Preliminary Analysis for Evaluation of Local Site Effects from Strong Motion Spectra by an Inversion Method

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Simultaneous separation of source, propagation path, and local site effects from observed strong motion records is carried out by an inversion method in the frequency range from 1 to 10 Hz for the purpose of empirical evaluation of the local site effects in different geological conditions. The analyzed data are S-wave portions of 167 accelerograms from 20 events observed at 7 stations along the Pacific coast of southern Tohoku and Kanto districts, Japan. These events are shallow earthquakes with magnitude from 4.0 to 6.7 and with hypocentral distance from 43 to 243 km. A linear inversion method is applied to the logarithm of the observed spectra, and solutions for source spectra, inelasticity factor of propagation path for S-waves (Qs-value), and factor of site amplification at each station are obtained in least squares sense. In the inversion, the factor of site amplification at a reference station (KDG) on an outcrop of bedrock is constrained to 2. The factors of site amplification G(f) obtained in the present study at two borehole stations are verified by comparisons with the theoretical transfer functions from bedrock to observation points. Obtained G(f) values increase with decrease of shear-wave velocities of the ground layers at the observation points. Qs-value obtained shows frequency dependency of the form Qs(f)  60f1.0, and amplitudes of displacement source spectra have 2-squared decay in the frequency range higher than the corner frequency. The site effect at the reference station (KDG) is also discussed in detail to examine the validity of the constraint condition adopted in the present study. On the basis of the mean acceleration spectrum obtained from the observed records and the calculated topographical effects by the two-dimensional BEM model at KDG, it is concluded that the constraint condition is satisfactory in the frequency range lower than 6 Hz. In the range higher than 6 Hz, it is suggested that KDG is influenced by the topographical effects.
1. Introduction

There has been a great progress in the last decade in the study of strong ground motions and its engineering applications (Joyner and Boore, 1988). Strong motion instrument arrays have been established for providing the basis for the estimation of strong ground motions in future earthquakes (e.g., Kitagawa et al., 1988; Kudo et al., 1988; Omote et al., 1980; Omote, 1983). In the meantime, there have been some destructive earthquakes such as the 1983 Nihonkai-chubu event \((M = 7.7)\), the 1985 Michoacan event \((M = 8.1)\), the 1989 Loma Prieta event \((M = 7.1)\) and others. After these events, it is reconfirmed that the ground conditions of the sites are closely connected with the damage of the structures (e.g., Singh et al., 1988). Many numerical techniques for estimating the wave propagation in an irregular ground structure such as a sedimentary basin have been developed to explain the local amplification of seismic waves (e.g., Aki and Larner, 1970; Sánchez-Sesma et al., 1988; Trifunac, 1971). To apply these analytical methods for evaluating the local site effects, detailed information of ground structure from bedrock to ground surface is required. However, such information is rarely obtained except for a few sites, because a large-scale geophysical exploration is necessary for estimating fine ground structure. Furthermore, the applicability of these methods is usually limited to two-dimensional analyses in a relatively long period range, because of the restrictions of the computational time and the capacity of the computer. Therefore, it is necessary to evaluate the local site effects empirically from the observed strong motion records, especially in high frequency range. Simultaneous separation of source, propagation path, and local site effects from strong motion records is effective for the purpose.

The separation method using inversion technique was first proposed by Andrews (1982) to separate the source and propagation spectra from strong motion records. Iwata and Irikura (1986, 1988) extended the method in order to consider both S-wave attenuation through the propagation path and the local site effect at each station. As indicated by Andrews (1982), there is one unconstrained degree of freedom in these inverse problems, and a constraint condition is needed to determine unknown parameters in absolute sense. Iwata and Irikura (1986, 1988) set up a constraint condition that the factor of site amplification must be 2 or over considering the free surface amplification. However, they indicated a problem that this constraint condition is unreliable in the frequency range higher than 5 Hz in their data, because the factor of the site amplification can be less than 2 due to the effect of inelastic attenuation within the surface layers. Abe et al. (1989) used the same constraint condition as that of Iwata and Irikura in spite of the problem. Tai et al. (1990) proposed a different constraint condition for borehole data at a depth of 950 m or less that the factor of site amplification in the bedrock must be 1 or over. This condition is invalid in consideration of the effects of the waves reflected from the ground surface. Another constraint condition was adopted for deep borehole data (Kinoshita and Mikoshiba, 1988) that the factor of site amplification is 1 at the observation point of GL-2300 m in the bedrock of the Shimohsa station and that of GL-2750 m of Fuchu station in Kanto district, Japan. These observation points are located at the bottom of the boreholes. The constraint condition by Kinoshita and Mikoshiba (1988) is valid if the incident S-waves to the bedrock can
be separated from the strong shaking parts of the observed seismic waves at these observation points. However, it is not clear whether the influence of the reflected waves from the boundaries of sedimentary layers between the bedrock and the ground surface is negligible or not. In addition, the applicable case of their constraint condition may be restricted, because the strong motion records at the deep boreholes such as Shimohsa and Fuchu are rarely obtainable.

In the present study, a station on an outcrop of bedrock is assigned as a reference station to avoid the influence of sedimentary layers on the constraint condition. The factor of site amplification at the reference station is constrained to 2 to solve the inverse problem. Strong motion records observed along the Pacific coast of southern Tohoku and Kanto districts are analyzed, and the local site effects in different geological conditions are evaluated empirically. The site effects at the reference station are also discussed to examine the validity of the constraint condition adopted in the present study.

2. Data

The analyzed data are the S-wave portions of 167 accelerograms from 20 events observed at 7 stations. The maximum values of observed acceleration are from 2 to 440 gal, and most of them are smaller than 100 gal. Figure 1 shows the observation stations and the locations of epicenters determined by Japan Meteorological Agency (JMA). These events are shallow earthquakes ranging in magnitude $M$ from 4.0 to 6.7 in the JMA scale and in hypocentral distance from 43 to 243 km. The magnitudes and the hypocentral distances of the observed events are summarized in Table 1. All of the

Fig. 1. Locations of observation stations and epicenters determined by Japan Meteorological Agency (JMA).
Fig. 2. Subsurface shear-wave velocity and the location of accelerometer at each station. \( D \) and \( V_s \) denote the depth from the ground level and the shear-wave velocity. Double circles indicate the location of observation points used in this study.

Table 1. Origin time, magnitude in Japan Meteorological Agency (JMA) scale, focal depth, and hypocentral distance of the events used in this study.

<table>
<thead>
<tr>
<th>Date (JST)</th>
<th>( M ) (JMA)</th>
<th>Depth (km)</th>
<th>Hypocentral distance (km)</th>
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<td></td>
<td></td>
<td></td>
<td>IWK</td>
</tr>
<tr>
<td>82 AUG 28</td>
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<td>4.9</td>
<td>60</td>
</tr>
<tr>
<td>82 SEP 14</td>
<td>03:03</td>
<td>5.0</td>
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</tr>
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<td>83 JUL 2</td>
<td>07:03</td>
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data were obtained by accelerometers with a flat amplitude response from 0.1 to 20 Hz. The sampling interval of the data is 0.01 s at CHS and 0.005 s at the other stations. Figure 2 shows the depth distribution of shear-wave velocity and the arrangement of the accelerometers at each station. In the present study, the accelerograms recorded at 11 observation points from 7 stations are used. These observation points are indicated by double circles in Fig. 2.

Tomioka (TMK) and Iwaki (IWK) stations consist of vertical array of accelerometers (Omot, 1983). Mesozoic granitic layer with shear-wave velocity \( V_s \) of about 2,800 m/s is located at 920 m depth (GL-920 m) for TMK and at 310 m depth (GL-310 m) for IWK. The Paleogene and Neogene sedimentary layers are accumulated on the granitic layer at TMK, while the Paleogene sedimentary layers on the granitic layer at IWK. Alluvial or diluvial layers are very thin at both stations. Subsurface structures at TMK and IWK were investigated by PS-logging, formation density logging, seismic refraction survey, and experimental testing of core samples (Omot, 1983). The shear-wave velocity \( V_s \) and \( Q_s \)-value for each layer were also identified from spectral ratios of observed seismic waves among the observation points in the vertical arrays (Ikeura et al., 1988).

Idegawa (IDG) and Hokidaira (HKD) stations are located within 15 km from TMK, and Kodamagawa (KDG) is about 7 km distant from IWK. According to the results by seismic refraction surveys, the thickness of sedimentary layers on Mesozoic granitic layer is less than 7 m at these stations. The accelerometers are installed on the ground surface at each station, and also at GL-10 m in the granitic layer at KDG (Takahashi et al., 1988). The natural frequency of the surface layers over the underground accelerometer at KDG is over 30 Hz. The elastic wave velocity obtained by the seismic refraction surveys at each station, geological map, and core samples of the borehole at KDG suggest that the granitic layer at IDG, HKD, and KDG corresponds to that at TMK and IWK. Accordingly, we designate the granitic layer as a bedrock in this region.

At Ooarai (OAR) and Choshi (CHS) stations, the accelerometers are installed at GL-14 m and GL-18 m in Mesozoic sedimentary layers. The geological profile by Omori et al. (1986) suggests that the depth to the bedrock is about 400 m at CHS, while there is no information regarding the depth to the bedrock at OAR. The natural frequencies of the surface layers over the underground accelerometers are about 11 and 8 Hz for OAR and CHS.

3. Method of Analysis

As described previously, several authors have tried to separate source, path, and site effects from observed seismic waves. In the present study, we adopt the inversion scheme by Iwata and Irikura (1986, 1988). The observed S-wave Fourier amplitude spectrum is expressed by

\[
O_{ij}(f) = S_i(f)G_j(f)R_{ij}^{-1} \exp\left(-\pi R_{ij}/Q_s(f)\right),
\]

where, \( O_{ij}(f) \), observed S-wave Fourier amplitude spectrum of \( i \)-th event at \( j \)-th station; \( S_i(f) \), source amplitude spectrum of \( i \)-th event; \( G_j(f) \), factor of site amplification at \( j \)-th station; \( R_{ij} \), hypocentral distance between \( i \)-th event and \( j \)-th station; \( Q_s(f) \), average...
$Q_S$-value along the wave propagation path; $v_S$, average S-wave velocity along the wave propagation path ($=3.7\text{ km/s}$).

By taking the logarithm, Eq. (1) is modified,

$$\log \bar{O}_{ij}(f) = -\log R_{ref} + \log S_i(f) + \log G_j(f) - \log e(\pi R_{ij}/R_{ref}) Q_S(f) v_S,$$ (2)

where $e$ is Napier’s number, $\bar{O}_{ij}(f) = (R_{ij}/R_{ref}) O_{ij}(f)$, and $R_{ref}$ is the arbitrary normalized distance. With regard to $S_i(f)$, the effect of directivity due to the radiation pattern coefficient is neglected, since the observed waves in high frequency range are usually less influenced by the radiation pattern coefficient (e.g., Iwata and Irikura, 1986, 1988; Koyama and Zheng, 1983; Liu and Helmberger, 1985). For each frequency, $I$ (source amplitude spectrum) + $J$ (factor of site amplification) + 1 ($Q_S$-value) parameters from $I \times J$ data sets are determined in least squares sense.

The accelerometer at KDG is installed in the bedrock with shear-wave velocity of 2,200 m/s and the natural frequency of the surface layers is very high in comparison with the frequency range of the inversion analysis. Accordingly, KDG can be regarded as the station on an outcrop of the bedrock, and the factor of site amplification is constrained to 2 irrespective of frequency. This constraint condition represents the free surface amplification effect. The inversion in the present study is executed by the least squares method with linear equality constraint by the singular value decomposition method (Lawson and Hanson, 1974).

Data processing is carried out by the following procedures. The S-wave portions of two horizontal components (NS and EW) of seismic ground motions are analyzed.

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Fig. 3. Examples of NS-component accelerograms observed at all stations for the event of April 23 in 1987 with $M$ of 6.5 in JMA scale. Arrows indicate the S-wave onset times and horizontal bars the analyzed portions determined by taking into consideration the duration time of the faulting.
The data length for the analysis is from 3 to 20 s after the onset of the S-waves with cosine tapered windows, which is determined by considering the duration time of faulting estimated from the earthquake magnitude by an empirical relation. Figure 3 shows examples of the NS-component accelerograms observed at all stations. The arrows in the figure show the S-wave onset time and the horizontal bars indicate the analyzed portions.

Fourier acceleration amplitude spectra of two horizontal components are computed by the method of the finite Fourier transformation and are summed vectorially. Since only the NS component is available at OAR, the amplitude of the spectra is multiplied by \( \sqrt{2} \) instead of the vectorial summation. The number of frequencies for the computation of Fourier spectrum is 310 in the range from 0.1 to 20 Hz, and \( n \)-th frequency \( f_n \) is determined as follows:

\[
\log f_n = -1 + 7.423 \times 10^{-3} n, \quad n = 0, 1, 2, \cdots, 310.
\]

By taking the logarithmic average every 10 data, 31 data in each spectrum are obtained. Figure 4 shows two examples of spectra observed at IWK. The amplitude of the spectrum for the 1984 event \( (M=4.0) \) increases in the frequency range lower than 0.5 Hz due to the noise of the instrument, while that of the 1987 event \( (M=6.7) \) is not affected by the noise because of its large signals in the same frequency range. In consideration of the accuracy of the observed spectral data, the reliable frequency range from 1 to 10 Hz is used for the inversion. The lower limit of the reliable frequency range, 1 Hz, is determined by the S/N ratios of the records for the small events, and the higher limit is determined in consideration of the sampling interval of digital data and the frequency characteristics of the instruments.

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Fig. 4. Two examples of Fourier acceleration amplitude spectra on the ground surface at IWK station. Dashed lines indicate the standard deviation for the spectra.
4. Results

4.1 Local site effect

Figure 5 shows the factors of site amplification $G_j(f)$ obtained at two borehole stations, TMK and IWK. Subsurface structures at TMK and IWK were well investigated by several different methods (Omote, 1983) as mentioned earlier, and provide us with good opportunities to calculate theoretical transfer functions from the bedrock to each observation point. The transfer functions are calculated by one-dimensional multiple reflection theory of SH-waves (Haskell, 1960) with incident angle of 0 degree, and superposed in Fig. 5 by thin lines. The shear-wave velocity and damping factor in each layer used for the calculation are obtained by Ikeura et al. (1988). The factors of site amplification $G_j(f)$ at TMK and IWK are well explained by the theoretical transfer functions in the frequency range lower than 6 Hz. The narrow peaks and troughs of the theoretical transfer functions cannot be identified in those of $G_j(f)$, since the data of the observed spectra used for the evaluation of $G_j(f)$ are smoothed in frequency domain. However, the broad peaks and troughs of the theoretical transfer functions correspond to those of $G_j(f)$. For example, the amplitudes of the theoretical transfer functions are 2.0 or less at the deepest points of both stations (GL-950 m at TMK, and GL-330 m at IWK), and those of $G_j(f)$ show the same characteristics. The consistency between the factors of $G_j(f)$ and the theoretical transfer functions can be seen not only

![Fig. 5. Factors of site amplification $G_j(f)$ at two borehole stations, TMK and IWK. Thick lines indicate the $G_j(f)$ obtained by the inversion analysis. Thin lines indicate transfer functions from the bedrock to each observation point obtained by the one-dimensional multiple reflection theory of SH-waves with incident angle of 0 degree.](image-url)
in the $G_j(f)$ of the deepest points, but also in those of intermediate depth (GL-100 m at TMK, and GL-20 m at IWK) and ground surface. This consistency indicates that the $G_j(f)$ obtained in the present study represents the site amplification due to the wave propagation from the bedrock to the observation points at least in the frequency range lower than 6 Hz. With regard to the frequency range higher than 6 Hz, a systematic discrepancy can be seen at each observation point. The values of $G_j(f)$ monotonously increase with frequency, and they are larger than those of the theoretical transfer functions. The cause of these phenomena is discussed in the next section from the viewpoint of the validity of constraint condition.

Figure 6 shows the factors of site amplification $G_j(f)$ at five other stations. $G_j(f)$ at KDG is fixed to be 2 irrespective of frequency as the constraint condition for solving the inverse problem. In the frequency range lower than 6 Hz, the relation between the factor of site amplification $G_j(f)$ and the shear-wave velocity $V_s$ of the ground layers at the observation points is investigated on the basis of the results shown in Figs. 5 and 6. Here, $V_s$ is defined as the average shear-wave velocity within 20 m depth from the observation point. The value of $G_j(f)$ is 6 to about 20 at the ground surface of TMK with $V_s = 500$ m/s, while the values are about 1.4 to 3 at IDG and HKD with $V_s = 1,700$ to 2,100 m/s. The value of $G_j(f)$ is about 2 to 4 at the ground surface of IWK with $V_s = 1,100$ m/s, and it is slight larger than those of IDG and HKD. Large peaks and troughs are seen in the $G_j(f)$ of OAR and CHS. The frequency of large trough of $G_j(f)$ at CHS, about 8 Hz, corresponds to the natural frequency of surface layers over the observation point of GL-18 m. The average value of $G_j(f)$ is about 3 at OAR with $V_s = 1,000$ m/s, and is about 4 at CHS with $V_s = 1,400$ m/s. It is found that the values of $G_j(f)$ increase with decrease of the shear-wave velocities of the surface layers under the observation points. This result indicates that the impedance ratio between

Fig. 6. Factors of site amplification $G_j(f)$ at KDG, IDG, HKD, OAR, and CHS. $G_j(f)$ at KDG is fixed to be 2 as the constraint condition.
the bedrock and the near-surface layers controls the factor of site amplification in this frequency range.

4.2 Source spectra and $Q_s$-value

Source spectra of 20 events are obtained by the inversion analysis. Figure 7 shows examples of the source spectra for the events with magnitude $M$ from 4.0 to 6.6. The source spectrum $M_s(f)$ is redefined from $S(f)$ so that its dimension is identical with that of the seismic moment. $M_s(f)$ is called effective seismic moment (Kanamori, 1972). When $M_s(f)$ is converted from $S(f)$, we assume the shear-wave velocity of 4.0 km/s, density of 3.0 g/cm$^3$, and the average point-source radiation coefficient of 0.6 (Takemura et al., 1989), respectively. For the events of $M < 6$, corner frequencies $f_c$ are seen in the

![Diagram](image_url)

Fig. 7. Examples of seismic moment density functions. Arrows and broken lines indicate the corner frequency and the seismic moment obtained by Takemura et al. (1989).
frequency range from 1 to 10 Hz. For example, the $f_C$ for the event with $M$ of 5.3 is about 2 Hz, and that with $M$ of 4.6 is about 3 Hz. Takemura et al. (1989) evaluated the seismic moment $M_o$ and the corner frequency $f_C$ for the same events from the records of velocity-type strong motion seismograph at IWK. In Fig. 7, their results of $M_o$ and $f_C$ are also plotted by broken lines and by arrows. The $M_o$ and $f_C$ by Takemura et al. (1989) are almost consistent with those of the present study. For the event of $M > 6$, corner frequencies $f_C$ are not found in the Fig. 7, since they may be lower than 1 Hz.

In the high frequency range of $f > f_C$, the decay rate of source spectra changes at about 6 Hz. That is, the amplitude of the spectrum is proportional to $\omega^{-2}$ in the frequency range lower than 6 Hz, while the amplitude shows a steeper decay in the range higher than 6 Hz. The meaning of the second corner of the source spectra at about 6 Hz is also discussed in the next section.

Figure 8 shows the $Q_S$-values as a function of frequency. The solid curve indicates the result obtained in this study, and a formula of $Q_S(f) = 60f^{1.0}$ fits to the result. The results by Aki (1980) and Sato and Matsumura (1980) are also shown in Fig. 8. Their results were obtained by the single station method at Tsukuba and at Iwatsuki in Kanto district. The result in this study is in-between. The result by Abe et al. (1989) was obtained from the data along the Pacific coast of southern Tohoku district by the same method and the same constraint condition as that of Iwata and Irikura (1986, 1988). This result shows a large scatter with frequency in comparison with other results. This may be caused by the problem of the constraint condition in the high frequency range indicated by Iwata and Irikura (1986, 1988).
5. Discussions

The validity of the constraint condition adopted for the factor of site amplification at a reference station (KDG) is discussed, since the monotonous increasing of \( G_j(f) \) in the frequency range higher than 6 Hz and the second corners of the source spectra at 6 Hz may be attributed to the constraint condition. As described before, the constraint condition is that \( G_j(f) \) is 2 at KDG, irrespective of frequency.

According to Hanks and McGuire (1981), Boore (1983), and Joyner (1984), the displacement source spectra for moderate earthquakes of \( 5 < M < 7 \) are explained by the \( \omega^2 \)-square spectrum with a high frequency cut-off \( f_{\text{max}} \). The value of \( f_{\text{max}} \) was determined to be 15 Hz by Boore (1986) so as to simulate the observed peak and r.m.s. accelerations for the events in western North America. If the displacement source spectrum has \( \omega^{-2} \) fall-off in the frequency range of \( f > f_c \), the acceleration spectrum observed on the bedrock shows a constant value for the same frequency range. \( Q_s \)-value along the wave propagation path does not influence the form of the source spectrum, since it is almost proportional to \( f^{1.0} \) according to the result in the present study. In this case, the form of observed spectrum represents the approximate form of the site amplification. Figure 9 shows a mean Fourier acceleration spectrum obtained from the observed records at KDG, which are corrected to the values with hypocentral distance \( R \) of 100 km using the geometrical spreading factor of \( R^{-1} \). To avoid the influence of the corner frequency \( f_c \) of source spectra, the mean spectrum is calculated for the 7 events of \( M > 6 \), which have \( f_c \) lower than 1 Hz. The mean spectrum is almost constant in the frequency range from 1 to 6 Hz. This result suggests that the site amplification at KDG is almost constant, and that the constraint condition adopted for KDG in the present study is satisfactory at least in the frequency range from 1 to 6 Hz.

On the other hand, the amplitude of the mean spectrum decreases with frequency higher than 6 Hz. The frequency of the corner of the mean spectrum, 6 Hz, is almost
the same as that of the second corners of the source spectra. There are two possible interpretations about the corner at 6 Hz of the mean spectrum from a viewpoint of origin of the cut-off frequency, $f_{\text{max}}$. One is that the corner is caused by the source-controlled $f_{\text{max}}$ and the other is that the corner is caused by the site-controlled $f_{\text{max}}$ (Kinoshita, 1988). Kinoshita and Mikoshiba (1988) analyzed the strong motion records of the 1987 east off Chiba Prefecture earthquake ($M=6.7$) observed simultaneously in the deep borehole and on the ground surface at Shimohsa, and estimated the source spectrum from the borehole data. According to the result of source spectrum, the source-controlled $f_{\text{max}}$ is identified at 22 Hz, while the observed $f_{\text{max}}$ on the ground surface is lower than 10 Hz. Thus, the $f_{\text{max}}$ of the spectrum on the ground surface was interpreted as the site-controlled $f_{\text{max}}$ caused by the effect of inelastic attenuation of the sedimentary layers on the bedrock. Hoshino and Kinoshita (1988) and Kinoshita (1986) also indicated that the site-controlled $f_{\text{max}}$ is about 4.8 Hz from the observed spectra on the thick alluvium in Tokyo lowlands. The frequency of the corner of the mean spectrum at KDG is very low, in comparison with the source-controlled $f_{\text{max}}$ for the 1987 event. Besides, the corner cannot be easily explained by the site-controlled $f_{\text{max}}$ caused by the effect of inelastic attenuation of the sedimentary layers, since the instrument at KDG is installed in the bedrock.

The observation point of KDG is located near the bottom of the valley as shown in Fig. 10, and an effort is made to examine the effect of surface topography around KDG. Two-dimensional elastic half space model of the vertical cross section of the valley is made from the topography around KDG as shown in Fig. 11. The shear-wave velocity and density are assumed to be 2,200 m/s and 2.5 g/cm$^3$. The transfer function due to unit harmonic incident SH-wave is calculated numerically by the boundary element method (BEM) for the two-dimensional model. Incident angle of the input wave is assumed to be 0 degree. Figure 12 shows the result of the transfer function, which has a corner at about 6 Hz. The form of the transfer function is found to be similar to that of the mean spectrum (see Fig. 9). According to this result, the corner of the mean spectrum at about 6 Hz is supposed not to be the effect of $f_{\text{max}}$ but to be the effect of the topography around KDG. This indicates that the validity of the
constraint condition is reconfirmed in the frequency range lower than 6 Hz, while it is necessary to revise the constraint condition in the range higher than 6 Hz in terms of the topographical effect around KDG. The second corners of source spectra and the characteristic of the monotonous increase of $G_j(f)$ higher than 6 Hz may be eliminated by the revision of the constraint condition.

6. Concluding Remarks

The source, propagation path, and local site effects are separated from the S-wave portions of strong ground motions observed at the stations along the Pacific coast of southern Tohoku and Kanto districts by a linear inversion method in the frequency range from 1.0 to 10 Hz. To solve this problem, the factor of site amplification at a reference station (KDG) on an outcrop of the bedrock is constrained to 2 irrespective of frequency. The validity of the constraint condition is discussed on the basis of the mean acceleration spectrum obtained from the observed records and the calculated

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topographical effects by the two-dimensional BEM model at KDG. It is concluded that the constraint condition is satisfactory in the frequency range lower than 6 Hz. The results in the frequency range are summarized as follows:

1. The factors of site amplification $G_j(f)$ at two borehole stations, TMK and IWK, are well explained by the theoretical transfer functions of the sedimentary layers from the bedrock to the observation points. This indicates that the $G_j(f)$ obtained in the present study represents the site amplification due to the wave propagation through multilayered media on the bedrock.

2. The values of $G_j(f)$ at the observation points on the ground surface and under thin sedimentary layers increase with decrease of the shear-wave velocity $V_S$ of the layers under the observation points.

3. $Q_S$-value along the propagation path shows frequency dependency of the form $Q_S(f) = Q_0 f^z$ with $Q_0 = 60$ and $z = 1.0$. The result is almost consistent with those in this region by other investigators.

4. Amplitudes of displacement source spectra for the events with $M$ from 4.0 to 6.6 have $\omega$-square decay in the frequency range higher than the corner frequency.

In the frequency range higher than 6 Hz, it is suggested that the reference station (KDG) is influenced by the topographical effects. The revision of the constraint condition is a future study to obtain reliable results in the frequency range higher than 6 Hz.

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