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COHERENCY OF QUALITY FACTOR OF SUBSURFACE GROUND IDENTIFIED USING VERTICAL ARRAY RECORDS OF EARTHQUAKE MOTIONS

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ABSTRACT

Quality factor, which denotes the degree of damping of earthquake motions, in the sedimentary layers of has not been well understood. In this study, an analytical method is proposed to identify the frequency-dependent quality factor using vertical array records of earthquake ground motions. Comparing the results of identification at the identical site using the records of ground motions obtained in different events of earthquake, the coherency of estimated quality factor is focused on and the reliability of the proposed method is discussed.

INTRODUCTION

Strong ground motions are largely affected by the amplification effect of subsurface layers of the ground. Therefore, it is very important to estimate dynamic soil properties of 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 and Sawada 1996, Sato et al. 1994, Annaka *et al*. 1994, Yoshida and Kurita 1995, Nakamura *et al*. 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 in particular to be identified.

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 identification of shear wave velocity has been improved. But, the improvement of accuracy is not very notable in the identification of quality factor.

Lately, assuming the soil deposits as a layer in the identification of quality factor, the detection of the frequency dependency of quality factor has become of major interest. Tsujihara and Sawada (2007) proposed the sweeping method in which the values of quality factor were estimated only at the frequency points where they were sensitive.

In this study, the sweeping method is modified so as to obtain the more reliable results of identification. Comparing the results of identification by this method at the identical site using the records of ground motions obtained in different events of earthquake, the coherency of estimated quality factor is focused on and the reliability of the proposed method is discussed.

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THEORY AND METHOD

Identification of shear wave velocity and quality factor

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. 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

$$U_{pq}(f_j) = X_p(f_j) / X_q(f_j) \tag{1}$$

where f_j is the discrete frequency. The 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

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

where $\boldsymbol{\alpha}$ denotes the unkown parameters to be identified and $\widetilde{X}_p(f_j, \boldsymbol{\alpha})$ is obtained by

$$\widetilde{X}_p(f_j, \boldsymbol{\alpha}) = \widetilde{U}_{pq}(f_j, \boldsymbol{\alpha}) X_q(f_j) \tag{3}$$

N_f is the total number of discrete frequency points. $\widetilde{U}_p(f_j, \boldsymbol{\alpha})$ is the transfer function between the points p and q, which is caculated by the multiple reflection theory (Haskell 1960).

The identification problem is schematically shown in Fig.2. The minimization of Eq.2 is carried out by the scheme of MSLP (Modified Successive Linear Programming; Sawada *et al.* 1992).

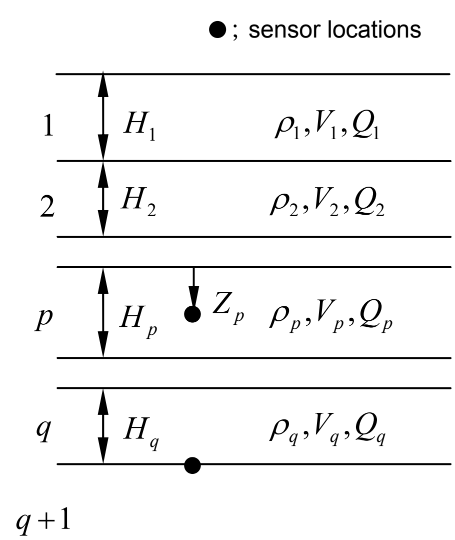


Figure 1. Analytical model of subsurface ground and sensor locations.

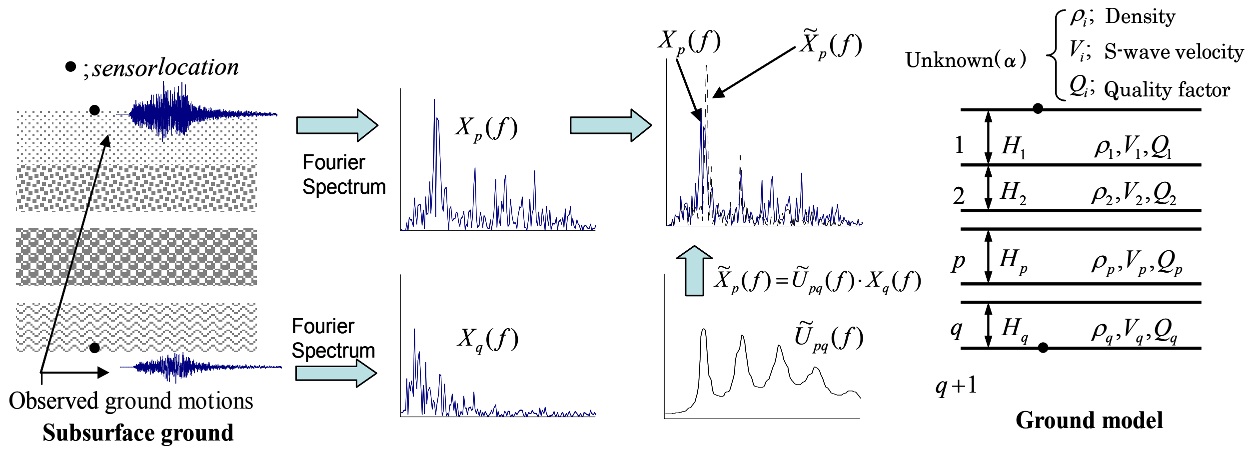


Figure 2. Schematic diagram of identification problem

Outline of Sweeping Method

The difficulties in the identification of quality factor have mainly its origin in the sensitivity of it to the transfer function. Fig.4 shows the sensitivities of 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 frequency where the transfer function has peaks, which means that the peak frequency points change with the shear wave velocity. The peaks move to the higher frequency when the shear wave velocity

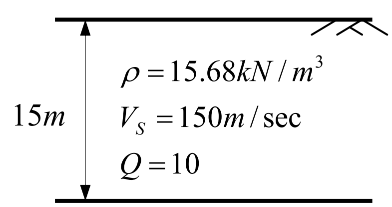


Figure 3. Subsurface ground model

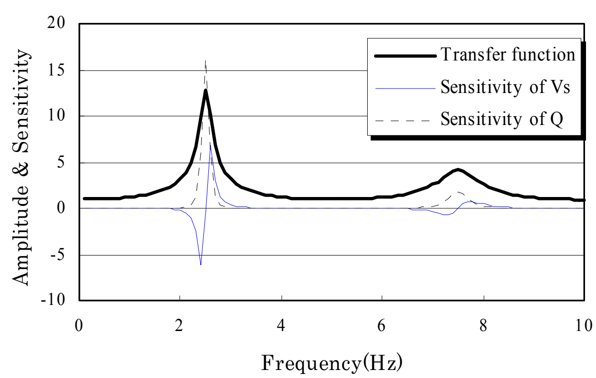


Figure 4. Transfer function and sensitivity of shear wave velocity and quality factor.

becomes large. On the other hand, quality factor has the effect to change only the level of amplitude of the transfer function. The common feature of both parameters is that they are sensitive just around the peak frequency points of the transfer function. When the detection of frequency-dependent quality factor is required, functions such as "$Q=Q_0f^n$ ", where "f" denotes frequency, are generally supposed and Q_0 and n, which are both constant, are to be estimated. Using Eq.2 as the objective function, the residual of the spectra at every frequency point is summed up. Since the spectra are generally contaminated by noises, it is difficult to adjust the damping parameters so as to get better fit between the spectra in the frequency bands where the quality factor is not sensitive. Though the residual at each frequency point in Eq.2 is considered to be multiplied by weighting coefficient, it is not easy to determine the proper coefficients. 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 estimated quality factor deteriorates in the frequency bands where it is not sensitive. In the sweeping method, quality factor is swept out of feasible range in such the frequency bands, utilizing the feature of sensitivity.

The procedure is shown in the followings.

Shear wave velocity of each layer and the average value of quality factor through the layers are identified in the first stage by Eq.2. Figs.5 and 6 show the comparison of the observed Fourier spectrum and

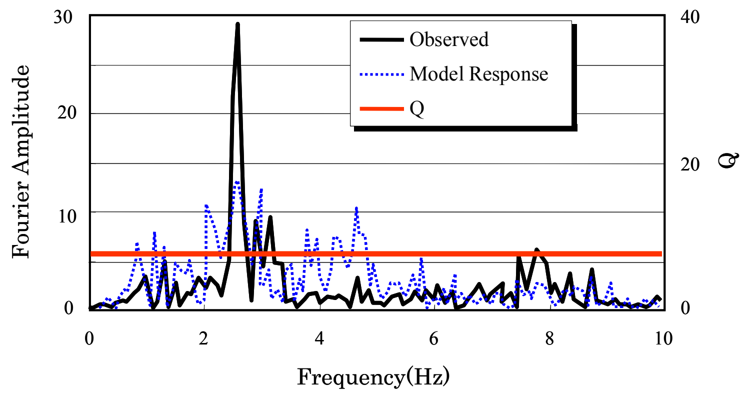


Figure 5. Comparison of observed Fourier spectrum and response of initial model with initially given quality factor

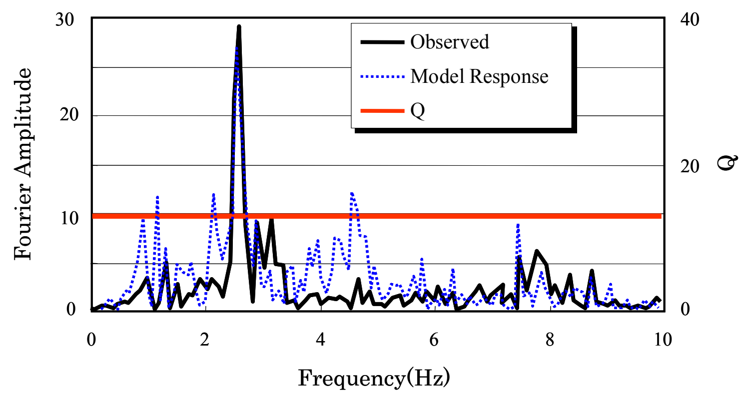


Figure 6. Comparison of observed Fourier spectrum and response of model identified in the 1st stage with identified quality factor

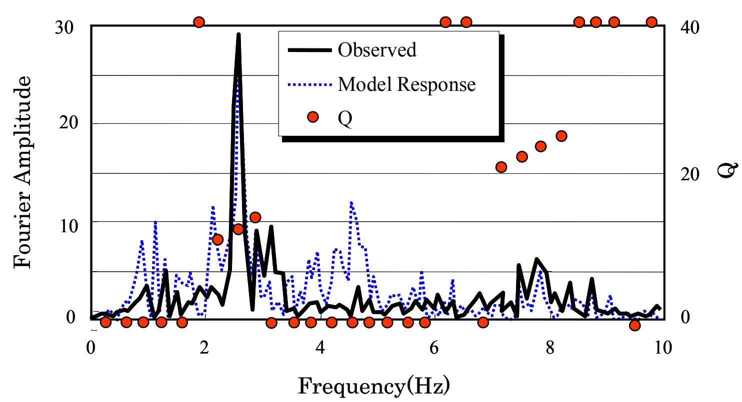


Figure 7. Comparison of observed Fourier spectrum and response of model identified in the 2nd stage with identified quality factor

the response of the initially given ground model and the identified ground model in the first stage, respectively. Quality factor is assumed to be independent of the frequency in this stage. Quality factor at every frequency point is identified in the second stage with the shear wave velocity fixed to the values estimated in the first stage. Quality factor estimated in the first stage is used as the initial value in the identification of the second stage by the iterative manner using MSLP. Quality factor at the frequency points where it is not sensitive is swept out in the process of the optimization as shown in Fig.7, because the residuals of spectra in Eq.2 at these frequency points can not be minimized however drastically quality factor may be modified. In practice, setting upper and lower limits for them, the identification is performed. Quality factor exceeds the limits in the iterations at the frequency points where it is not sensitive. In the application of this method to the identification of actual ground, 3 and 100 are given as the lower and upper limits, respectively. Eventually, quality factor is expected to remain in between the limits in only the significant frequency bands.

Modified Sweeping Method

Nevertheless, quality factor even at the insensitive frequency points is often left in between the limits without being swept out, which makes it difficult to show clear and consistent frequency-dependent quality factor.

Then, the third stage is added in the procedure of identification. The values of quality factor are estimated by Eq.4 only at the frequency points where the sensitivity curve of quality factor has peaks.

$$Q(f_i) = \frac{\sum_{j=i-2}^{i+2} c(f_j) \cdot Q'(f_j)}{\sum_{j=i-2}^{i+2} c(f_j)} \tag{4}$$

where $Q(f_i)$ is finally estimated values at frequency points f_i, $i = 1,2,\cdots,n$ where the sensitivity curve of quality factor has peaks. $c(f_j)$ and $Q'(f_j)$ are the values of sensitivity and quality factor estimated in the second stage of identification, respectively. If $Q'(f_j)$ is not in between the upper and lower limits, they are omitted in Eq.4.

APPLICATIONS

About KiK-net

The network of the digital strong-motion seismographs, so called KiK-net, is deployed at nearly 700 sites in Japan by National Research Institute for Earth Science and Disaster Prevention (NIED). Each site has six channels of strong-motion seismograph. The sensors of 1-3 and 4-6 channels are installed at the bottom of the borehole and on the ground surface, respectively. The sensors of 1 and 4 channels are installed in the North-South direction, 2 and 5 channels in the East-West direction and 3 and 6 channels in the Up-Down direction. Borehole tests were carried out at all the stations, and the values of shear wave and primary wave velocity in the layers were estimated. Since the density of soil in the layers is not available, it is approximated by the following equation (Gardner *et al*. 1974).

Table 1. Locations of observation sites and depth of lower sensor locations

Site Code	Site Name	Latitude [degree]	Longitude [degree]	Depth of lower sensor[m]
IWTH06	NINOHE-W	40.2583	141.1744	100
IWTH08	KUJI-N	40.2658	141.7867	100
IWTH21	YAMADA	39.4706	141.9372	100
IWTH23	KAMAISHI	39.2717	142.8267	103
IWTH26	ICHINOSEKI-E	38.9661	141.0047	100

Table 2. Profiles of earthquake

Event No.	Date	Latitude [degree]	Longitude [degree]	Magnitude	Depth [km]
EQ1	2005/12/17	38.45	142.18	6.1	40
EQ2	2005/8/16	38.15	142.28	7.2	42
EQ3	2005/2/26	40.68	142.60	5.7	45
EQ4	2002/11/3	38.89	142.14	6.1	46
EQ5	2002/10/14	41.15	142.28	5.9	53
EQ6	2001/8/14	41.01	142.42	6.2	43

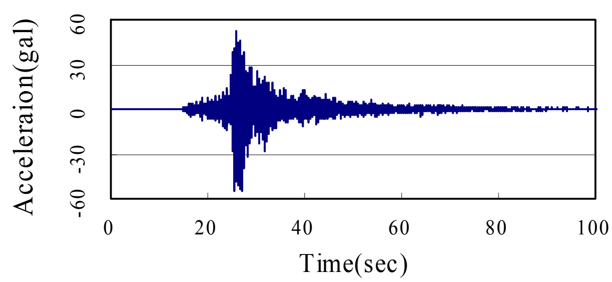
$$\rho = 0.3V_p^{1/4} \tag{5}$$

where V_p denotes primary wave velocity.

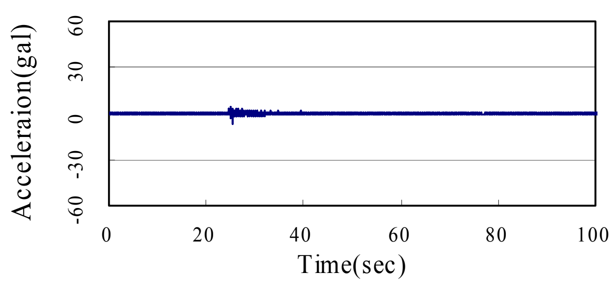
Identification of quality factor using KiK-net data

The modified sweeping method is applied to the identification at 5 sites in KiK-net as shown in Table 1. All of the sites are in Iwate Prefecture which is located in the northern part in Japan and is the quake-prone area. Many of the KiK-net sites in this prefecture, like in other prefecture, are located in the mountain-ringed region. The selected 5 sites are in or near the plain field.

The data of the events of earthquake are shown in Table 2. As an example, the identification at the site IWTH08 in the event EQ3 is described in detail. The records of ground motions at the ground surface and G.L.-100m are shown in Figs. 3 (a) and (b), respectively. They are the transverse components to the epicentral direction. The intervals of strong ground motions are selected, which are to be used in the identification. Shear wave velocity and quality factor, which are estimated in the first stage identification, are shown in



(a) Ground surface



(b) G.L.-100m

Figure 8. Acceleration of ground motions recorded at IWTH08 in the event EQ3

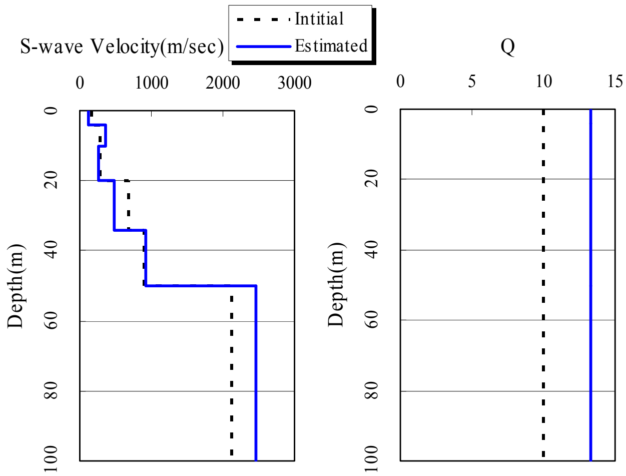


Figure 9. Identified shear wave velocity and quality factor in the first stage of identification

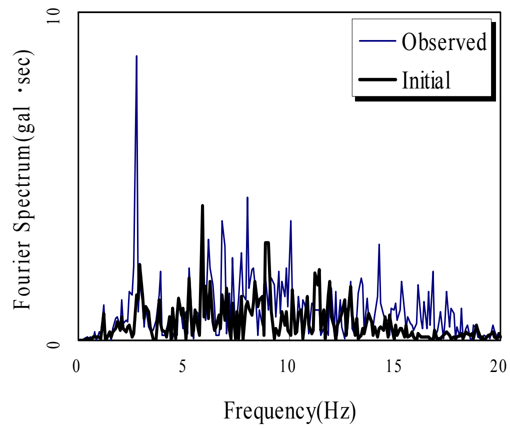


Figure 10. Target Fourier spectrum and its estimation calculated with the initial ground model

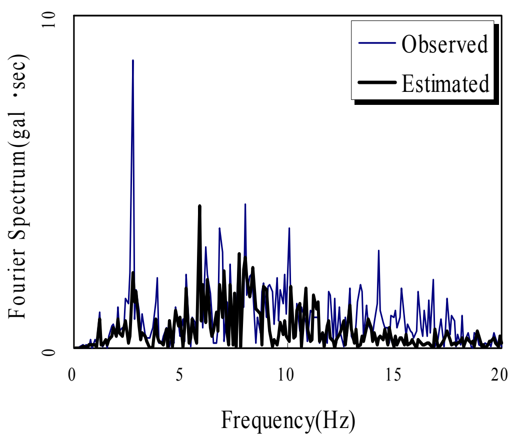


Figure 11. Target Fourier spectrum and its estimation calculated with the ground model identified in the 1st stage

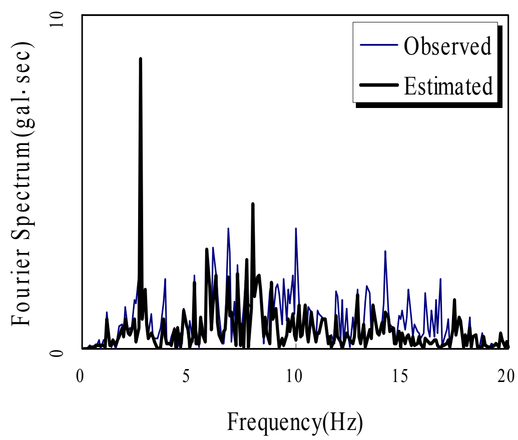


Figure 12. Target Fourier spectrum and its estimation calculated with the ground model identified in the 2nd stage.

Fig.9. The values of shear wave velocity estimated by borehole test are given as the initial values. In the first stage, quality factor is assumed to be constant throughout the frequency band between 0 and 20 Hz. Fourier spectrum of the ground motions at the surface calculated with the initial ground model is shown in Fig.10 together with the target spectrum. The estimated Fourier spectrum calculated with the model which is identified in the first and second stages are shown in Figs.11 and 12, respectively. The fitness between the target and estimated spectra gets better in the second stage identification. The values of quality factor identified in the second stage are shown in Fig.13. Many of the values are as large as 100 which is set as the upper limit or as small as 3 which is set as the lower limit. Fig.14 shows those which are estimated in between the upper and lower limits with the sensitivity of quality factor to the transfer function. Most of the values at the frequency bands, where the sensitivity of quality factor is very small,

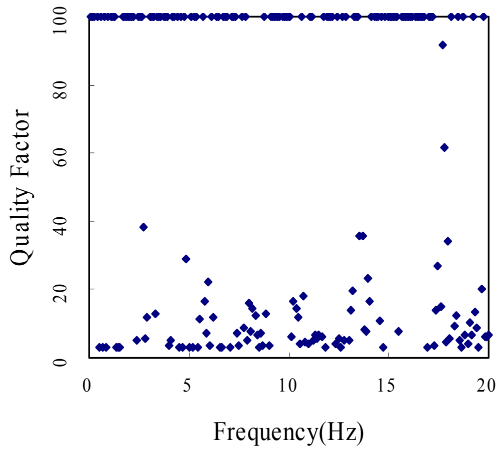


Figure 13. Quality factor estimated in the 2nd stage identification.

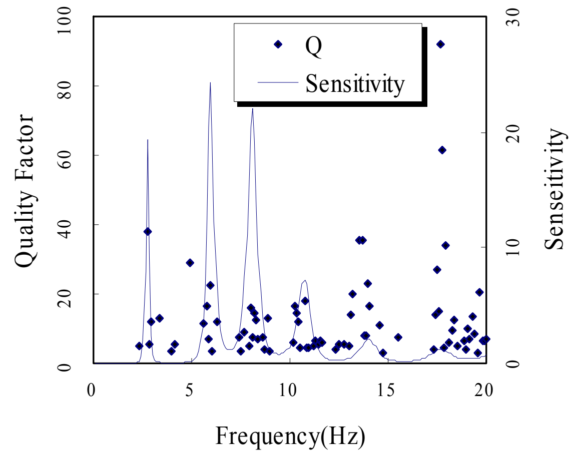


Figure 14. Quality factor estimated in the 2nd stage identification and its sensitivity

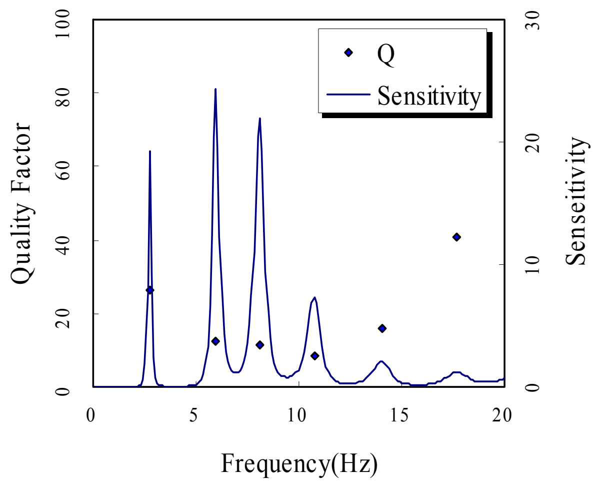


Figure 15. Quality factor estimated in the 3rd stage identification and its sensitivity.

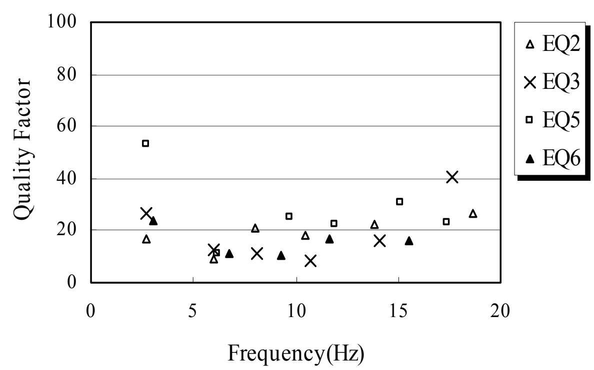
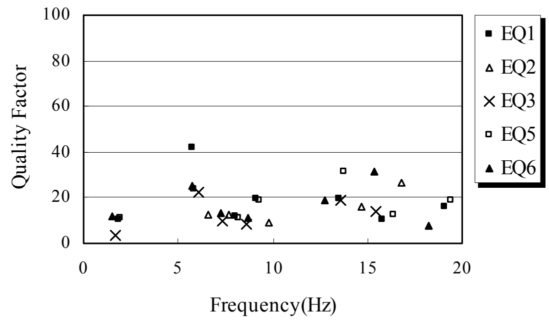


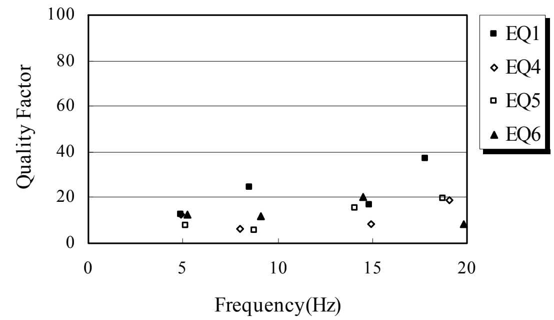
Figure 16. Estimated values of quality factor at IWTH08 in the third-stage identification using 4 events of earthquake

are not seen in the figure because they exceed the limits. Fig.15 shows quality factor estimated in the third stage identification. In the same way, the identification at IWTH08 is carried out using the records of ground motions obtained in other events of EQ 2, 4 and 6. Figure 16 shows the estimated values of quality factor. A fairly good agreement can be seen in the estimated values, and the clear trend can also be recognized that up to about 5 Hz quality factor becomes small and then gradually becomes large with the frequency.

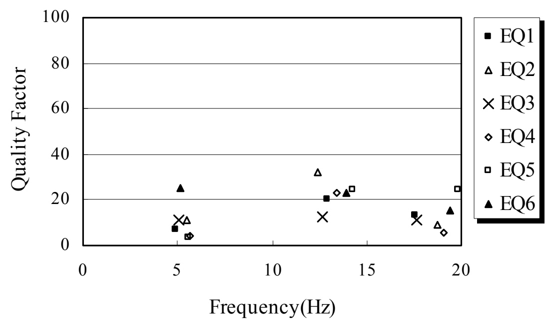
The results of identification at other sites are also shown in Fig.17. Though the trends of quality factor are not same, looking at the estimated values at each site, the variation of the estimated values of quality factor is not so large. It is indicated by this results that rather coherent estimates of quality factor can be obtained by the proposed method.



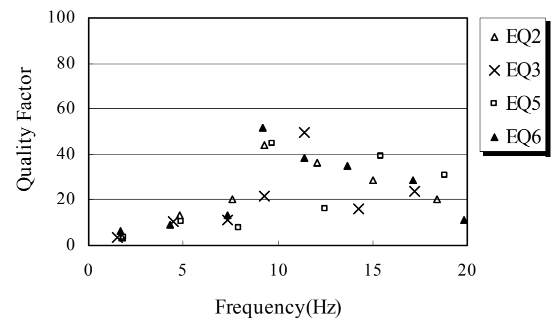
(a) IWTH06



(b) IWTH21



(c) IWTH23



(d) IWTH26

Figure 17. Estimated values of quality factor in the third-stage identification at IWTH06, IWTH21, IWTH23, and IWTH26

CONCLUSIONS

In this study, modified 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 quality factor is estimated by three stages in the process of identification. Quality factor in the frequency band where it is not sensitivity is swept out. As a result the values of quality factor at significant frequency points are highlighted. Moreover, the weighted averages at the frequency points where the sensitivity curve of the quality factor has peaks are taken as the representative values. The proposed method is applied to the identification at 5 sites in KiK-net using the ground motions observed in several different events of earthquake.

The major results in this study are as follows.

(1) The trends of the frequency dependency of quality factor can be recognized.
(2) The similarity of the estimated values of quality factor can be recognized at the identical site even using different events of earthquake.

Accumulation of the analytical results of identification is necessary for the goal to propose the model of the frequency-dependent quality factor.

ACKNOWLEDGEMENTS

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