13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2393

EVALUATION OF SITE AMPLIFICATION FACTORS BASED ON SPECTRAL INVERSION ANALYSIS

Kenichi ABE[1], Kazuhiko YASHIRO[2], Mitsugu MASHIMO[3], Ryoichi NAKAMURA[3], Shigeki SEKIYA[4], and Takashi KUBO[4]

SUMMARY

In this paper it is shown that site amplification factors, directly separated from observed Fourier spectra by spectral inversion analysis, are equivalent to the amplification factors normalized at an outcrop basin. This is true, if the observed spectra are obtained from a properly deployed strong-motion array from rock to soil sites.

The spectral inversion analysis used here is in principle the method proposed by Iwata and Irikura[1)]. They assumed that the observed Fourier spectrum of S-wave portion, which directly reached, is presented as the product of three effects: source, propagation, and site. Concerning the site effects, they introduced the constraint that the factors for the local site effects must be at least two, due to the free surface amplification effects ($G(f) \geq 2.0$). In application to this method, the algorithm has been modified by one of the authors[2)]. The most suitable epicentral distance can be obtained not by using arbitral distance. To keep the accuracy in the numerical analysis, the reciprocals of the singular values less than the machine precision can be changed to zero. For topographical site effects, inequality constraints are changed from 2.0 to 0.05.

The amplification factors obtained by the inversion analysis are compared with the factors calculated by 2-D or 1-D modeling analytical method based on geological layers by PS logging at outcrops of basin sites. In spite of only inequality constraints for site effects, the separated site factors from the inversion analysis showed good agreement with the analytical factors based on site investigations.

It is concluded that site amplification factors normalized at an outcrop basin can be accurately given by the spectral inversion analysis of a properly deployed strong-motion array.

INTRODUCTION

Site amplification factors in array observation systems deployed on plane, directly separated from observed Fourier spectra by spectral inversion analysis or spectral regression analysis, are usually provided assuming that the smallest amplification factor of every frequency is 2.0. When relative basin

[1] National Research Institute for Earth Science & Disaster Prevention, Japan, ken-abe@bosai.go.jp
[2] Tokyo Electric Power Company, Japan, t0667733@pmail.tepco.co.jp
[3] Tokyo Electric Power Services Co., Ltd., Japan, mashimo@tepsco.co.jp
[4] Kumagaigumi Co., Ltd., Japan, ssekiya@ku.kumagaigumi.co.jp

outcrop site, what is so-called reference point, is included in the array system, amplification factors of other sites are normalized by the factors of relative basin site. Although granite sites are usually regarded as reference points, these sites are weathered near these surfaces in many cases and the amplification factors are apt to be greater at approximately 10 Hz higher frequency range. If topographical site effect contains in the basin site, contrarily the factors can be less than 2.0.

The authors apply the spectral inversion analysis to the array observation system properly deployed from rock to soil sites, adding relative basin outcrop sites whose layer properties and topographical effects near surface were already investigated and showed that amplification factors can be evaluated accurately by only observed spectra from the array system in site of irregular basin effect by weathering and configuration near surface.

ARRAY OBSERVASION SYSTEM AND EVENT DATA

An array observation system, deployed in both prefectures of Miyagi and Fukushima, provided the earthquake records used in this study. The system, named KASSEM [3], is a combination of the local laboratory array and simple extended array. The authors used the record from the simple extended array deployed at 8 sites from rock to soil. In this system, the elastic velocity structure and the dense structure were investigated at the granite site named S4. [4] Near the surface, S-wave velocity is 1,100m/s and is up to 2,400m/s under the depth of 25m. Another observation site is also added. This granite site involves topographical effect, whose amplification factor were already evaluated by two dimensional F.E.M [5].

The ground motions of 41 events observed from 1984 to 1993 are used, and observation sites and epicenters are given in Fig.1. Here, to limit the body wave propagation through the uniform crust structure, selected motion records satisfy the conditions as follows: 1) The magnitude by the J.M.A(Japan Meteorological Agency),M, is greater than or equal to 4.5. 2) The epicentral depth, D, is less than or equal to 60km. 3) The epicentral distance is less than or equal to 200km.

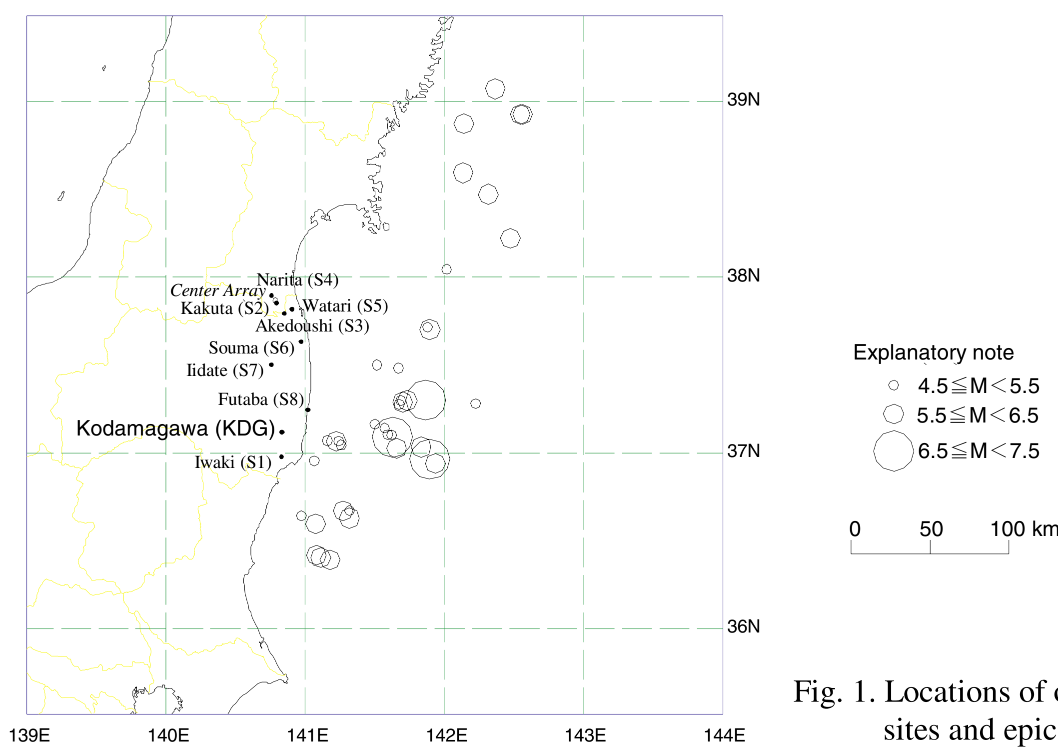

Fig. 1. Locations of observation sites and epicenters.

SPECTRAL INVERSION ANALYSIS

We use the velocity response spectra of damping coefficient 0% in frequency domain to apply spectral inversion analysis. The reason why these spectra were used is that the spectral amplitudes in frequency domain better agree with Fourier amplitudes of acceleration waves and can also present the response of another damping coefficient by exchanging factors. The spectra were calculated for the duration of 20 seconds from the starting point of S-wave in observed acceleration waves because the direct S-wave portion of the event magnitude less than 7.0 is exactly involved in the duration time. The calculated spectrum of the event observed at each station for the inversion was obtained by the vectorial summation of the two horizontal components (NS and EW).

In this study we apply Iwata and Irikuras' inversion method[3)], in which they extended the Andrews' method to consider both S-wave attenuation throughout the propagation path and the local site effect at each station. Assuming that the quality factor of the wave attenuation is independent of the path and only depends on frequency, they introduce a linear equation as following.

$$\mathbf{Log(O'_{i\,j}) = -\log(R_{ref}) + \log(S_i) + \log(G_j) - \log e\,(\pi f R_{ij}/Q_s V_s)} \tag{1}$$

where e is the Napier's number, $O'_{i\,j}=(R_{ij})/(R_{ref})O_{ij}$; O_{ij} , observed S-wave amplitude spectrum ; R_{ij}, epicentral distance; R_{ref}, the arbitrary normalized distance; S_i, source amplitude spectrum; G_j, local site effect; Q_s, average quality factor of the path for S-wave; V_s, average S-wave velocity. The number of events, noted by i here, is 41 and the number of sites named Sj(j=1~8) and Kodamagawa is 9.

According to the constraint due to the site effects, the minimum value of spectral amplitudes along all frequencies is assumed to be 2.0 whose value is the factor of the free surface of an ideal basin. However, The S1 site and the kodamagawa site added in this study exist on granite and are evidently characterized by topographical site effect, so that their amplification factors should become less than 2.0 at any frequency. Consequently, we give the minimum limit of amplification factor for only two sites to 0.05. The constraints of site effect are as following inequalities.

$$\mathbf{G_j \geq 2.0}, \tag{2}$$
$$\mathbf{G_j \geq 0.05.} \tag{3}$$

We solved the resulting linear least squares problem with linear inequality constraints using the singular value decomposition method. In this study, using the modified method[4)] by one of authors, we decided the most suitable $\mathbf{R_{ref}}$, not arbitrarily, and put the reciprocals of the singular values less than the machine precision to zero to be capable of keeping the accuracy of the Qs value in the numerical analysis.

RESULTS

The inversion analysis was conducted in frequency range between 0.1Hz and 50.0Hz. The variation of R_{ref} in frequency range is shown as Fig.2, and R_{ref} is variable in 7th power or thereabout between 0.7Hz and 25Hz. The average epicentral distance in observed waves is 103.6km being equal to the order of 7^{th} power of 10 cm, and the suitable solutions should be given between 0.7Hz and 25Hz in frequency range.

Qs-value is as shown in Fig.3, and each site effect, in Fig.4, Fig.5, and Fig.6. In Fig.3, Qs values are remarkably variable in frequency range less than 0.7Hz and the numerical modification are of little effect on the Qs value due to S/N ratio of recorded waves in low frequency range.

Fig.4 compares the amplification factors of three relative outcrop basin sites on granite. The factors of S4 site, greater in 10Hz higher range, should be affected by weathering near surface, and for both factors of Kodamagawa and S1, less than 2.0 due to the constraint of Eq.(3), topographical effect should have a great influence. Fig 5 shows the factors of three soft rock sites, and Fig 6 indicate the factors of two remarkable weathering granite sites and the one soil site named S5.

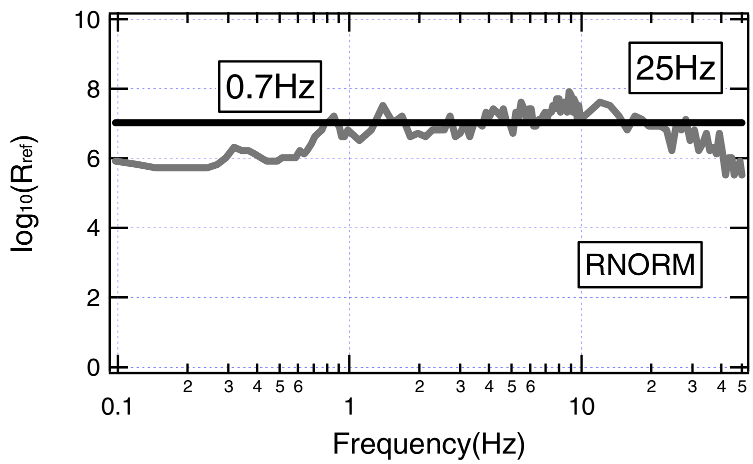

Fig. 2. The variation of R_{ref} in frequency range.

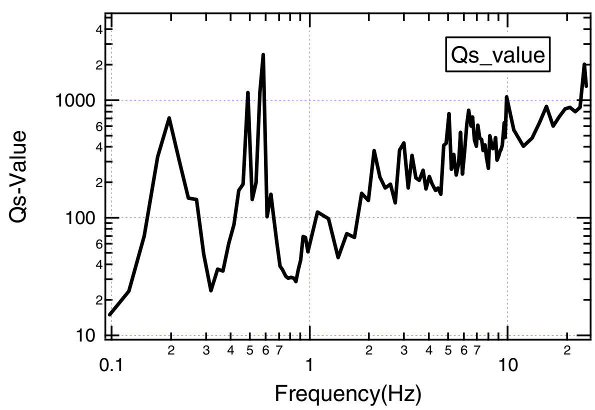

Fig. 3. Qs values.

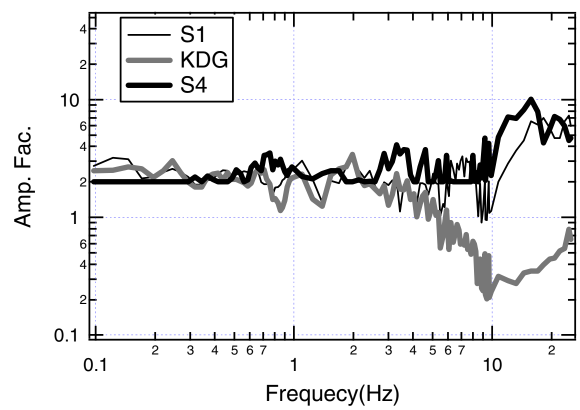

Fig. 4. The amplification factors of three relative outcrop basin sites on granite.

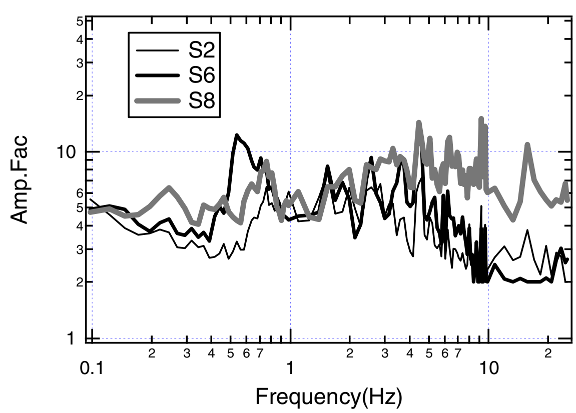

Fig. 5. The amplification factors of three soft rock sites.

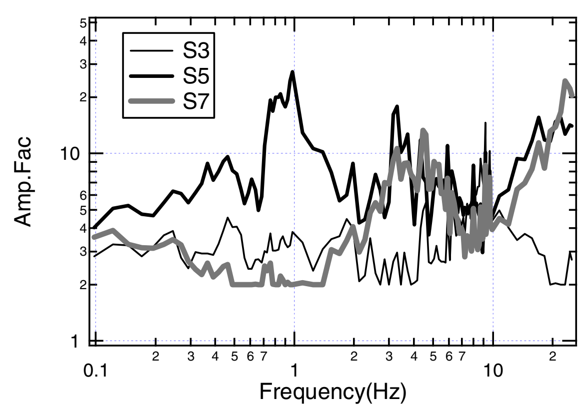

Fig. 6. The factors of two remarkable weathering granite sites and the one soil site named S5.

DISCUSSIONS

The amplification factors obtained by the inversion analysis are compared with the factors calculated by 1-D or 2-D modeling analytical method based on geological layers. Fig.7 shows the comparison of the factors by 1-D modeling and the inversion analysis results for the outcrop of the granite rock site, S4. An acceleration seismograph was set at the depth of 25m in non-weathered rock, constituting a vertical array with the seismograph on the outcrop in the site. Using the Fourier spectral ratios of the observed waves on and in the rock, the elastic velocity structure by PS-logging was suitably modified for the transfer function of 1-D modeling. On the basis of the suitable velocity structure, the amplification factors of S4 site for the hypothetical surface at the depth of 25m were calculated by 1-D modeling of anelastic layers. The tendency of factors by the inversion analysis agrees well with the result of 1-D modeling analysis. Fig.8 shows the case of 2-D modeling for Kodamagawa site contains topographical effect. The factors of this site are, as a reference point for the another array system, calculated by 2-D FEM modeling, and are apt to decrease by second power of frequency from 5Hz in higher frequency range. Similarly, the factors by 2-D modeling analysis results are in good agreement with the ones by the inversion analysis.

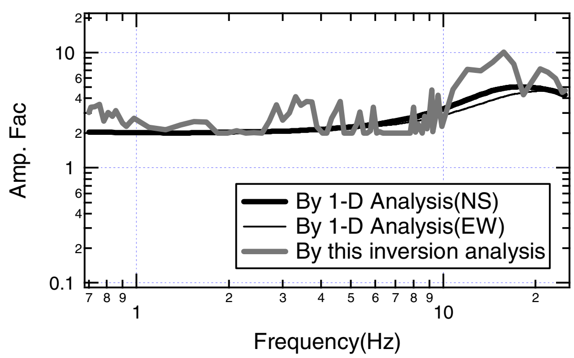

Fig. 7. Comparison with 1-D modeling analysis.

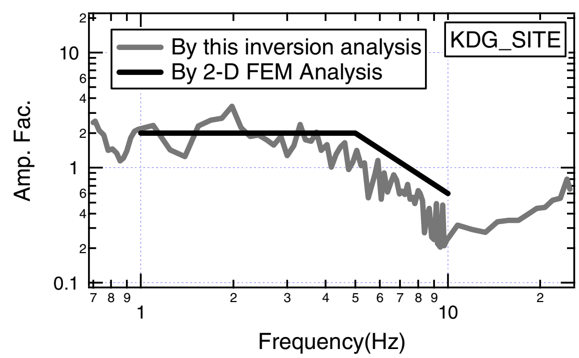

Fig. 8. Comparison with 2-D modeling analysis.

Fig. 9 shows the revision of the Qs value of Fig.3 in frequency range between 0.7Hz and 25Hz, and indicates the comparison with results of several researchers. Their results were obtained by another array system, which is called ‘Denkyoken Array Observation System’, covered the same region in Fukushima prefecture. The Qs values by the inversion analysis seem to be in direct proportion to about first power of frequency, and vary in the deviation range of their Qs values with frequency.

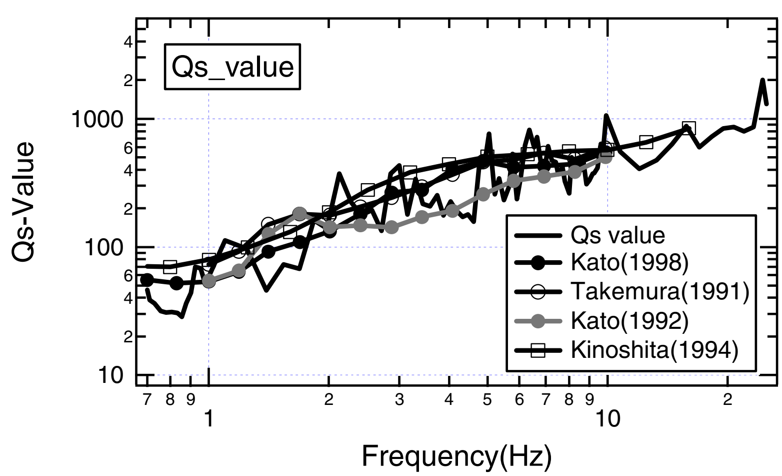

Fig. 9. Qs values compared with results of several researchers.

CONCLUSION

In application to Iwata and Irikuras' method, the algorithm has been modified by one of the authors (Abe, 1995). The most suitable epicentral distance can be obtained not by using arbitral distance. To keep the accuracy in the numerical analysis, the reciprocals of the singular values less than the machine precision can be changed to zero. For topographical site effects, inequality constraints are changed from 2.0 to 0.05. The separated site factors from the inversion analysis show a good agreement with the analytical factors based on site investigations, and further, the tendency of the Qs value coincides with the one obtain by other researchers.

It is concluded that site amplification factors normalized at an outcrop basin can be accurately given by the spectral inversion analysis of a properly deployed strong-motion array, and, in addition, the obtained Qs values are admitted to be estimated properly.

On the basis of the conclusion, we will estimate the vertical amplification factor for normalized outcrop basin as well as the horizontal one, and furthermore, will detect the phase information for the basin in Special Project for Earthquake Disaster Mitigation in Urban Areas.

REFERENCES

1. Iwata, T and K. Irikura (1988). Source parameters of the 1983 Japan Sea earthquake, J. Phys. Earth, 36,155-184,1988
2. Abe, K (1995). Properties of earthquake observed motions on rock -Proposal of vertical design spectrum due to S wave-, Saitama Univ., Doctoral thesis, 1995.3
3. Shimizu, T, K. Abe, K. Kasuda and E. Ynagisawa(1988). The development of the dense instrumental array system KASSEM and the analysis of observed earthquake waves, Proc. 9th World Conf. Earthq., Vol.8, 137-142, 1988
4. Abe, K and H. Watanabe (1996). A study on amplification factors of earthquake motions observed at a granite site and relationships between their vertical and horizontal motions, 11th World Conf. Earthq.
5. Kato, K, M. Takemura, and K. Yashiro(1998). Properties of source spectra in short period range estimated by observed strong motions, Zisin, No.2, Vol.51, 123-138, 1998