IDENTIFICATION OF Q IN SUBSURFACE GROUND BY SWEEPING METHOD USING VERTIVAL ARRAY RECORDS OF EARTHQUAKE GROUND MOTIONS

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ABSTRACT :

The objective of this study is to identify the damping property Q (quality factor) of subsurface ground by *Sweeping Method*, which was proposed by the authors, using the vertical array records of earthquake ground motions. National Research Institute for Earth Science and Disaster Prevention (NIED) deploys digital strong-motion seismographs (KiK-net) all over the country in Japan, which 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, which can be used for the identification of such parameters of subsurface laminated layers as shear wave velocity and quality factor. In this study, using KiK-net data, the frequency-dependent characteristics of the quality factor is extracted.

KEYWORDS: quality factor, identification, subsurface ground, earthquake ground motions, sweeping method

1. 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 ground or lifeline facilities buried underground.

Recently, several studies (Ohta 1975, Tsujihara 1996, 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 in particular to be identified.

Vertical array observations of ground motions are energetically carried out in Japan. Digital strong-motion seismographs so called KiK-net are deployed by 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 on the web site. They give us big chances to identify the dynamic properties of subsurface ground.

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. The influence of the damping models and conditions of analysis on the accuracy was investigated (Tsujihara & 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 differs 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 in the same accuracy as the shear wave velocity of the layers, when these parameters were identified simultaneously.

The detection of the frequency dependency of quality factor has become of major interest lately. In this study, using KiK-net data, the frequency-dependent characteristics of the quality factor is extracted.

2. IDENTIFICATION OF SHEAR WAVE VELOCITY AND QUALITY FACTOR

2.1 Identification problem

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

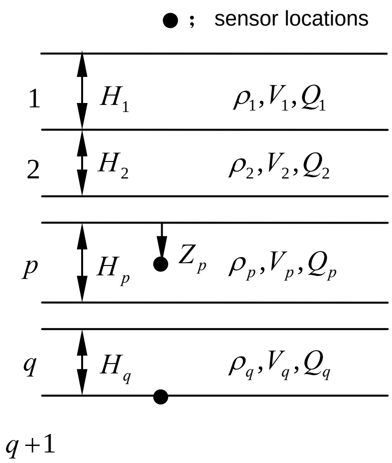


Figure 1 Analytical model of subsurface ground and sensor locations

density, shear wave velocity and quality factor, respectively. The damping constant h is related to Q by h=1/(2Q). 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

$$U_{pq}(f_j) = X_p(f_j) / X_q(f_j) \tag{2.1}$$

where f_j is the discrete frequency. The transfer function between the points p and q can be calculated by multiple reflection theory (Haskell 1960, Toki 1981). Then, 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

$$S(\boldsymbol{\alpha}) = \sum_{j=1}^{N_f} \left\{ \tilde{U}_{pq}(f_j, \boldsymbol{\alpha}) - U_{pq}(f_j) \right\}^2 \rightarrow \min \tag{2.2}$$

where $\tilde{U}_{pq}(f_j,\boldsymbol{\alpha})$, $\boldsymbol{\alpha}$ and N_f are the transfrer function, unknown parameters and total number of discrete frequencies, respectively. The objective function represented by Eqn.2.3 can be also used instead of Eqn.2.2.

$$S(\boldsymbol{\alpha}) = \sum_{j=1}^{N_f} \left\{ \tilde{X}_p(f_j, \boldsymbol{\alpha}) - X_p(f_j) \right\}^2 \rightarrow \min \tag{2.3}$$

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

$$\tilde{X}_p(f_j,\boldsymbol{\alpha}) = \tilde{U}_{pq}(f_j,\boldsymbol{\alpha}) X_q(f_j) \qquad (2.4)$$

The minimization of Eqn.2.2 or 2.3 is carried out by the scheme of MSLP (Modified Successive Linear Programming) (Sawada 1992).

2.2 Sweeping method (Tsujihara and Sawada 2007)
Accurate identification of frequency-dependent quality factor supposing such functions as "$Q=Q_0 f^n$" seems to be difficult, since the problem of the extreme difference of its sensitivity over the frequency band exists. 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 band, utilizing the feature of sensitivity. The procedure is shown in below.

Shear wave velocity of each layer and the average value of quality factor through the layers are identified in the first stage by Eqn.2.2 or 2.3. Quality factor is assumed to be independent of frequencies in this stage. 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. Quality factor estimated in the first stage is used as the initial value in the identification 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, because the residuals of spectral ratio and transfer function in Eqn.2.2 or 2.3 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. Quality factor exceeds the limits in the iterations at the frequency points where it is not sensitive. Eventually, quality factor remains in between the limits in only the significant frequency bands.

3. APPLICATIONS

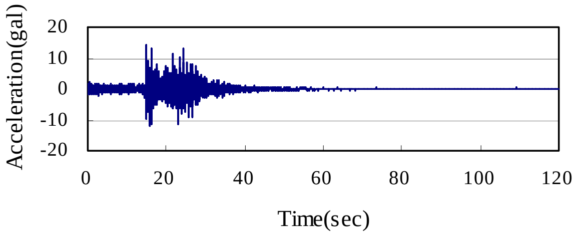
The *sweeping method* is applied to the identification at 17 sites of KiK-net as shown in Table 1 where vertical array sensors are installed at ground surface and G.L.-100m, using the records of ground motions obtained in the earthquakes whose data are shown in Table 2. The results of identification at the site "WKYH01" are illustrated in below.

Table 1 Locations of observation sites

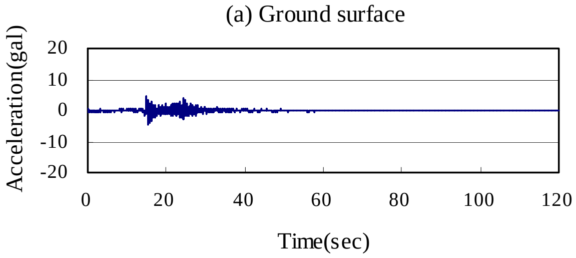
No.	Site code	Site name	Latitude	Longitude
1	WKYH01	HIROGAWA	33.9771	135.2150
2	WKYH02	HANAZONO	34.1340	135.5397
3	WKYH03	NOKAMI	34.1281	135.3272
4	WKYH04	SUSAMI	33.5525	135.5482
5	WKYH05	NACHIKATSUUR	33.6038	135.8648
6	WKYH10	INAMI	33.8214	135.2200
7	NARH03	KAWAKAMI	34.2892	136.0050
8	NARH04	KUROTAKI	34.3028	135.8397
9	NARH07	TENRI	34.5811	135.8569
10	OSKH03	TAISHI	34.5215	135.6636
11	IWTH06	NINOHE-W	40.2583	141.1744
12	IWTH08	KUJI-N	40.2658	141.7867
13	IWTH10	ASHIRO	40.1364	140.9564
14	IWTH12	KUNOHE	40.1506	141.4281
15	AKTH06	OGACHI	38.9772	140.4986
16	YMTH04	KAMINOYAMA	38.0783	140.3011
17	YMTH15	NSHIKAWA-E	38.4228	140.1283

Table 1 Profiles of earthquakes

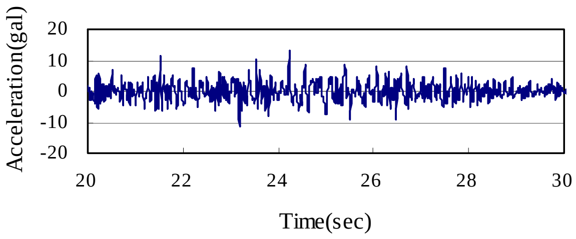
Event No.	Date	Latitude	Longitude	Depth (km)	Magnitude
1	2004/9/7	33.355	137.295	41	6.4
2	2004/9/5	33.143	137.142	44	7.4
3	2003/7/26	38.402	141.173	12	6.2
4	2005/8/16	38.147	142.282	42	7.2



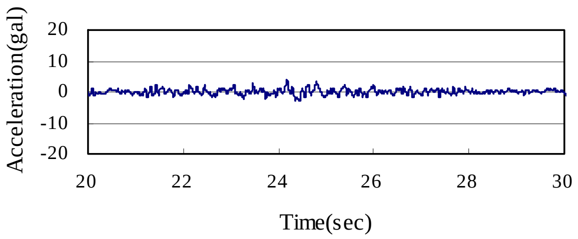
(a) Ground surface



(b) G.L.-100m



(c) Ground surface (selected interval)



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

Figure 2 Acceleration of ground motions recorded at WKYH01 in event 1

The records of ground motions at ground surface and G.L.-100m are shown in Figures 2 (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 Figures 2 (c) and (d), to be used in the identification. Borehole test and PS-logging were carried out at the site. The thickness, shear wave velocity and primary wave velocity of each layer are available. The values of shear wave velocity estimated by PS-logging are used as the initial values in the identification. The density of soil of each layer is approximated by the following equation (Gardner 1974).

$$\rho_i = V_{pi}^{1/4} \tag{3.1}$$

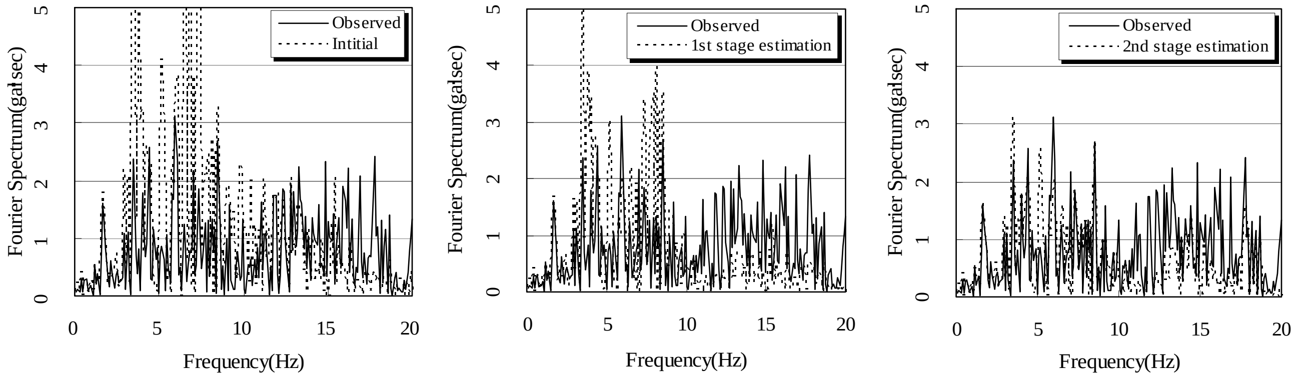


Figure 3 Observed and estimated Fourier spectra at WKYH01 in event 1

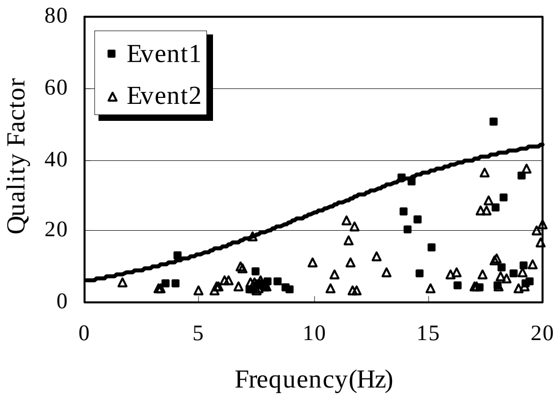


Figure 4 Identified frequency-dependent quality factor at WKYH01

where V_{pi} is the primary wave velocity of the layer "i". The amplitude of the Fourier spectrum of ground motions at the surface is used as the target in the identification to avoid the influence of the smoothing of spectrum. Figure 3 shows the target Fourier spectrum and its estimations calculated with the initial and estimated model of subsurface ground in the first and second stages. The identified quality factor in the first stage is 4.0. In the second stage identification, the shear wave velocity is fixed to the values estimated in the first stage and 4.0 is given to the quality factor as its initial value. The fitness of Fourier spectra is much better in the second stage identification. Identified quality factor at each frequency point is shown in Figure 4. At some frequency points the values of 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 values of quality factor which are estimated using the ground motions in the event 2 are also shown in Figure 4. The upper bound of the quality factor is approximated by the following equation.

$$Q = Q_0 \frac{1}{1 + \exp\{-b(f - f_u)\}} \tag{3.2}$$

where Q_0=50, b=0.2, f_u=10 and f denotes frequency. The equation is expressed as the curve in Figure 4. The results at other sites are shown in Figure 5. Generally the values of identified quality factor become large as frequencies increase, and there is some similarity between the identified quality factor at an identical site. However, in many cases, there is a significant different between the identified values of quality factor even at nearby frequency points. At this stage, the results are not as reliable as they should be. More study is required for the quantitative evaluation of the dependency of quality factor on frequency.

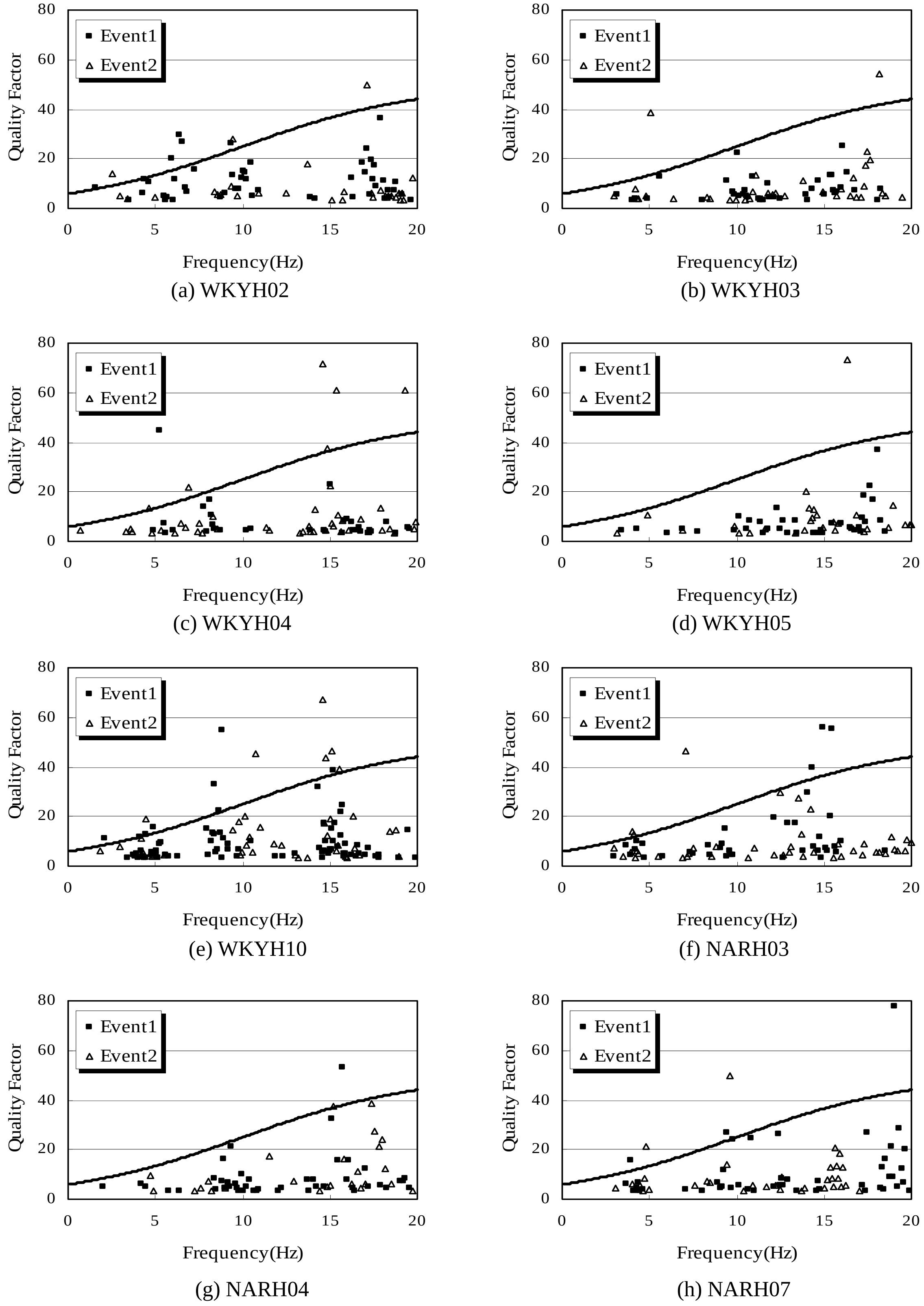
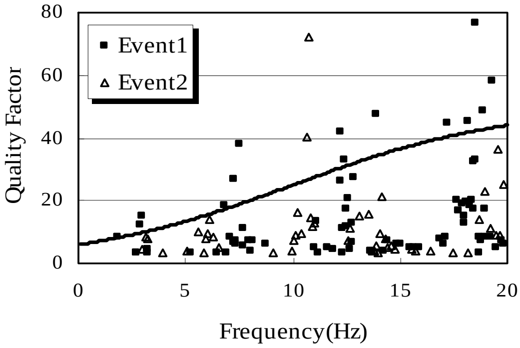
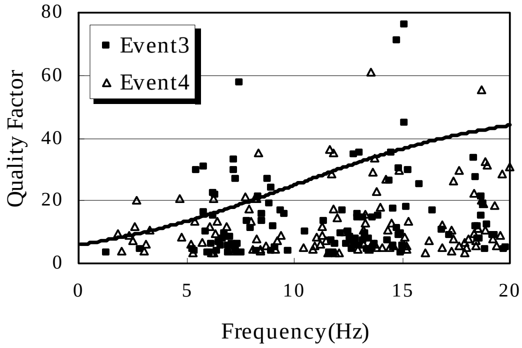


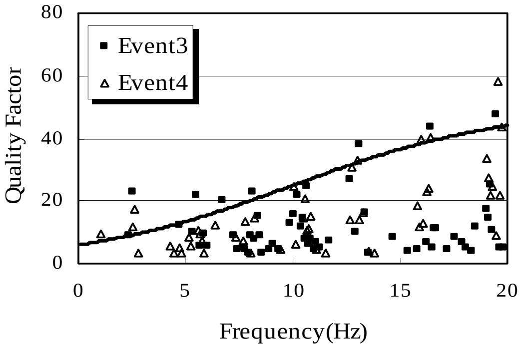
Figure 5 Identified frequency-dependent quality factor, the bold line comes from Eqn.3.2.



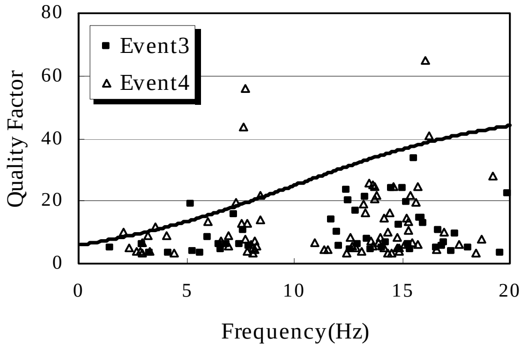
(i) OSKH03



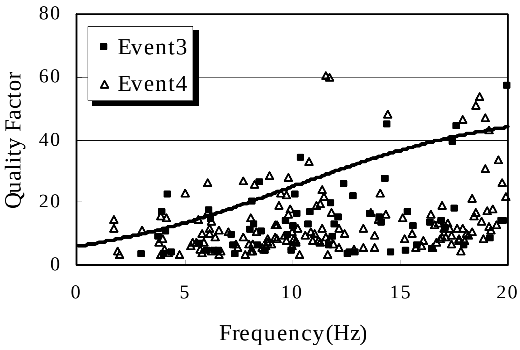
(j) IWTH06



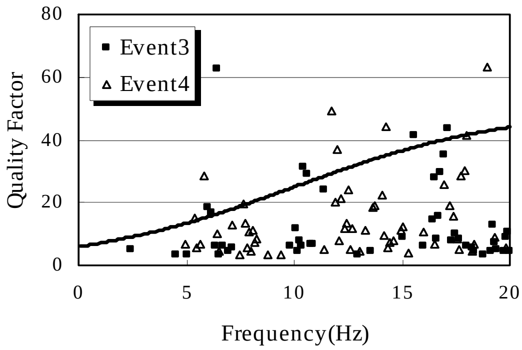
(k) IWTH08



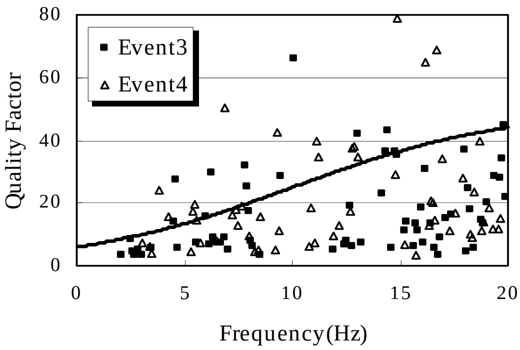
(l) IWTH10



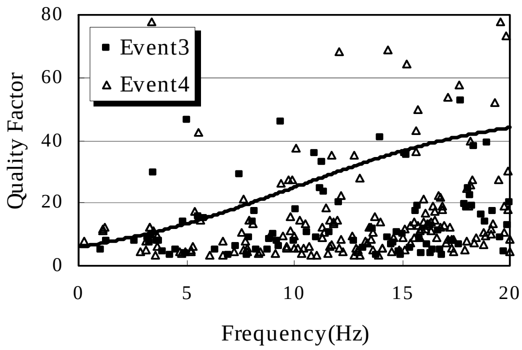
(m) IWTH12



(n) AKTH06



(o) YMTH04



(p) YMTH15

Figure 5 *Continued*

CONCLUSIONS

Frequency-dependent quality factor of subsurface ground of soil is estimated by two stages in the process of identification using earthquake ground motions recorded by vertical array of seismographs. 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.

The major results in this study are as follows.

(1) The trend of 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 quality factor can be seen at the identical site using different events of earthquakes.

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

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