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QUALITY FACTOR IDENTIFIED USING KIK-NET IN JAPAN

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ABSTRACT

Many seismographs have been installed in Japan since the 1995 Hyogoken-Nanbu earthquake, which brought severe damage to the city of Kobe and the surrounding area. The National Research Institute for Earth Science and Disaster Prevention (NIED) deploys digital strong-motion seismographs (KiK-net) all over the country in Japan, to provide vertical array records of ground motions. The total number of observation sites is nearly 700. Data observed by KiK-net can be downloaded on the website. They can be used to identify the dynamic properties, such as shear wave velocity and quality factor of the subsurface ground. In this study, a new approach is proposed to identify the quality factor. It is applied to some KiK-net sites to extract the frequency-dependent characteristics of the quality factor.

Introduction

Strong ground motions are largely affected by the amplification effect of subsurface layers of the ground. Therefore, it is very important to estimate the dynamic soil properties of the subsurface ground in order to predict the characteristics of strong ground motions that influence the behavior of structures based on the ground or lifeline facilities buried underground.

Recently, several studies (Ohta 1975, Tsujihara 1996, 2004, Sato 1994, Annaka 1994, Yoshida 1995, Nakamura 2002, *etc.*) have been done on the identification of dynamic soil properties of subsurface ground using vertical array records of ground motions. Among the properties, the damping is known to be difficult to be identified in particular.

Vertical array observations of ground motions are energetically carried out in Japan. Digital strong-motion seismographs, so called KiK-net, are deployed by the National Research Institute for Earth Science and Disaster Prevention (NIED) at nearly 700 sites. An enormous amount of data has been accumulated since 1997 and can be downloaded from the website, providing a great opportunity to identify the dynamic properties of subsurface ground.

The shear wave velocity and quality factor are generally identified as the stiffness and damping parameter, respectively, supposing one-dimensional multiple reflection of shear wave in the horizontally laminated soil deposits. The accuracy of identifying the shear wave velocity has been improved. But, the improvement of accuracy is not very notable in identifying the quality factor. Several models were proposed for the quality factor. Some researchers identified the quality factor of each layer and others the average through the layers. The influence of the damping models and conditions of analysis on the accuracy has been

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investigated (Tsujihara and Sawada 2006). It was reported that when the damping parameter of every layer was identified, the accuracy of identification was remarkably deteriorated with the increase of the layers. In the numerical experiments, it was demonstrated that there was the case in which the accuracy of the estimated damping parameter differed by a few hundreds times, depending on estimating the value of the parameter in every layer or the average value through the layers. However, it was also reported that the average value of damping through the layers could be estimated almost to the same level of accuracy as the shear wave velocity of the layers, when these parameters were identified simultaneously.

The detection of the frequency dependency of the quality factor has become of major interest lately. In this paper, a new method, called the *Sweeping Method*, is proposed to detect it. The quality factor is estimated by two stages in the process of identification. In the first stage, the quality factor is identified assuming that it is independent of frequencies together with shear wave velocity of laminated each layer. In the second stage, the quality factor at each frequency point is identified with shear wave velocity fixed. The quality factor in the frequency bands where it is not sensitive is swept out. As a result, the values of the quality factor at significant frequency points are highlighted.

Theory and Method

Multiple Reflection Theory

Horizontally laminated soil deposits are assumed to be excited by vertical incident SH wave. Consider the identification of subsurface ground model as shown in Fig. 1, in which *H*,*ρ*, *V* and *Q* denote the thickness, density, shear wave velocity and quality factor, respectively.

The displacement and shear stress at the points p in the p-th layer and q in the q-th layer are represented by multiple reflection theory as follows(Haskell 1960, Toki 1981).

$$\begin{Bmatrix} u_p \\ \tau_p \end{Bmatrix} = \left[R_p\right] \begin{Bmatrix} u_0 \\ 0 \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} u_q \\ \tau_q \end{Bmatrix} = \left[R_q\right] \begin{Bmatrix} u_0 \\ 0 \end{Bmatrix} \tag{2}$$

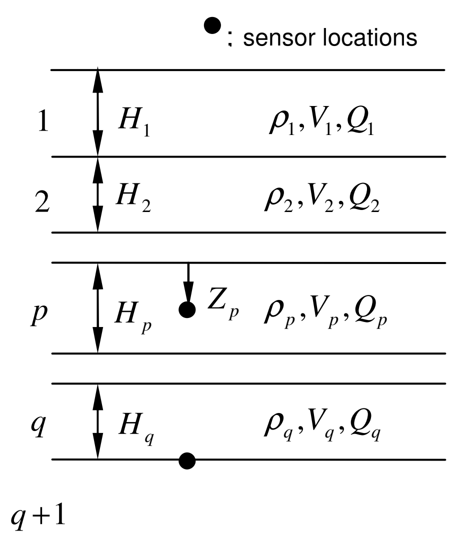


Figure 1. Analytical model of subsurface ground and sensor locations.

where u_p, u_q and u_0 denote the displacement at the points p, q and ground surface, respectively. τ_p and τ_q denote the shear stress at the points p and q, respectively. [R_p] and [R_q] are the 2×2 matrices obtained by

$$[R_P]=[T_p][S_{p-1}]\cdots[S_1] \tag{3}$$

$$[R_q]=[T_q][S_{q-1}]\cdots[S_1] \tag{4}$$

where [S_m] is the 2×2 matrix representing the state of the m-th layer. The elements in the matrix are given by

$$\begin{cases} S_{m\cdot 11}=[\exp(ia_m\omega)+\exp(-ia_m\omega)]/2 \\ S_{m\cdot 12}=[\exp(ia_m\omega)-\exp(-ia_m\omega)]/(2ib_m\omega) \\ S_{m\cdot 21}=ib_m\omega[\exp(ia_m\omega)-\exp(-ia_m\omega)]/2 \\ S_{m\cdot 22}=S_{m\cdot 11} \end{cases} \tag{5}$$

in which $\omega(=2\pi f)$ is circular frequency, $i(=\sqrt{-1})$ is imaginary unit, and

$$a_m=H_m/(V_m\sqrt{1+i/Q_m}) \tag{6}$$

$$b_m=\rho_m V_m\sqrt{1+i/Q_m} \tag{7}$$

H_m, ρ_m, V_m and Q_m are the thickness, density, shear wave velocity and quality factor of the m-th layer, respectively. [T_m] (m=p or q) in Eqs. 3 and 4 denote the similar matrix to [S_m] but Z_m is used in place of H_m.

Identification of Shear Wave Velocity and Quality Factor

Denoting Fourier spectra of the vertical array records at the points p and q(p<q) by $X_p(f)$ and $X_q(f)$, the amplitude of quasi transfer function between p and q can be obtained by

$$U_{pq}(f_j)=X_p(f_j)/X_q(f_j) \tag{8}$$

where f_j is the discrete frequency. On the other hand, the theoretical transfer function can be derived from Eqs. 1 and 2 by

$$\tilde{U}_{pq}(f_j,\boldsymbol{\alpha})=\gamma_p(f_j,\boldsymbol{\alpha})/\gamma_q(f_j,\boldsymbol{\alpha}) \tag{9}$$

where $\boldsymbol{\alpha}$ denotes the unkown parameters to be identified and $\gamma_m(f_j,\boldsymbol{\alpha})$ (m=p or q) denotes the (1,1) element of matrix [R_m]. The thickness and density of each layer are assumed to be known.

Then, identification problem of unknown parameters such as shear wave velocity and quality factor of the layers above the point q can be reduced to the problem of optimization, which is represented by

$$S(\boldsymbol{\alpha})=\sum_{j=1}^{N_f}\left\{\tilde{U}_{pq}(f_j,\boldsymbol{\alpha})-U_{pq}(f_j)\right\}^2\rightarrow\min \tag{10}$$

where N_j is the total number of discrete frequencies. The objective function represented by Eq.11 can be also used instead of Eq.10.

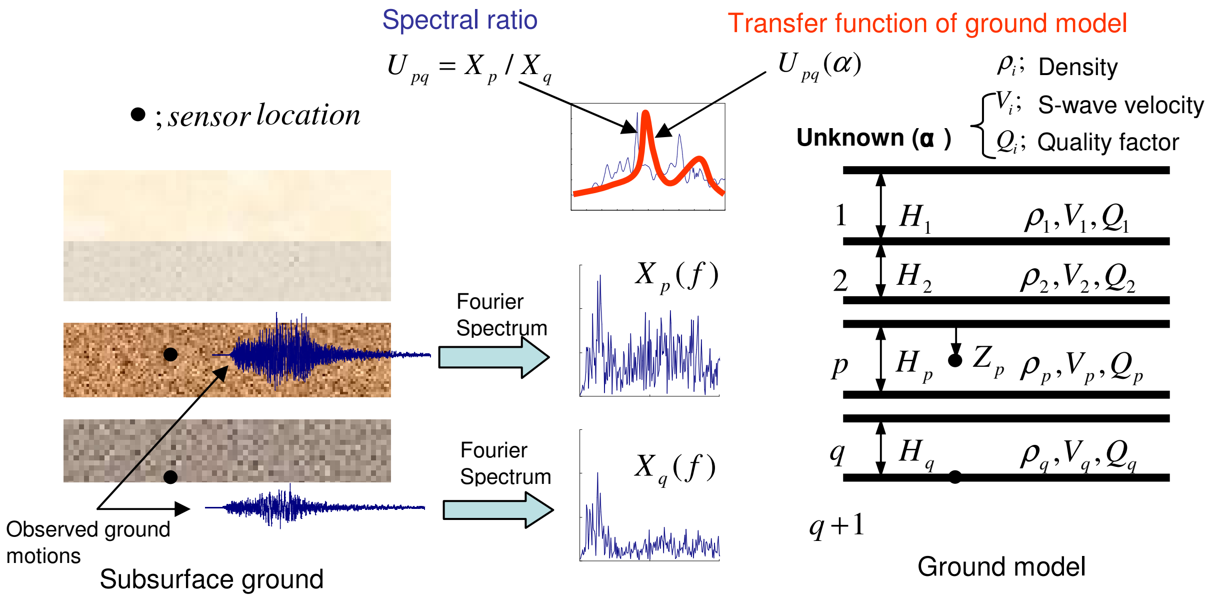


Figure 2. Schematic diagram of identification problem.

$$S(\boldsymbol{\alpha}) = \sum_{j=1}^{N_f} \left\{ \tilde{X}_p(f_j, \boldsymbol{\alpha}) - X_p(f_j) \right\}^2 \rightarrow \min \tag{11}$$

where $\tilde{X}_p(f_j, \boldsymbol{\alpha})$ is obtained by

$$\tilde{X}_p(f_j, \boldsymbol{\alpha}) = \gamma_p(f_j, \boldsymbol{\alpha}) / \gamma_q(f_j, \boldsymbol{\alpha}) X_q(f_j) \tag{12}$$

The identification problem is schematically shown in Fig.2. The minimization of Eq.10 or 11 is carried out by the scheme of MSLP (Modified Successive Linear Programming) (Sawada 1992).

Sweeping Method

The difficulties in the identification of the quality factor have, for the most part, its origin in the sensitivity to the transfer function shown by Eq.9. Fig.4 shows the sensitivities of the shear wave velocity and quality factor to the transfer function of subsurface ground model shown in Fig.3. The feature of the sensitivity of shear wave velocity is that the sign changes from minus to plus at the frequencies where the transfer function has peaks, which means that the peak frequencies change with the shear wave velocity. The peaks move to the higher frequencies when the shear wave velocity becomes large. On the other hand, the quality factor has the effect to change the level of amplitude of the transfer function. The common feature for both parameters is that they are sensitive just around the peak frequencies of the transfer function. When the detection of the frequency-dependent quality factor is required, functions such as “$Q=Q_0f^n$“, where “f” denotes frequency, are supposed and Q_0 and n are estimated. Using Eq.11 as the objective function, the residual of the spectral ratio and the transfer function at every frequency point is summed up. Since the spectral ratio is generally contaminated by noise, it is difficult to adjust the damping parameters so as to get a better fit between the spectral ratio and transfer function in the frequency bands where the quality factor is not sensitive. Though the objective function is considered to be multiplied by weighting coefficients at frequencies, it is not easy to determine the proper coefficients.

Accurate identification of the frequency-dependent quality factor supposing such functions as

"$Q=Q_0f^n$" seems to be difficult, since the problem of the extreme difference of sensitivity over the frequency band exists.

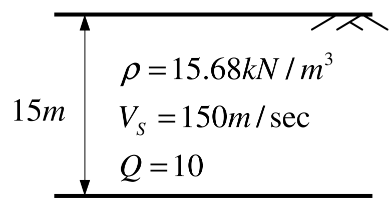


Figure 3. Subsurface ground model.

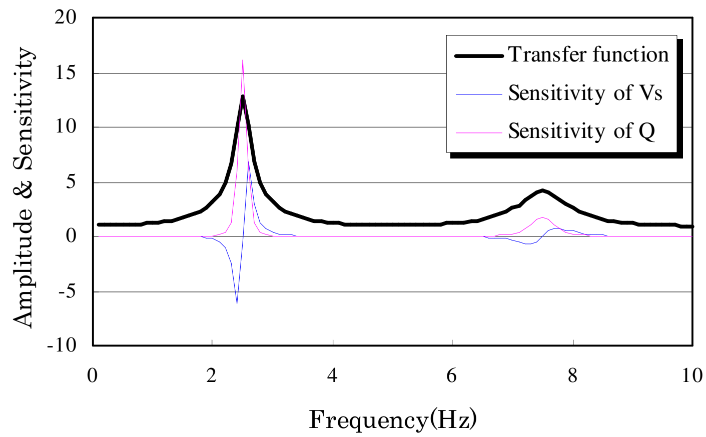


Figure 4. Transfer function and sensitivity of shear wave velocity and quality factor.

The quality factor is then considered to be estimated at every frequency point independently. However, the problem of its sensitivity also stands in the way. Namely, the accuracy of the estimated quality factor deteriorates in the frequency bands where it is not sensitive. In the method proposed in this study, the quality factor is swept out of feasible range in such a frequency band, utilizing the feature of sensitivity. The procedure is shown in following sections.

Shear wave velocity of each layer and the average value of the quality factor through the layers are identified in the first stage by Eq.10 or 11. The quality factor is assumed to be independent of frequencies in this stage. The quality factor at every frequency point is identified in the second stage with the shear wave velocity fixed to the estimated values in the first stage. The quality factor estimated in the first stage is used as the initial value in the identification by the iterative manner using MSLP. The quality factor at the frequency points where it is not sensitive is swept out in the process of the optimization, because the residuals of spectral ratio and transfer function in Eq.10 at these frequency points can not be minimized however drastically the quality factor may be modified. In practice, setting upper and lower limits for them, the identification is performed. The quality factor exceeds the limits in the iterations at the frequency points where it is not sensitive. The limits play the role of absorber. Eventually, the quality factor remains in between the limits in only the significant frequency bands.

Application of Sweeping Method

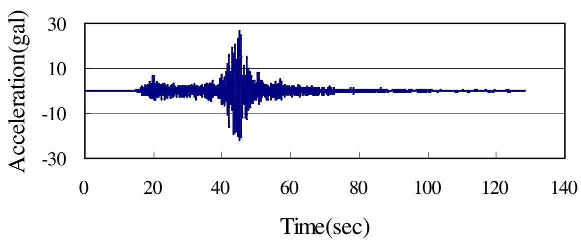
The *Sweeping Method* is applied to the identification of 7 sites as shown in Table 2 of KiK-net, where vertical array sensors are installed at the ground surface and G.L.-100m, using the records of ground motions obtained in the earthquakes whose data are shown in Table 1. Among the 7 sites, the results of identification at the site whose code is "IWTH08" in the event 1 are described in detail in the following.

Table 1. Profiles of earthquakes.

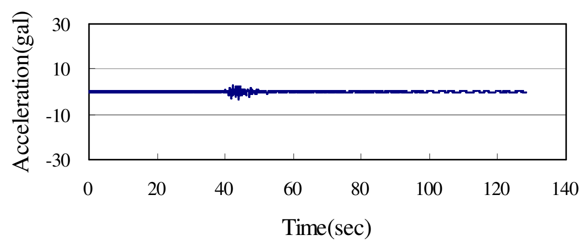
Event No.	Date	Latitude	Longitude	Depth(km)	Magnitude
1	2003/7/26	38.402	141.173	12	6.2
2	2005/8/16	38.147	142.282	42	7.2

Table 2. Profiles of sites.

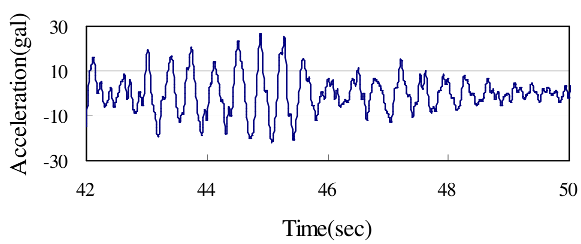
No.	Site Code	Site Name	Latitude	Longitude
1	IWTH06	NINOHE-W	40.2583	141.1744
2	IWTH08	KUJI-N	40.2658	141.7867
3	IWTH10	ASHIRO	40.1364	140.9564
4	IWTH12	KUNOHE	40.1506	141.4281
5	AKTH06	OGACHI	38.9772	140.4986
6	YMTH04	KAMINOYAMA	38.0783	140.3011
7	YMTH15	NSHIKAWA-E	38.4228	140.1283



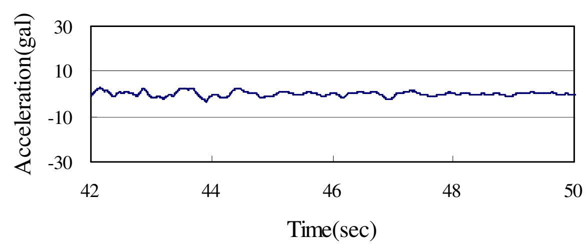
(a) Ground Surface



(b) G.L.-100m



(c) Ground Surface (selected interval)



(d) G.L.-100m (selected interval)

Figure 5. Acceleration of ground motions recorded at IWTH08 (site code) by KiK-net.

The records of ground motions at ground surface and G.L.-100m are shown in Fig.5 (a) and (b), respectively. They are the transverse components to the epicentral direction. The intervals of strong ground motions are selected, which are shown in Figs.5 (c) and (d), to be used in the identification. Borehole test and PS-logging were carried out at the site. The structure of the subsurface ground was estimated as shown in Table 3. The ratio of Fourier spectra of the ground motions shown in Figs.5 (c) and (d) is illustrated in Fig.6 together with the transfer function of the ground model shown in Table 3. In the calculation of the transfer function, the quality factor of 10 is given, and the density of soil of each layer is approximated by the following equation (Gardner 1974).

$$\rho_i = V_{pi}^{1/4} \tag{13}$$

where V_{pi} is the primary wave velocity of the layer “i”.

Table 3. Structure of subsurface ground estimated by borehole test and PS-logging.

No.	Thickness (m)	S-wave Velocity (m/sec)	P-wave Velocity (m/sec)
1	4.0	150.0	360.0
2	6.0	280.0	600.0
3	10.0	280.0	2150.0
4	14.0	680.0	3000.0
5	16.0	900.0	3000.0
6	50.0	2120.0	3680.0

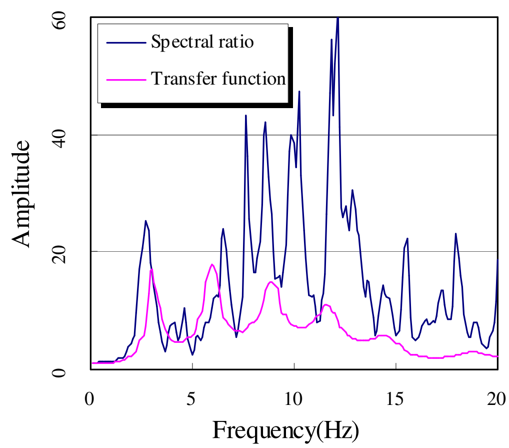


Figure 6. Spectral ratio and transfer function.

The results of the first-stage identification are shown in Figs.7 and 8 (b). The amplitude of the Fourier spectrum of ground motions at the surface is the target in the identification to avoid the influence of the smoothing of spectrum. Fig. 7 shows the identified shear wave velocity and quality factor which is assumed to be independent of frequency. Fig. 8 shows the target Fourier spectrum and its estimates calculated with the initial and estimated model of subsurface ground in the first and second stages. The identified shear wave structure coincides with the initial one, which is estimated by PS-logging. The identified quality factor is 18.2. The results of the second-stage identification are shown in Figs. 8 (c) and 9(a). The shear wave velocity is fixed to the values estimated in the first stage and 18.2 is given to the quality factor as its initial value. Comparing Fig. 8 (b) with (c), the fitness of Fourier spectra is much better in (c). The identified quality factor at each frequency point is shown in Fig. 9 (a). At some frequency points the values of the quality factor converge to the upper or lower limit which is 80 and 3, respectively. The trend that values of the quality factor become large as the frequencies increase can be recognized clearly, though the variations are not small enough. The estimated values using the ground motions in the event 2 are shown in Fig. 9 (b). The trends of the estimated values in the different events correspond to each other. The results at other sites are shown in Fig.10. Generally the values of identified quality factor become large as frequencies increase. The similarity of the results can be seen at the identical site.

Conclusions

In this study, the *Sweeping Method* is proposed to identify the quality factor of subsurface ground using earthquake ground motions recorded by vertical array of seismographs. The frequency-dependent

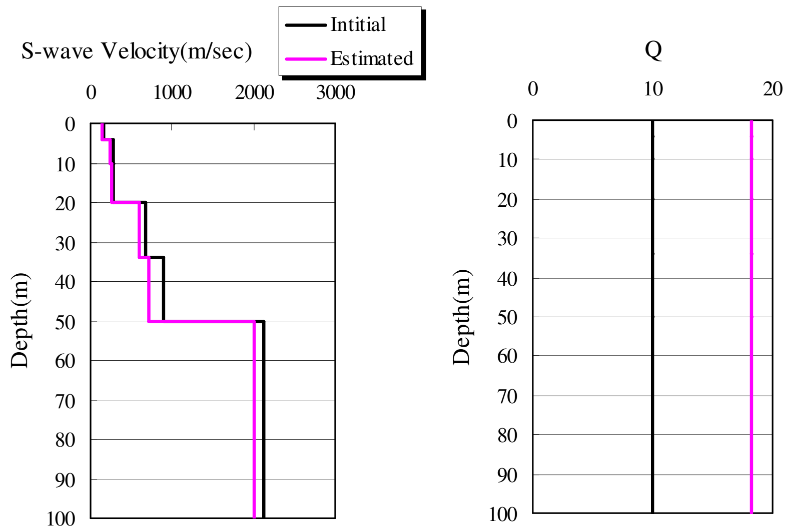
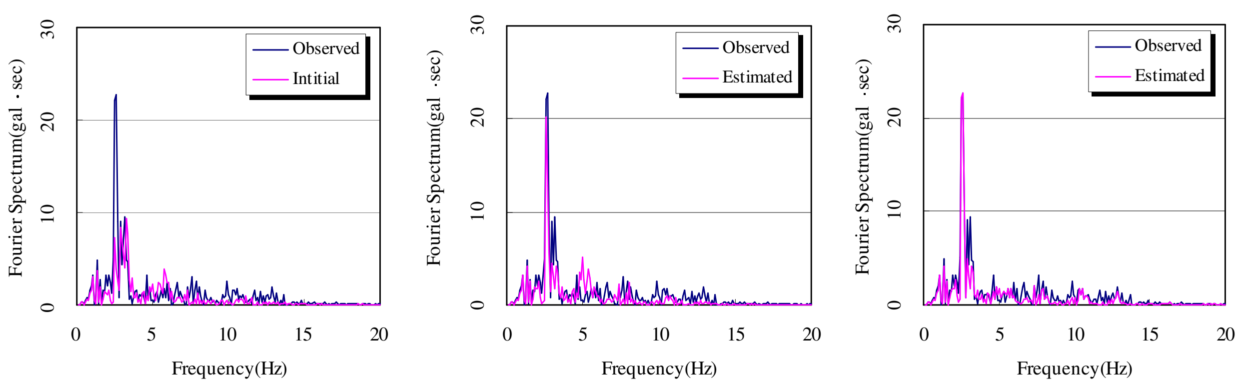


Figure 7. Initial values of parameters and their estimations in the first stage.

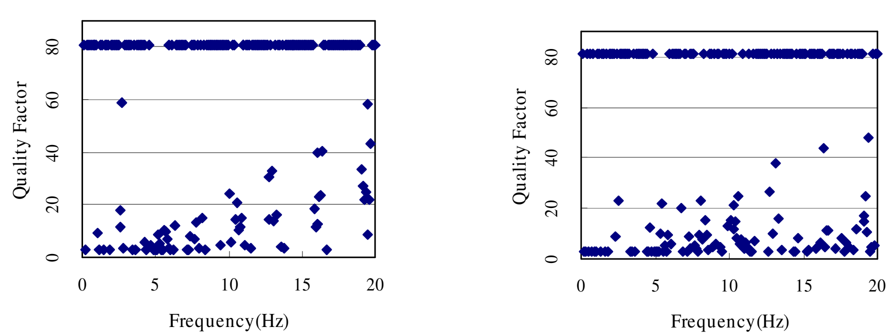


(a) Observed & Initial

(b) Observed & Estimated
in the first stage

(c) Observed & Estimated
in the second stage

Figure 8. Fourier Spectrum at ground surface and its estimations in the first and second stages.



(a) event1

(b) event2

Figure 9. Identified quality factor at IWTH08 in the second stage using the records of events 1 and 2.

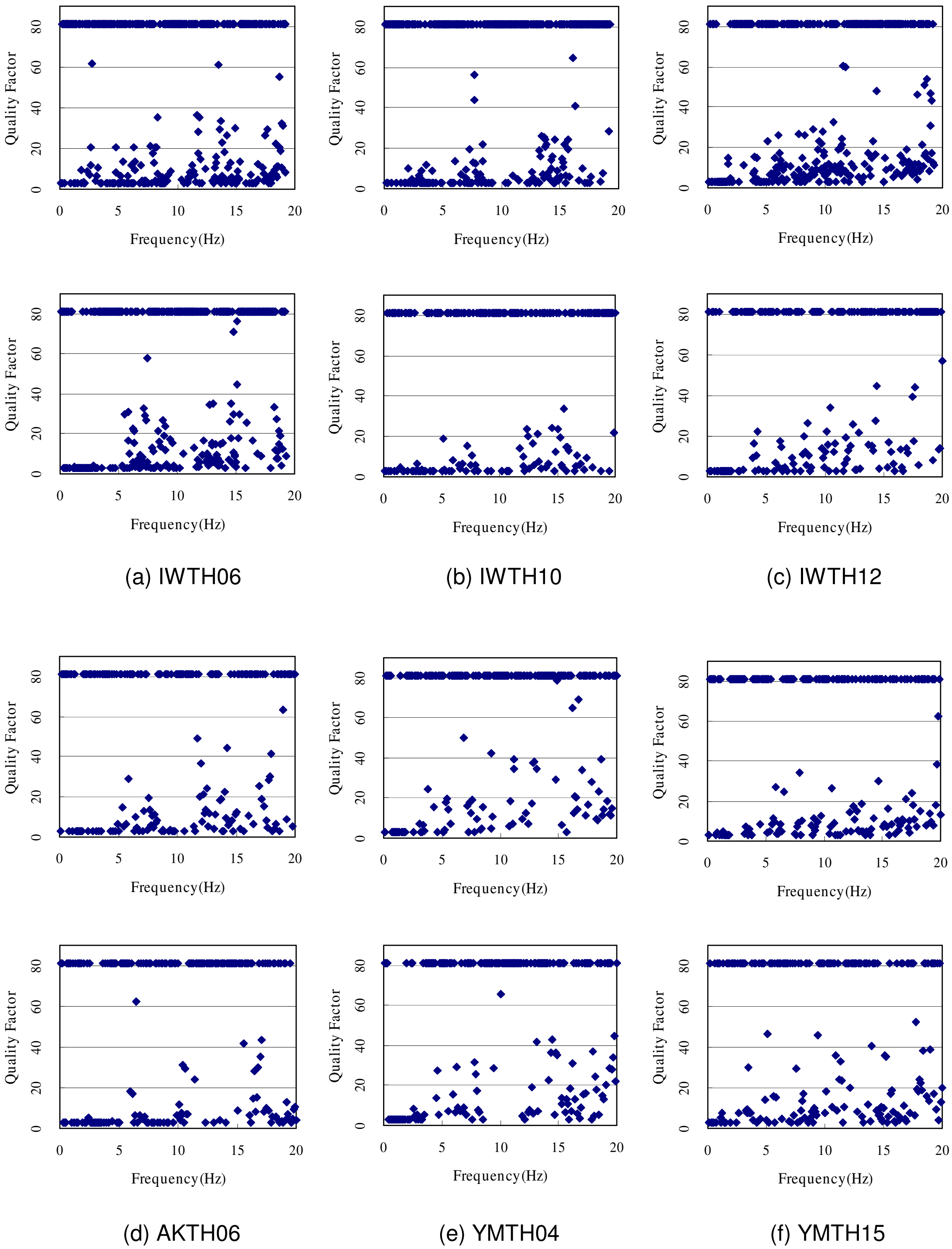


Figure 10. Identified quality factor in the second stage using the records of event 1 (upper) and event 2 (lower) at each site.

quality factor is estimated by two stages in the process of identification. The quality factor in the frequency band, where it is not sensitive, is swept out. As a result, the values of the quality factor at significant frequency points are highlighted.

The major results of this study are as follows.

(1) The trend of the quality factor whose values increase according to frequencies can be recognized, though the variations are not small enough.
(2) The similarity of the estimated values of the quality factor can be seen at the identical site using different events of earthquakes.

Since the variations of the estimated values of the factor are not small enough, it is too early to discuss its dependency on frequencies quantitatively. Accumulation of analytical results for identification is necessary as well as the development of the method proposed in this study for the goal of modeling the frequency-dependent quality factor of subsurface ground.

Acknowledgments

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