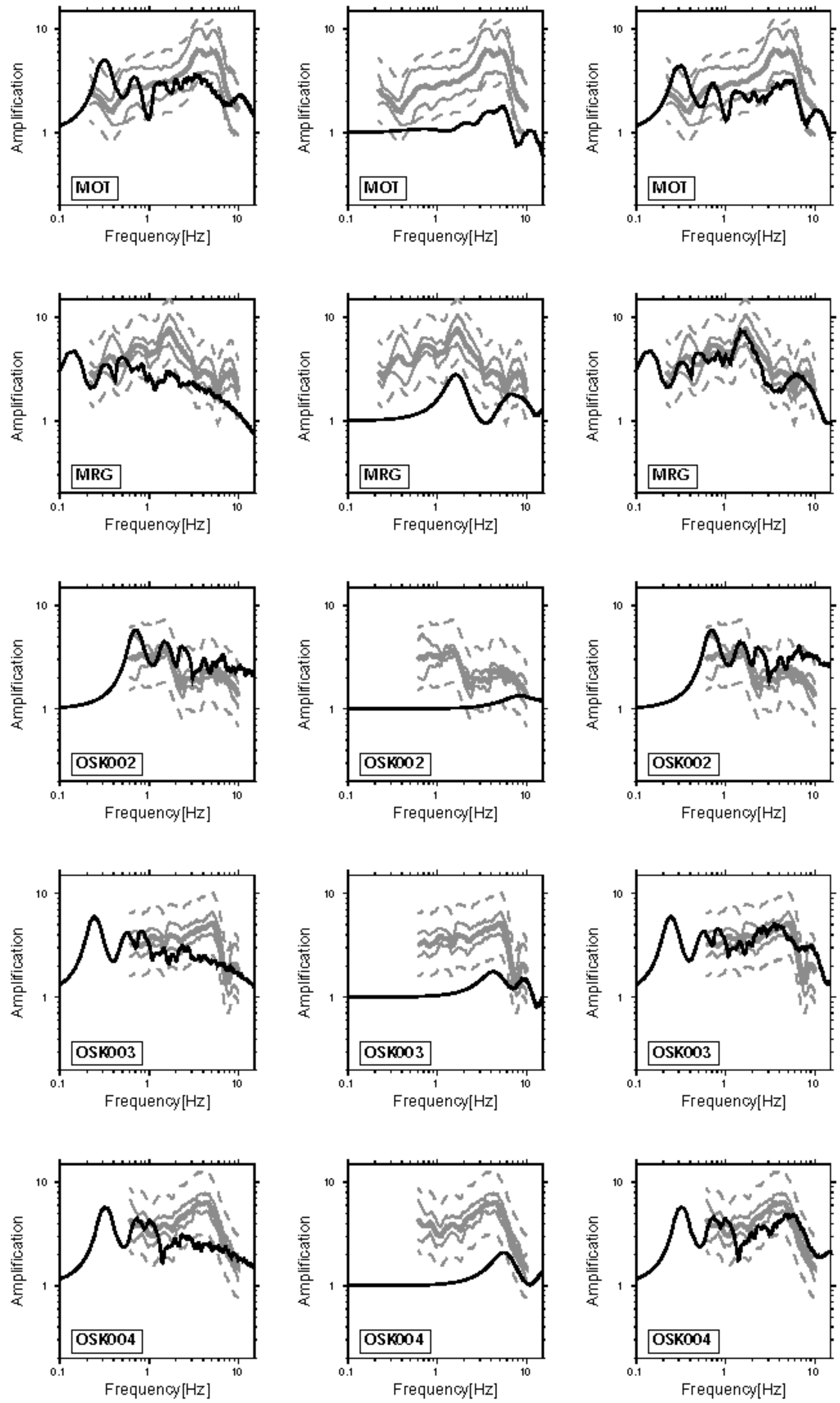


Fig. 6 Comparison between the theoretical (solid line) and empirical (shaded lines) site amplifications. Shaded thick and thin lines correspond to average and standard deviation, respectively. Shaded dashed lines indicate half and twice of the average. The left, center and right panels correspond to the theoretical evaluations using the deep, shallow and combined models, respectively. The meaning of the items on the right is as follows. 1) location of PS logging. 2) agreement index between theoretical and empirical site-amplification characteristics. Circle is assigned to sites with good agreement in spectral overview and absolute value at least up to 5Hz; cross to ones with remarkable misfit in spectral shape, such as quite different peak frequencies; triangle to ones of intermediate agreement. 3)remarks



MOT:
1) just point
2) △
3) systematic underestimation (1-10Hz)

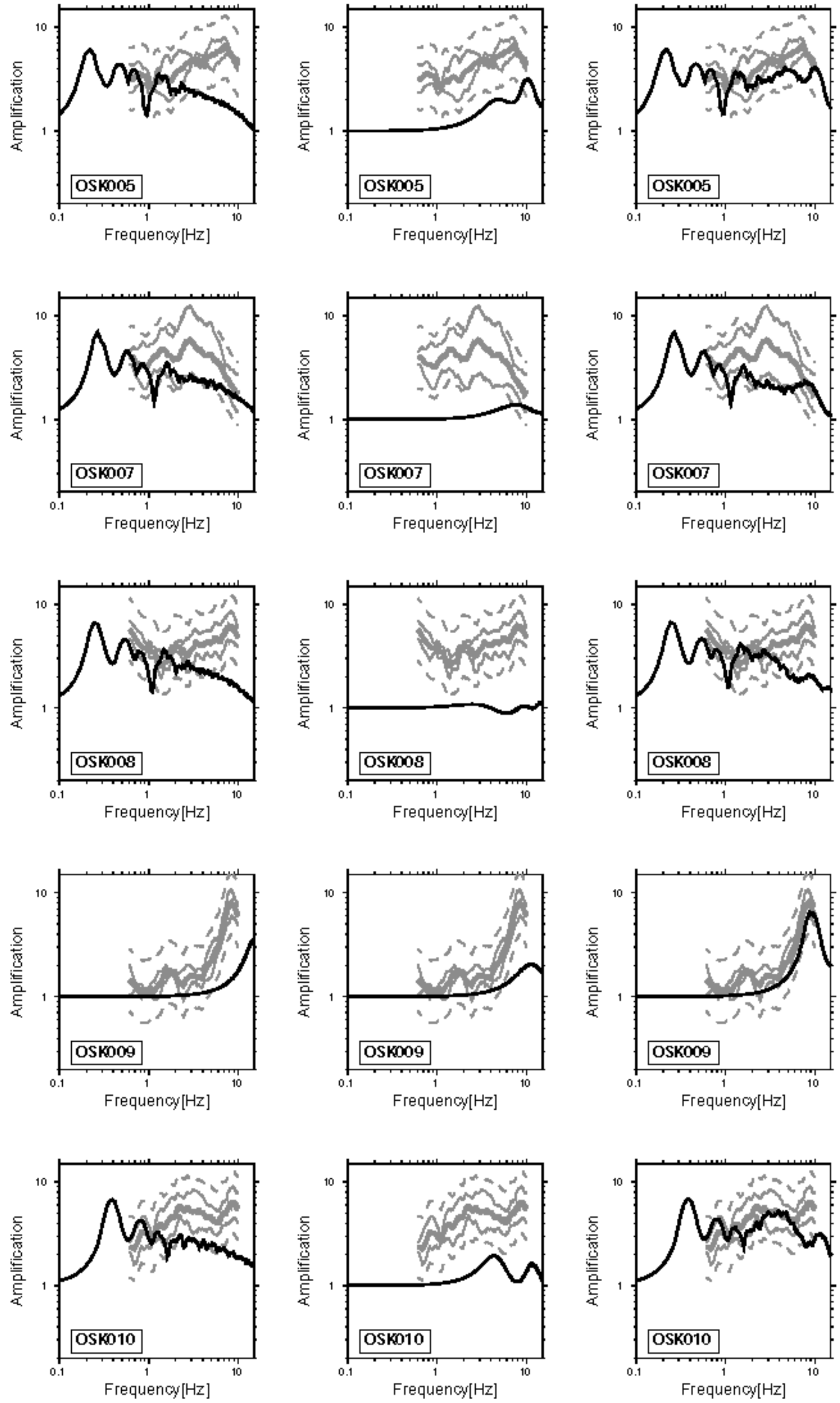
MRG:
1) just point
2) ○

OSK002:
1) just point
2) ○

OSK003:
1) just point
2) ○

OSK004:
1) just point
2) △
3)systematic underestimation (1.2-5Hz)

Fig. 6　Continued.



OSK005:
1) just point
2) ○

OSK007:
1) just point
2) ×
3)remarkable difference in spectral peak (trend)(under-estimation)(1.0-10Hz)

OSK008:
1) just point
2) ×
3)remarkable difference in spectral trend (underestima-tion)(3-10Hz)

OSK009:
1) just point
2) ○

OSK010:
1) just point
2) ○

Fig. 6 Continued.

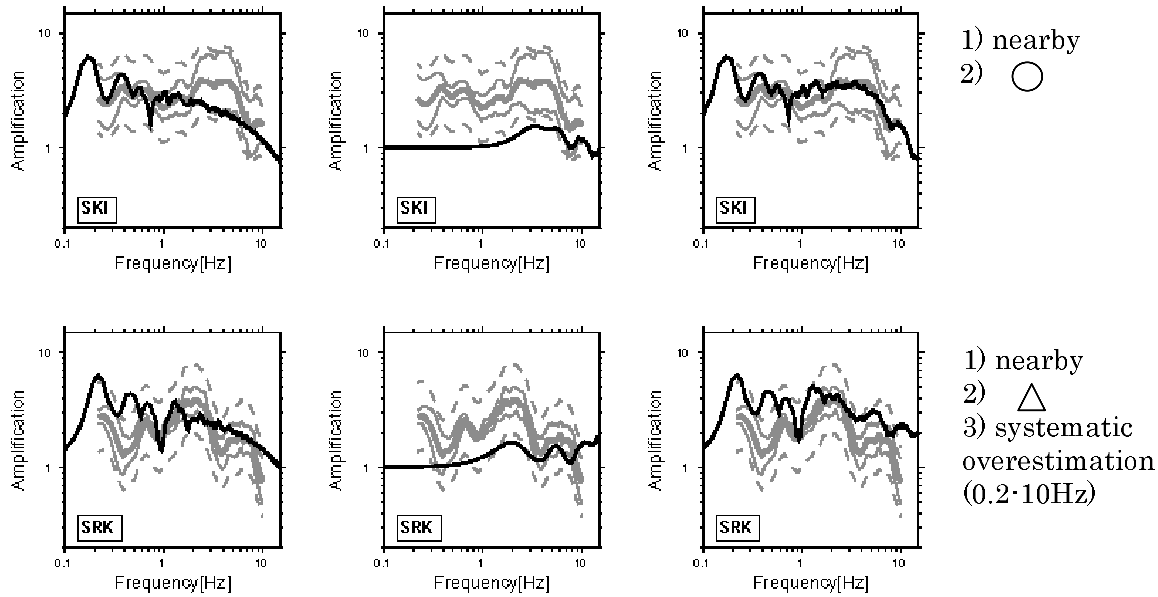


Fig. 6 Continued.

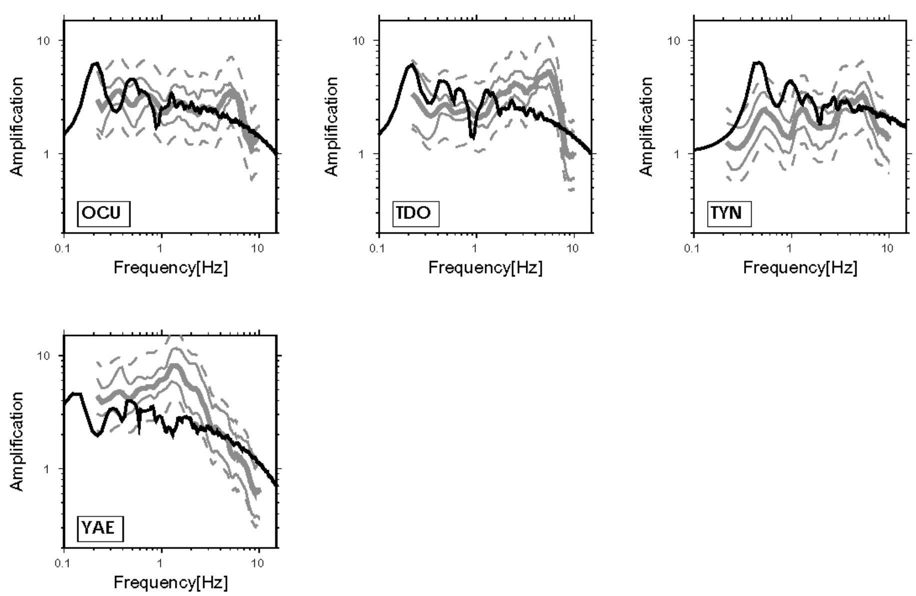


Fig. 7 Same as Fig. 6 except that the theoretical site amplifications (solid line) are evaluated by using only deep models.

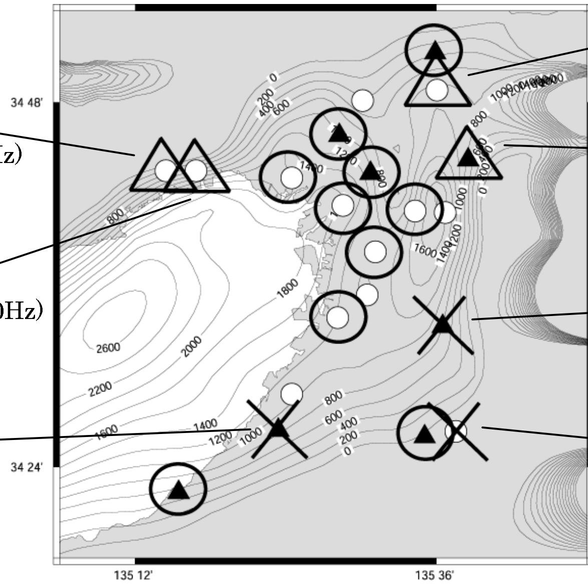


Fig. 8 Spatial variation in agreement between theoretical and empirical site amplifications. Circle is assigned to sites with good agreement in spectral overview and absolute value at least up to 5Hz; cross to ones with remarkable misfit in spectral shape, such as quite different peak frequencies; triangle to ones of intermediate agreement.

We notice here the frequency range lower than about 5 Hz. Then, ten of seventeen sites having the shallow models show good agreements in spectral overview and absolute values (see Fig. 6). Fig. 8 shows spatial distribution of sites with the agreement index shown in Fig. 6. The agreement index distribution seems to depend on site location. The better-agreement-index sites are locating apart from the basin edges. Most of the sites showing in poor agreement are located near the basin edges. Although there are few sites with poor fits, our subsurface structure model with 1-D theory can be used for evaluation of theoretical site amplifications.

Especially, the sites CHY, OSK007 and OSK008 show poorer agreement. Actually, the site CHY is the weathered seismic bedrock (granite) site and lies out of the sedimentary basin model. Therefore, we should not construct the combined model with a same procedure for the basin sites. We have just put the shallow model using PS-logging data to estimate the site amplifications. The misfit shows insufficient information for the shallower part of the subsurface structure at this site.

At sites OSK007 and OSK008, the poor agreements are seen in frequency ranges higher than 1Hz. Theoretical evaluations are systematically smaller than empirical ones (Figs. 6 and 8). It is suspected that the attenuations of the deep model are inappropriate (see Fig. 4), or that the shallow models themselves are inappropriate. In the former case, the sites with less agreement would not appear sparsely as seen in Fig. 8. Thus, the misfits are likely to stem from the shallow models.

For example, PS logging data at site OSK007 show that S-wave velocities reach almost 0.35km/s at surface. However, it does not necessarily mean that the ground surface is the outcropped engineering bedrock on which input seismic motions have commonly defined. To make sure, we need to collect regional information of shallow subsurface structures. Also for the other sites, some examinations of the shallow models in the same light would be needed. Our basic idea is that when one uses PS logging data as a shallow model, he has to consider their fluctuation before using them even though just-point PS logging data are available. We should be aware of that PS logging data only represent a 1-D subsurface structure at a point.

CONCLUSIONS

We propose an approach for modeling subsurface structure to evaluate theoretical site-amplifications in the Osaka basin, Japan. The subsurface structure model consists of simplified-deep and detailed-shallow subsurface structure models. 1-D linear S-wave propagation theory was adopted to examine the validity of this approach. We compared theoretical S-wave amplifications with those evaluated empirically from observed S-waveforms.

It was found that the empirical and theoretical amplifications show fairly good agreement at most sites. This means that we can evaluate site amplifications in wide-frequency ranges only by adding a detailed-shallow subsurface structure to a simplified-deep one having been modeled for the use in low frequency ranges. We should take care whether shallow information used for constructing a shallow model appropriately describes real subsurface structure at and around the site or not.

The modeling approach proposed in this study is expected to be an effective tool to make wide-frequency and spatially-dense evaluations of site amplifications for strong-motion predictions.

Acknowledgements This work is contribution to the Special Project for Earthquake Disaster Mitigation in Urban Areas by the Ministry of Education, Culture, Sports, Science and Technology, Japan. The strong-motion data provided by the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) and those of K-NET, deployed by National Research Institute for Earth Science and Disaster Prevention (NIED) were used in the analyses.

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