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PREDICTION OF STRONG-MOTION CHARACTERISTICS OF BEDROCK MOTION IN YOKOHAMA, JAPAN, BASED ON SOURCE REGION CLASSIFICATION

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SUMMARY

A method is presented to predict incident spectra from bedrock to subsurface soils in Yokohama, Japan. Source regions are classified into six by taking epicenters, focal depths, and focal mechanisms into account. Accelerographs observed at vertical array observation stations are used to identify S-wave and Qs profiles. By using the identified profiles, site-amplification characteristics are removed and incident spectra from bedrock are evaluated. A spectrum referred to as 'residual spectrum' obtained from the incident spectrum, standard source and propagation spectra is defined. A simple function referred to as 'fitted residual spectrum' is defined to represent the average residual spectrum for each source region. With the fitted residual spectrum, and standard source and propagation spectra, Fourier spectra on exposed bedrock are evaluated. The estimates show good agreement with the observations showing the validity of the method.

INTRODUCTION

It is widely accepted that ground motion is affected by three major characteristics: source; propagation; and local site amplification. The first one is characterized by source parameters such as seismic moment and focal mechanism while the second one is characterized by attenuation factors like quality factors of the crust. The third one is affected by S-wave velocity and thickness of subsurface soils. Thus, the above mentioned parameters are essential to predict ground motion. However, significant difference of ground motion is sometimes observed even on bedrock with comparable magnitudes and hypocentral distances. The difference suggests that source and propagation paths have regional characteristics. In this article we study accelerographs observed at vertical array observation stations in Yokohama, the southwestern part of the Tokyo Metropolitan area, Japan, and classify surrounding source regions. The regional characteristics of source and propagation path are evaluated in terms of 'residual spectrum', which is newly introduced herein. The applicability of the procedure using the residual spectrum is discussed.

SOURCE REGION CLASSIFICATION

Figure 1 shows the locations of the observation stations used in this study. Solid circles indicate the stations where vertical array observations are made while the triangle indicates an observation station on exposed bedrock. The stations are located in and around Yokohama, the southwestern part of the Tokyo metropolitan area. As the stations are located within 20 x 20 km^2, we can assume that underlain bedrock is practically identical throughout the area. All the stations have P- and S-wave profiles by elastic wave explorations. The deepest accelerographs were installed in soft rocks with S-wave velocity of about 600 m/s and depth of GL-75 to –100 m. Figure 2 shows epicenters, focal depths, and magnitudes of the earthquakes during which one or more stations recorded strong motions with resultant horizontal motions stronger than 10cm/s^2. It is found that focal depths in Tokyo Bay are deeper than 70 km whereas those in the east of Yamanashi are shallower than 35 km. This is because the earthquakes in the former region occur along the boundary between the Philippine Sea plate and the Pacific plate while the earthquakes in the latter region occur along the boundary between the Philippine Sea plate and the Eurasian plate [Okada, 1990]. Thus, source characteristics such as focal mechanism and stress drop might depend on regions. Because the epicenters surround Yokohama, propagation paths also change with

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source regions and therefore propagation characteristics might depend on the regions. For these reasons, source regions are classified into six by taking epicenters, focal depths, and focal mechanisms into account. The result is shown in Figure 3.

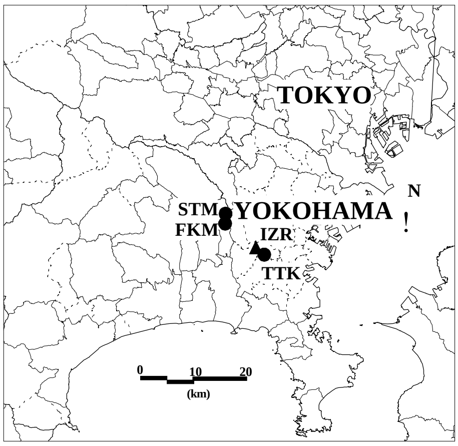


Figure: 1 Locations of vertical array observation stations

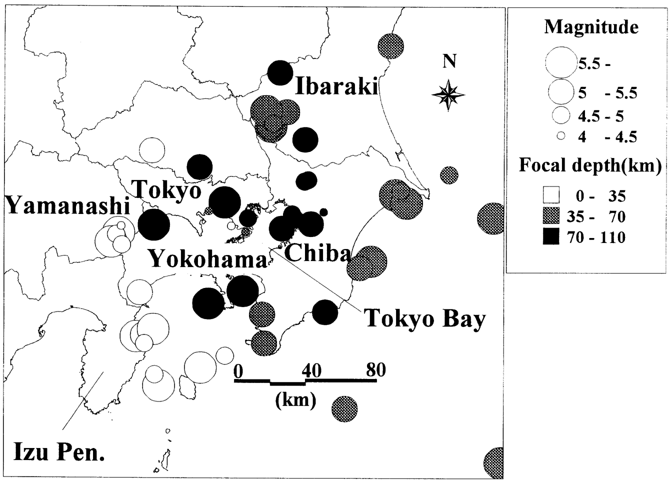


Figure: 2 Epicenters of events observed at vertical array observation stations

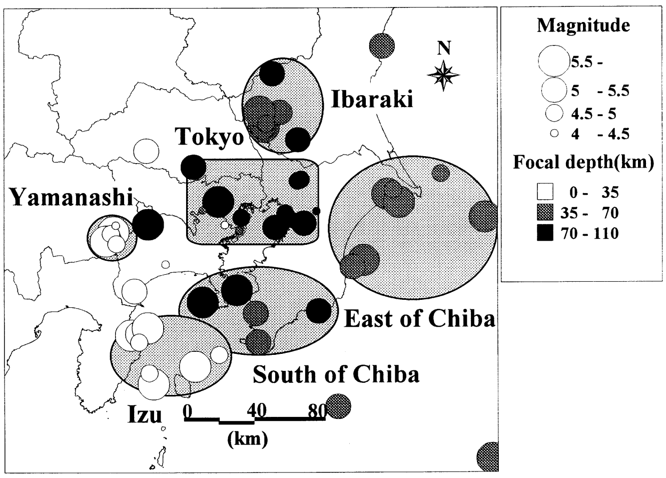
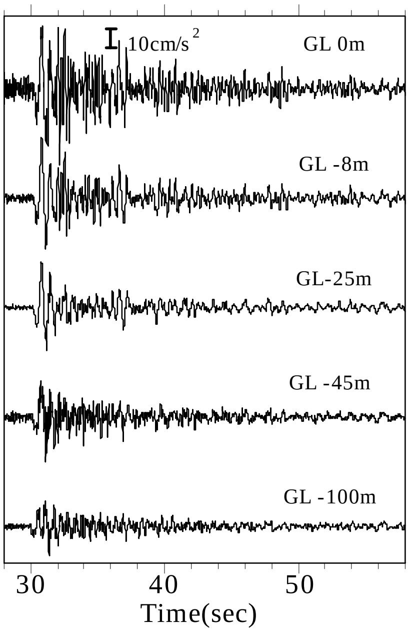


Figure: 3 Classification of source regions

DECONVOLUTION OF SITE-AMPLIFICATION CHARACTERISTICS

Figure 4 shows an example of acceleration time histories in the north-south component observed at STM. The maximum accelerations at the GL+0 m and GL-100m are 42 cm/s^2 and 16 cm/s^2 showing that seismic waves are amplified in the subsurface soils. To remove the effect of the subsurface soils, site amplification characteristics are evaluated after identifications of S-wave and Qs (quality factor for S waves) profiles: 1) For each station, 20.48-sec S-wave parts of accelerograms in the N-S and E-W components were Fourier transformed; 2) Horizontal spectrum was obtained as the resultant Fourier amplitude of the N-S and E-W components; 3) S-wave and Qs profiles were identified from the horizontal spectra and initial profiles [Tsujihara and Sawada, 1992]; 4) Transfer functions of the free surface to vertical incidence of SH wave from bedrock were evaluated from the identified S-wave and quality factor profiles; 5) Incident spectra from bedrock to subsurface soils were evaluated by dividing the horizontal spectra at the free surface by the transfer functions.



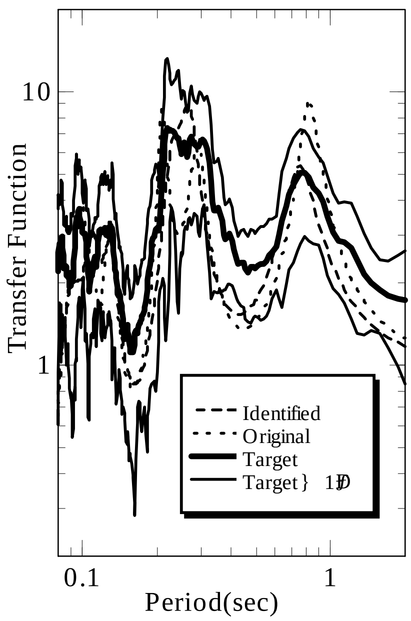


Figure: 4 Examples of accelerographs observed at vertical array observation station (Left)
Figure: 5 Comparison of spectral ratios of the free surface to bedrock (Right)

Table: 1 Initial and identified values of S-wave velocity and quality factor for STM

#	Soil type	Density	S-wave velocity (m/s)		Depth	$Q_s(f)=Q_0*f^n$	
			initial	Identified		Q_0	N
1	Volcanic ash	1.3	190	135	7	2	0.7
2	Volcanic ash	1.6	270	260	15	2	0.6
3	Sandy gravel	2.1	640	690	34	8	0.4
4	Silt/ Fine	1.9	350	350	43	2	0.7
5	Humus/ Silt	1.7	260	280	53	2	0.7
6	Soft rocks	2.0	650	650	86	8	0.4
7	Soft rocks	2.1	520	650	100	8	0.4
8	Soft rocks	2.1	520	650	-	8	0.4

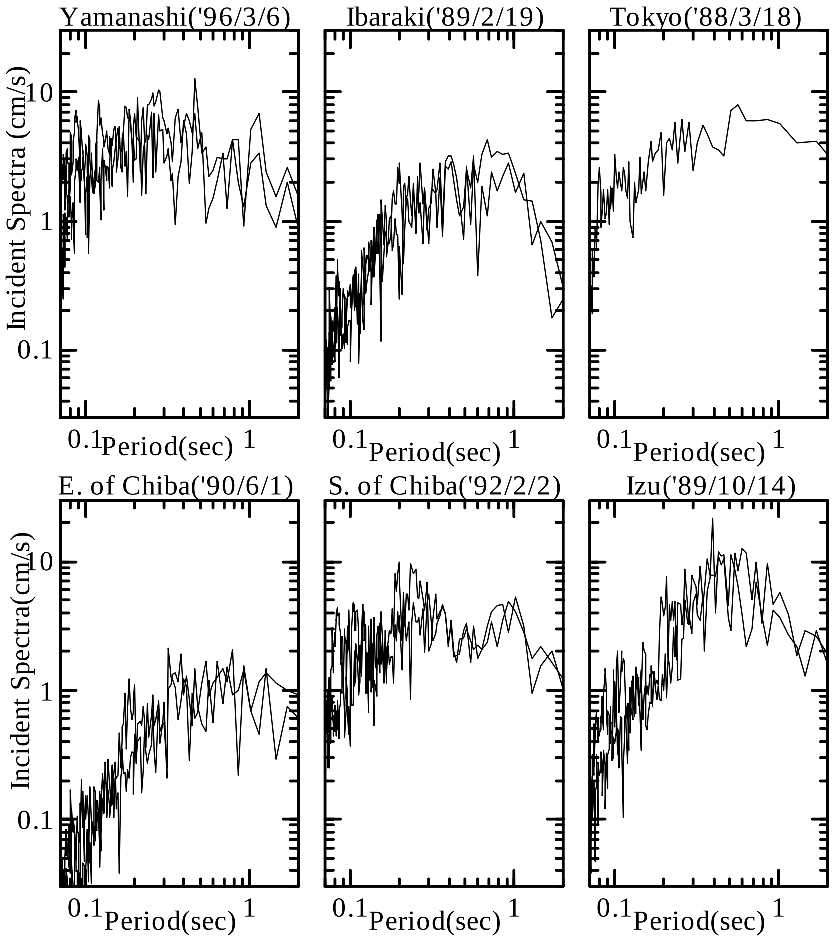


Figure: 6 Examples of deconvolved spectra for each source region

Figure 5 shows spectral ratios of the free surface to bedrock obtained for STM. The thick line indicates the average of the observation (target) while the thin lines indicate the standard deviation from the average. The dotted line indicates the ratio obtained from the initial profiles while the broken line indicates the ratio from the identified profiles. Although some discrepancies are still found in the period range of higher modes, the ratio from the identified profiles becomes closer to the average of the observation. Table 1 shows the identified values of S-wave velocity and Qs for STM. S-wave velocities of the volcanic ash decrease and those of the sandy gravel increase after the identification. The identified values of Qs range from 2 to 30 for the volcanic ash and silt, from 3 to 30 for the sandy gravel, and from 3 to 20 for the soft rocks in the period range 0.1 to 1 sec. These values are consistent with a conventional estimate [Fukushima and Midorikawa, 1994].

From the identified profiles, transfer functions of the free surface to the vertical incidence of SH wave from bedrock to subsurface soils were evaluated. Then, incident spectra at the basement were evaluated by dividing the horizontal spectra at the surface by the S-wave transfer functions. Examples of the results for the classified source regions are shown in Figure 6. The magnitudes of these earthquakes are from 5.6 to 6.0. Little differences are found between stations showing that the deconvolutions were successfully made. Figure 6 demonstrates that the spectra for the classified regions have their own characteristics: spectra for Yamanashi and South of Chiba are almost flat; the short-period components of the spectra for Ibaraki and East of Chiba are small; and the long-period components of the spectra for Izu are large. The difference of the spectral characteristics is probably due to the difference of the source characteristics and propagation paths.

RESIDUAL SPECTRA

In order to obtain the source, propagation path, and site-amplification characteristics from observation records, the inversion method is usually employed [Iwata and Irikura, 1986]. The method is useful when various ranges of magnitudes, hypocentral distances, and appropriate criteria are available. In this study, however, hypocentral distances for each source region have less variation because a specific region is considered. For this reason another approach is proposed herein.

When the source, propagation path and site-amplification spectra are expressed as $S(T)$, $P(T)$, and $G(T)$, observed spectrum $O(T)$ is

$$O(T) = S(T) \cdot P(T) \cdot G(T) \tag{1}$$

in which T denotes period. By removing the effect of subsurface soils above bedrock, the incident spectra from bedrock, $I(T)$, can be expressed:

$$I(T) = S(T) \cdot P(T) \tag{2}$$

When standard source and propagation-path spectra are introduced as $S_0(T)$ and $P_0(T)$, Eq.(2) can be replaced by:

$$I(T) = S_0(T) \cdot P_0(T) \cdot R(T) \tag{3}$$

in which $R(T)$ is defined as

$$R(T) = \frac{S(T) \cdot P(T)}{S_0(T) \cdot P_0(T)} \tag{4}$$

In this study, $R(T)$ is referred to as 'residual spectrum'. By using Eq. (3) residual spectra can be obtained from the incident spectra, standard source spectra, and standard propagation-path spectra. The standard source spectra can be defined:

$$S_0(T) = \frac{R_{\theta\phi} \cdot FS \cdot PRTITN \cdot M_0}{4\pi\rho V_S{}^3} \cdot \frac{(2\pi/T)^2}{1 + (T_C/T)^2} \tag{5}$$

where $R_{\theta\phi}$ is the coefficients for the radiation pattern, FS is the effect of the free surface, $PRTITN$ is coefficients for energy distribution in horizontal components, M_0 is the seismic moment, ρ and V_S are mass density and S-wave velocity in source region, and T_C is the corner period.

Similarly, the standard propagation-path spectra can be defined:

$$P_0(T) = e^{\frac{-\pi X}{Q_S(T) \cdot T \cdot V_S}} \cdot \frac{1}{X} \tag{6}$$

where X is the hypocentral distance, Q_S and V_S are velocity and quality factor of S waves of the crust. By defining the standard source and propagation-path spectra, and from the incident spectra obtained in the previous section, residual spectra can be obtained for each source region.

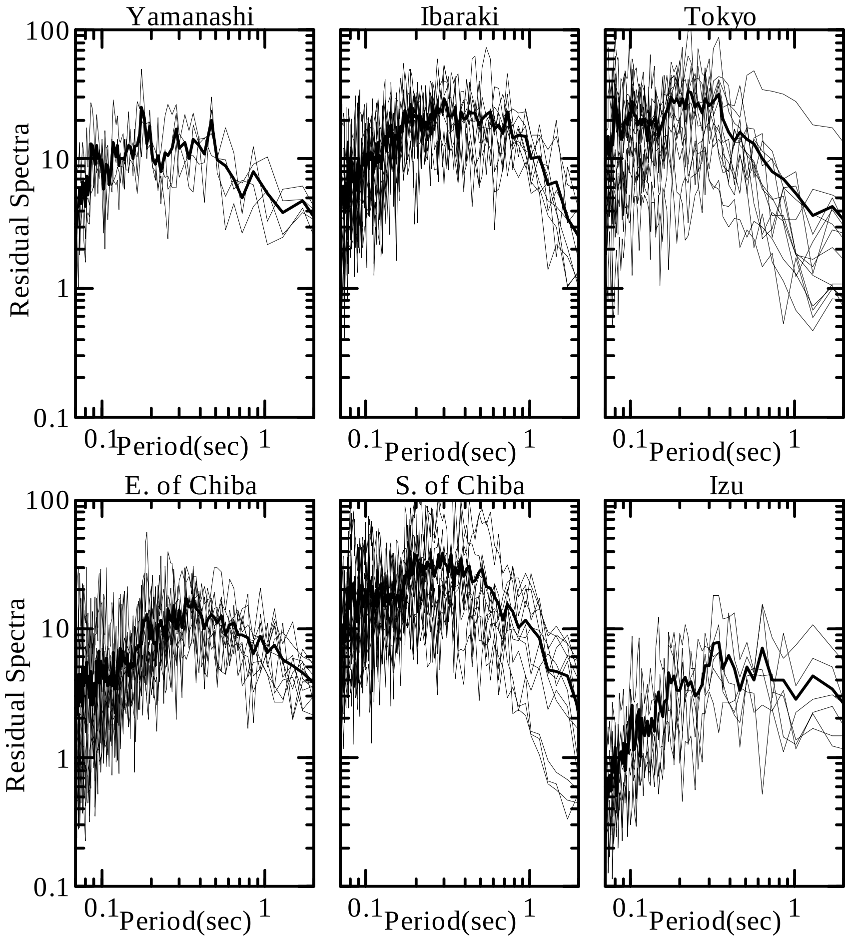


Figure: 7 Residual spectra for each source region

Figure 7 shows residual spectra obtained for each source region. For each source region, thin lines are residual spectra and the thick line is their average. The magnitudes of the events range from 4.5 to 5.8 (Yamanashi), from 5.1 to 5.6 (Ibaraki), from 4.5 to 6.0 (Tokyo), from 5.4 to 6.6 (East of Chiba), from 4.5 to 5.9 (South of Chiba), and 4.0 to 6.5 (Izu). It is found that residual spectra obtained for each source region have small variation and have their own characteristics: the amplitudes for Yamanashi and South of Chiba are almost flat in the period range shorter than 0.5 sec and decrease with period in the period range longer than 0.5 sec; the amplitudes for Ibaraki and East of Chiba increase with period in the period range shorter than 0.3 sec and decrease with period in the period range longer than 0.4 sec; the amplitudes for Tokyo are large in the period range shorter than 0.4 sec; and the amplitudes for Izu decrease with period in the period range shorter than 0.3 sec and is almost flat in the period range longer than 0.3 sec. The residual spectra have amplitudes from 1 to 20 including the effects of the regional characteristics of source, propagation path, and amplification which occurs between the seismic bedrock and soft rocks.

It is said that stress drop increases with focal depth [McGarr, 1984]. Because the focal depths for Tokyo are located deeper than 70 km, the stress drops might be relatively larger and therefore the short-period components are likely generated. Sekiguchi [1991] evaluated the distribution of Qp, quality factor for P waves, for the Kanto district. According to the estimates, Tokyo Bay and Yokohama have high Qp zone from GL 0 to –32km, and the southern part of Boso peninsula and Yokohama have high Qp zone from GL –60 to –90 km. If we assume that Qs is proportional to Qp, the estimates are supports for the high amplitudes of the residual spectra for the South of Chiba and Tokyo.

EVALUATION OF INCIDENT SPECTRA

The previous section derived residual spectra for each source region and made some explanation of the spectral characteristics. In this section, incident spectra from bedrock to subsurface soils are evaluated from the residual spectra. Figure 8 shows residual spectra for South of Chiba and Yamanashi. Broken lines are the average of the residual spectra and thin solid lines are the standard deviation from the average. In order to make a practical representation of the spectral characteristics, the following simple function is defined and to be referred to as 'fitted residual spectrum'.

$$\log R(T) = a \cdot (\log T)^2 - b \cdot \log T + c \tag{7}$$

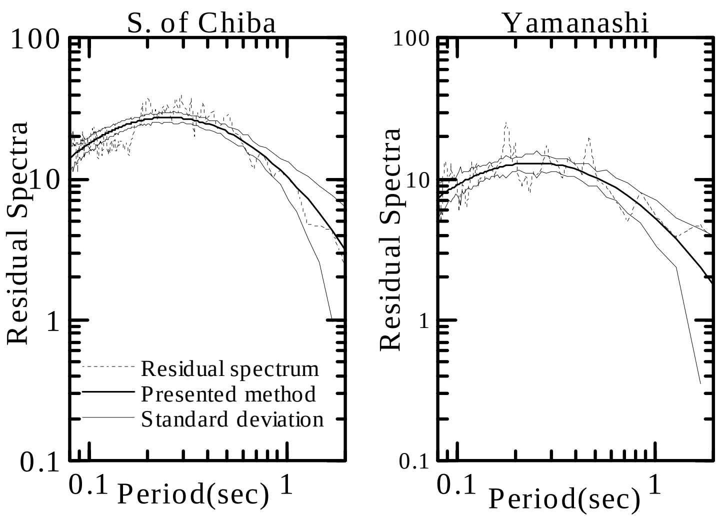


Figure: 8 Examples of residual spectra and their fitted curves

The parameters of the function are determined by the least-squares method. The results are tabulated in Table 2.

Table: 2 Parameters to characterise residual spectra

Source region	a	b	c	Cor. Coef.
Yamanashi	-1.04	1.27	0.73	0.66
Ibaraki	-1.40	-1.30	1.06	0.93
Tokyo	-1.56	-2.10	0.70	0.88
East of Chiba	-1.16	-0.89	0.90	0.88
South of Chiba	-1.17	-1.40	1.02	0.76
Izu	-1.36	-0.90	0.58	0.92

$\log R(T) = a \cdot (\log T)^2 - b \cdot \log T + c$

From the fitted residual spectra and Eq. (3), incident spectra from bedrock can be obtained. To check the validity of the procedure, Fourier amplitude-spectra of accelerograms observed on exposed bedrock station, IZR (see Figure 1 for the location), are evaluated. Figure 9 shows the comparisons between observations and estimates. Note that the events employed for the comparisons were not used for the determination of the parameters in Eq. (7). Thin, thick, and broken lines in the figure are observation, estimates from this procedure and from a conventional method. It is found that the fitted residual spectra well express the spectral characteristics of the observations and that the conventional estimates are far smaller than the observations.

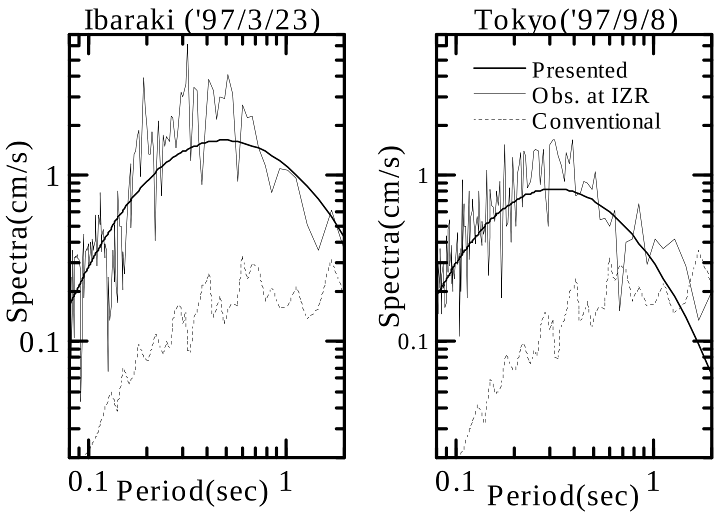


Figure: 9 Comparisons between observed and estimated spectra on exposed bedrock

CONCLUDING REMARKS

This article introduces a method to predict incident spectra from bedrock to subsurface soils in Yokohama, Japan. Because the tectonics beneath the Tokyo metropolitan area is complicated, source and propagation characteristics have regional characteristics. Thus, source region classification is preferable for prediction of strong-motion characteristics. To express the regional characteristics of source and propagation path, residual spectrum is newly introduced. As strong-motion characteristics of exposed bedrock motions are well evaluated, the validity of the method is confirmed. Although the application of the evaluated residual spectra is limited to the vicinity of Yokohama, the procedure can be applied in other areas if sufficient bedrock-motion records are available.

REFERENCES

Fukushima, Y. and Midorikawa, S. (1994), "Evaluation of site amplification factors based on average characteristics of frequency dependent Q^{-1} of sedimentary strata", *J. Struct. Constr. Eng. AIJ.*, 160, pp37-46 (in Japanese with English abstract).

Iwata, T. and Irikura, K. (1986), "Separation of source, propagation and site effects from observed S-waves", *Zisin*, 39, pp579-593 (in Japanese with English abstract).

McGarr, A. (1984), "Scaling of ground motion parameters, state of stress, and focal depth", *Journal of Geophysical Research*, 89, pp6969-6979.

Okada, Y. (1990), "Seismotectonics in the Southern Kanto District", *Zisin*, 43, pp153-175 (in Japanese with English abstract).

Sekiguchi, S. (1991), "Three-dimensional Q structure beneath the Kanto- Tokai district, Japan", *Tectnophysics*, 195, pp83-104.

Tsujihara, O. and Sawada, T. (1992), "Development of SLP for identification of structural systems", *Proceedings of the 10th World Conference on Earthquake Engineering*, 1, pp395-403.