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A LOCALIZED IDENTIFICATION OF DYNAMIC SOIL PROPERTIES OF SUBSURFACE LAYERS IN GROUND BY VERTICAL ARRAY RECORDS

O. TSUJIHARA[1] and T. SAWADA[2]

1) Wakayama National College of Technology,77,Noshima,Nada,Gobo,Wakayama,644,Japan
2) Dept.of Civil Engrg.,Unv.of Tokushima,Minami-Josanjima,Tokushima,770,Japan

ABSTRACT

The objective of this study is to develop a localized identification method which can identify dynamic soil properties such as shear wave velocity and quality factor of specified local subsurface layers, by using vertical array records of earthquake ground motions. It is assumed that horizontally layered ground is excited by vertical incident SH wave from the base. The method is formulated in frequency domain by the mulitiple reflection theory. It is shown from numerical analysis using vertical array records that the proposed method is effective to identify shear wave velocity and quality factor of specified local subsurface layers of the ground.

KEYWORDS

Localized Identification,Subsurface Ground,Properties,Shearwave Velocity,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 dymamic soil properties of subsurface layers in order to predict the characteristics of strong ground motion that influence the behavior of structures based on the ground. The dynamic soil properties such as shear wave velocity for small amplitude of vibration can be estimated by reflection and refraction methods, borehole tests and *etc.*. However,the values estimated by the methods are rather different from those during strong earthquake motions whose amplitude are very large.

In recent years, a lot of array observations for strong ground motions have been carried out and a large number of records were accumulated(Association for Earthquake Disaster Prevention,1992;Katayama *et al.*,1990;Sugito,*et al.*,1987). Using such array records, we can investigate characteristics of strong ground motions as well as dynamic soil behaviors during earthquakes. Especialy,vertical array records are very useful for estimating the dynamic soil properties in subsurface layers of the ground.

We previously presented the method for identifying the shear wave velocity and quality factor in subsurface layers by using vertical array records(Tsujihara *et al.*,1990), in which such unknown parameters as shear wave velocity and quality factor of all layers overlying the deepest recording point were simultaneously identified. However, when the number of the layers to be identified increases, the accuracy and convergency of the solutions by this method are deteriorated. In such a case, a localized identification method is very useful, in which the parameters of the specified local layers can be identified independently.

In this study, we develop a localized identification method to estimate the dynamic soil properties such as the shear wave velocity and the quality factor in the specified local subsurface layers, by using vertical array records. The method is based on the spectral fitting of the records observed at 3 points in a borehole and is formulated in frequency domain by the multiple reflection theory.

FORMULATION

Multiple Reflection Theory

In this study, we assume that the horizontally layered ground (see Fig.1) is excited by vertical incident SH wave from the basement. Consider the identification of a 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. When vertical array records are assumed to be obtained at 3 points located at the top of p-th layer, the arbitrary depth ($=Z_q$) of q-th layer and the bottom of r-th layer in Fig.1 (hereafter denoting these 3 points by p, q and r), we formulate a localized identification method to estimate the shear wave velocity and quality factor of the layers between the points p and r.The relation of the displacements and shear stress of the points p, q and r is represented by multiple reflection theory as follows (Haskell,1960; Toki,1981).

$$\left\{ \begin{matrix} u_p \\ \tau_p \end{matrix} \right\} = [R_p] \left\{ \begin{matrix} u_q \\ \tau_q \end{matrix} \right\} \tag{1}$$

$$\left\{ \begin{matrix} u_r \\ \tau_r \end{matrix} \right\} = [R_r] \left\{ \begin{matrix} u_q \\ \tau_q \end{matrix} \right\} \tag{2}$$

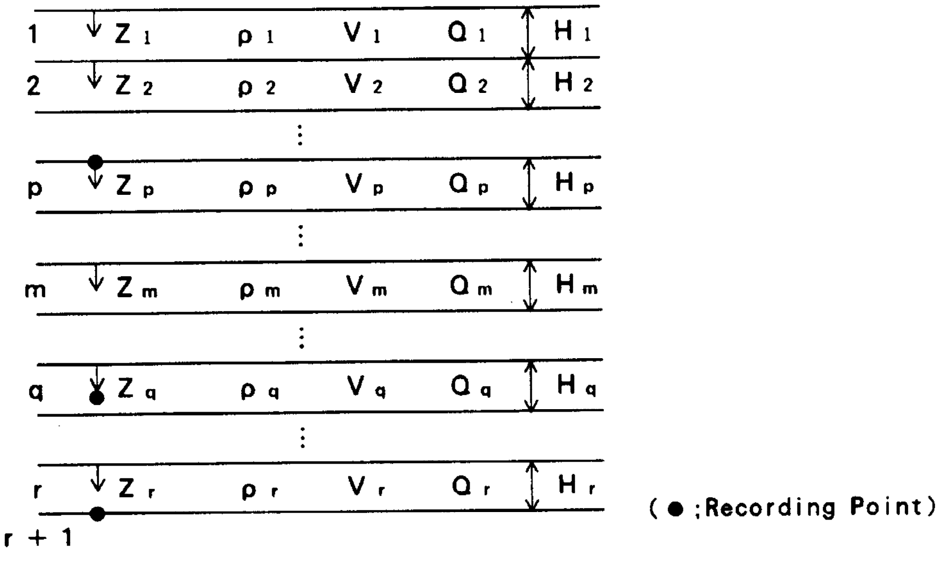


Fig.1 Horizontally layered ground model

where u and τ denote the displacement and shear stress,respectively. $[R_p]$ and $[R_r]$ are the 2×2 matrices as follows.

$$[R_p] = [S_p]^{-1}[S_{p-1}]^{-1}\cdots[S_{q-1}]^{-1}[S_{qU}]^{-1} \tag{3}$$

$$[R_r] = [S_r][S_{r-1}]\cdots[S_{q+1}][S_{qL}] \tag{4}$$

where $[S_m], m = q,\cdots,r$ is the 2×2 matrix representing the state of m-th layer whose elements are given as

$$\left\{\begin{array}{lcl} S_{m\cdot 11} & = & \{exp(\theta)+exp(-\theta)\}/2 \\ S_{m\cdot 12} & = & \{exp(\theta)-exp(-\theta)\}/\left(2i\omega\rho_m V_m\sqrt{1+i/Q_m}\right) \\ S_{m\cdot 21} & = & i\omega\rho_m V_m\sqrt{1+i/Q_m}\{exp(\theta)-exp(-\theta)\}/2 \\ S_{m\cdot 22} & = & S_{m\cdot 11} \end{array}\right. \tag{5}$$

in which

$$\theta = \frac{i\omega H_m}{V_m\sqrt{1+i/Q_m}}$$

and ω = circular freqency, i = imaginary unit, H_m = thickness, ρ_m =density, V_m = shear wave velocity and Q_m = quality factor of m-th layer, respectively. The inverse matrix $[S_m]^{-1}, m = p,\cdots,q$ is given using the elements in Eq.5 as follows.

$$[S_m]^{-1} = \left[\begin{array}{cc} S_{m\cdot 22} & -S_{m\cdot 12} \\ -S_{m\cdot 21} & S_{m\cdot 11} \end{array}\right] \tag{6}$$

Localized Identification

Next two equations are obtained from Eqs.1 and 2.

$$\left\{\begin{array}{lcl} u_p & = & p_{11}u_q + p_{12}\tau_q \\ u_r & = & r_{11}u_q + r_{12}\tau_q \end{array}\right. \tag{7}$$

where p_{ij} and r_{ij} are the (i,j) elements of the matrices $[R_p]$ and $[R_r]$, respectively. The shear stress, τ_q should be eliminated from Eq.7, since the shear stress is not generally observed during earthquakes. Solving Eq.7 with respect to u_q, displacement of the point q can be obtained with those of the points p and r as follows.

$$u_q = \frac{r_{12}u_p - p_{12}u_r}{p_{11}r_{12} - p_{12}r_{11}} \tag{8}$$

When Fourier spectra at the points p and r, $F_{po}(f)$ and $F_{ro}(f)$ are calculated from vertical array records, Fourier spectrum at the point q, $F_q(f)$, can be obtained analytically from the relation in Eq.8.

$$F_q(f) = \frac{r_{12}F_{po} - p_{12}F_{ro}}{p_{11}r_{12} - p_{12}r_{11}} \tag{9}$$

in which f = frequency. $F_q(f)$ in Eq.9 is the nonlinear function of parameters in the layers between the points p and r, because the coefficients p_{ij} and r_{ij} in Eq.9 are the elements of the matrices $[R_p]$ and $[R_r]$ in Eqs.3 and 4 which are the nonlinear functions of these parameters.

In this study, the thickness and density of each layer are assumed to be known. Then, the unknown parameters, V_m and $Q_m, m = p,\cdots,r$ are to be identified so as to fit $F_q(f)$ in Eq.9 to the recorded Fourier spectrum,$F_{qo}(f)$, which is calculated at the point q using the array record. Denoting these unknown parameters by $\boldsymbol{\alpha} = (\alpha_1, \cdots, \alpha_N) = (V_p, \cdots, V_r, Q_p, \cdots, Q_r)$, the localized identification is carried out by minimizing the following error criterion.

$$S_e = \sum_{i=1}^{N_f} \{|F_q(f_i;\boldsymbol{\alpha})| - |F_{qo}(f_i)|\}^2 \longrightarrow min \tag{10}$$

in which f_i = i-th discrete frequency, N_f = the number of frequencies and $F_q(f_i;\boldsymbol{\alpha}) = F_q(f_i)$ in Eq.9.

Introduction of frequency dependency of quality factor

In recent years, several reseachers pointed out that the quality factor (Q-value) depends on frequency, that is, the quality factor increases as the frequency becomes larger. The frequency dependency of the quality factor can be represented by

$$Q_m = Q_{m0} f^n \tag{11}$$

in which Q_{m0} = quality factor of m-th layer at the frequency of 1Hz(Q_0-value) and n = positive coefficient reperesenting the frequency dependency. In this study, the coefficient n is assumed to be identical throughout all the layers between the points p and r. The Q_m in Eq.11 is used as the quality factor and is substituted into Eq.5. Then,the unknown parameters to be identified consist of $V_m, Q_{m0}, m = p, \cdots, r$ and the coefficient n.

NUMERICAL ANALYSIS

The vertical array records are used which have been observed at the center array of Chiba Experimental Station of the Institute of Industrial Science,the University of Tokyo (Katayama et al.,1990 and Association for Earthquake Disaster Prevention,1992). At the center array, 5 accelerometers are vertically installed at the depth of GL-1m, GL-5m, GL-10m, GL-20m and GL-40m.The 3 records at GL-5m, GL-10m GL-20m are used to identify the 2 layers between GL-5m and GL-20m.

Table 1 shows the soil profile of subsurface layers between the ground surface and GL-20m, in which shear wave velocity is of PS-logging test. Fig.2 shows the shear wave velocity by PS-logging test as well as the location of seismometers, in which the vertical axis is the depth and the horizontal one the shear wave velocity. Until now, a large number of records have been observed. In the following analysis, we select the array records at 4 earthquakes with rather deep hypocenter (see Table 2), which are denoted by events S1 to S4.

Table 1 Dynamic soil properties

Layer No.	Thickness (m)	Density (t/m³)	Shear wave velocity(m/s)
1	5	1.15	140
2	5	1.50	320
3	10	1.95	320

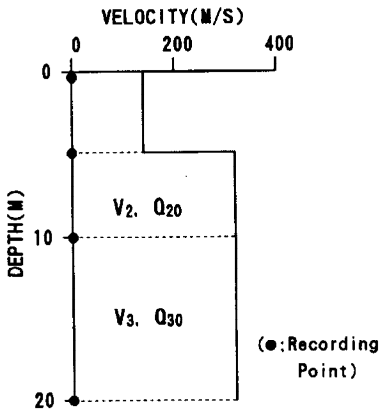


Fig.2 Shear wave velocity by PS-logging test

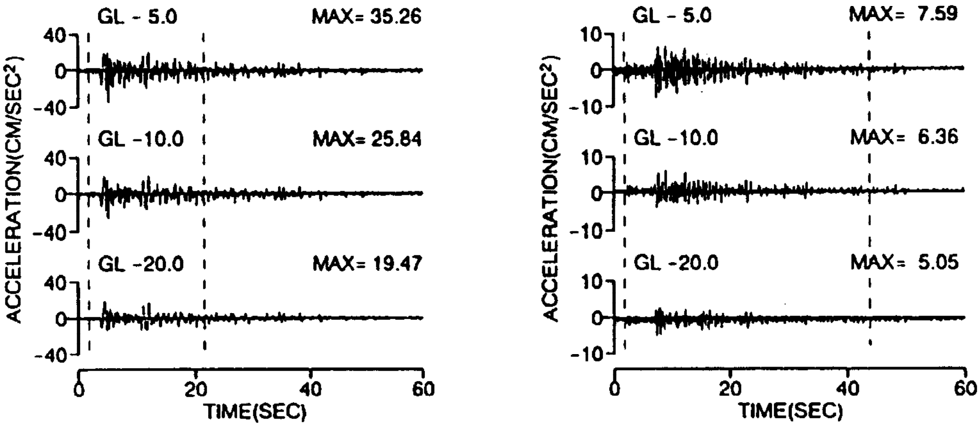
Table 2 List of earthquakes

Event Name	JMA Magnitude	Focal Depth (km)	Epicentral Distance (km)
S 1	6. 0	7 2. 0	3 5. 1
S 2	5. 0	4 9. 0	4 5. 9
S 3	4. 8	6 4. 2	1 5. 5
S 4	6. 1	7 8. 4	2 7. 8

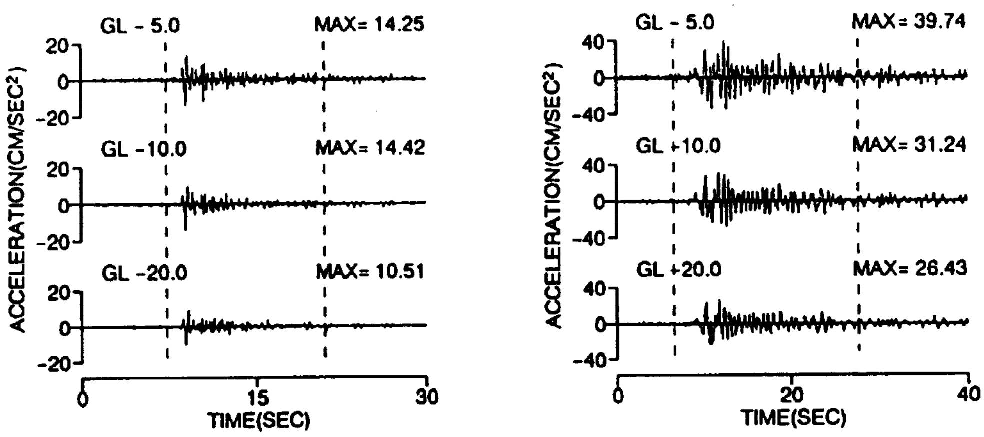
Fig.3 shows the vertical array accelerograms at GL-5m,GL-10m and GL-20m of the transverse components to the epicenteral direction for each event, in which dotted lines show the strong parts of the time histories that are used in identification.

As mentioned above, the unknown parameters to be identified are shear wave velocity and quality factor (in Eq.11) of the 2nd and 3rd layers in Fig.2 (V_2, V_3, Q_{20} and Q_{30}) and the coefficient n representing the frequency dependency of quality factor. In this analysis, the coefficient n is changed discretely as follows, and the optimum value of n is determined which gives the smallest S_e in Eq.10.

$$n = 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.5 \tag{12}$$



(a) S 1 (b) S 2



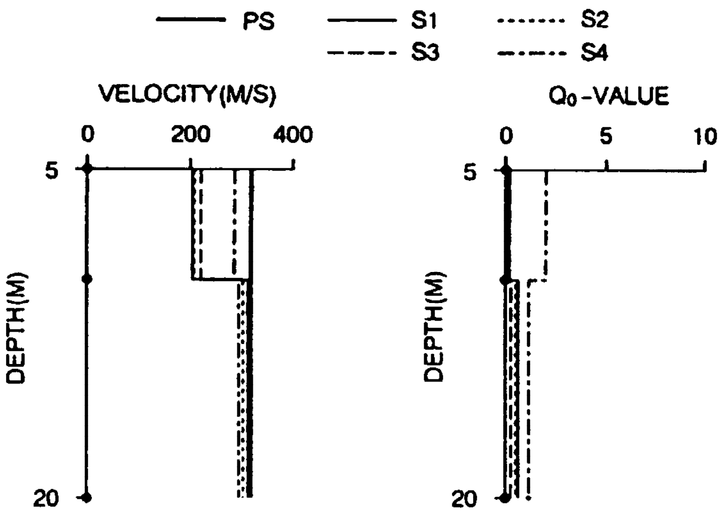
(c) S 3 (d) S 4

Fig.3 Transverse components of the ground accelerations observed at Chiba Experiment Station (Katayama et al.)

In the first stage of identification, initial values of V_m and $Q_{m0}, m = 2, 3$ are given. We use the shear wave velocity by PS- logging test (see Fig.2) as the initial values of V_m and 10 as those of Q_{m0}. Starting from the initial values, the unknown parameters can be identified for each given value of n in Eq.12. The results of identification are shown in Table 3 and Fig.4. In Fig.4, the vertical axis is the depth (GL-5m to GL-20m), and the horizontal one the shear wave velocity (Fig.4(a)) and the Q_0-value (Fig.4(b)), respectively. The identified values by events S1 to S4 are shown in each figure and the shear wave velocity by PS-logging test (denoted by PS) is also shown in Fig.4 (a). It is found from Table 3 and Fig.4 that identified shear wave velocity by 4 events are consistent with each other but they are a little smaller than that of PS-logging test,especially in the 2nd layer. The difference between the identified shear wave velocity and PS-logging is acceptable because the amplitude level of the ground during earthquakes is larger than that of PS-logging test. The Q_0-value identified by 4 events are considerably different from each other and are rather small. Thus the estimated values of Q_0 seem to be less reliable than those of shear wave velocity. This may be because the relative amplitudes at peak frequencies in Fourier spectra are different in each event, as shown in Fig.5. Quality factor is the parameter that represents the damping and energy dissipation in the subsurface layers and affects on the level of amplitude in Fourier spectrum, which is sensitive to the noise included in the records.

Table 3 Identification results

Event Name	Shear wave velocity (m/s)		Q_0-value		n
	V_2	V_3	Q_{20}	Q_{30}	
S 1	209	313	0.2	0.6	0.6
S 2	209	305	0.2	0.5	0.6
S 3	222	313	0.2	0.3	0.8
S 4	288	296	2.0	1.1	0.0



(a) S-wave velocity

(b) Q_0-value

Fig.4 Estimated values of shear wave velocity and Q_0-value

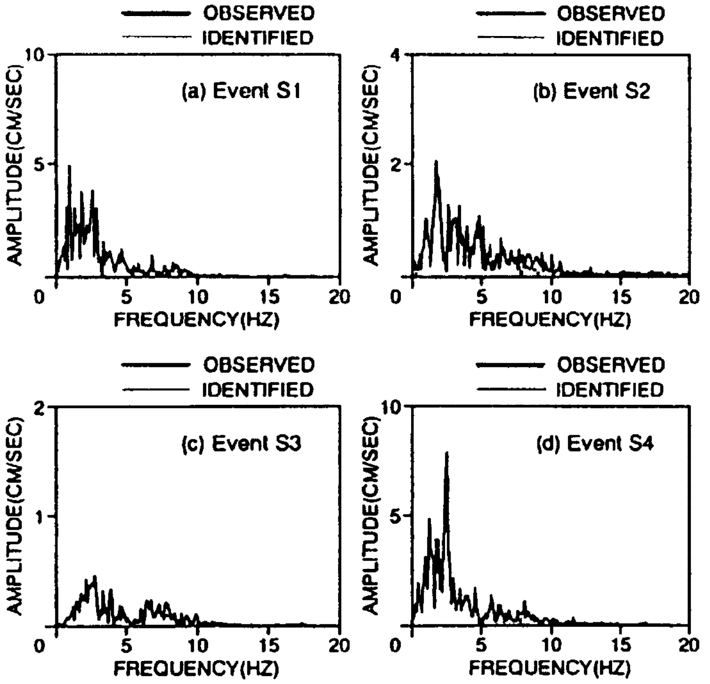


Fig.5 Observed and identified Fourier spectra (Event S1 ~ S4)

As to the coefficient n, the identified values are between 0.6 and 0.8 except for event S4. This fact may indicate that the quality factor increases as the frequency becomes larger.

CONCLUSIONS

A localized identification method has been developed in order to estimate the dynamic soil properties such as shear wave velocity and quality factor of specified local subsurface layers. The frequency dependency of the quality factor was also considered in the identification. The method has been formulated in frequency domain by multiple reflection theory. In numerical analysis, subsurface ground model with 3 layers was used and the lower 2 layers were identified by using 4 sets of vertical array records obtained at the center array of Chiba Experimental Station of the Institute of Industrial Science, the University of Tokyo.

The major results in this study are summarized as follows.

1. Shear wave velocity and quality factor of specified local subsurface layers could be identified by the proposed method using the vertical array records at 3 points in a borehole.
2. Consistent results could be obtained for identification of shear wave velocity although they were a little smaller than those of PS-logging test.
3. Q_0-value was identified assuming that the quality factor,Q , could be represented by $Q = Q_o f^n$. The identified Q_0-value was inconsistent in each event and was smaller than the previous studies (Kobayashi, *et al.*,1990). Therefore, it seems that the reliability of the identified Q_0-value is poorer than those of shear wave velocities.
4. The coefficient n that represents the frequency dependency of quality factor was identified in between 0.6 and 0.8 except for one event. This fact indicates that the quality factor is more or less dependent on the frequency.

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