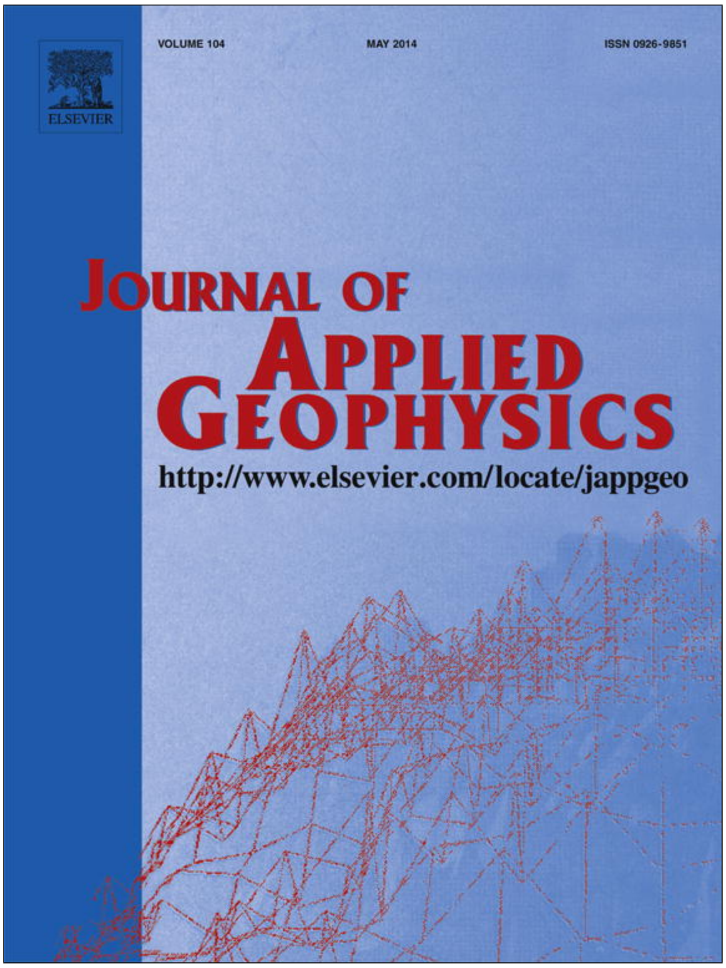
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Identification of rock mass characteristics using microtremor in the boring hole

Ailan Che [a,*], Huan Wang [a], Shaokong Feng [a], Takeshi Siguyama [b]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, China
[b] Chuo Kaihatsu Corp., Japan

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ABSTRACT

An identification analysis method of the rock mass characteristics is proposed using microtremor measurements in the boring hole. The method is based on the assumption that the epicenter of incident waves of each observation point in the same boring hole almost agrees. And the calculations are deconvoluted by the multiple reflection theory. The procedure applicable to the identification of the average elastic characteristics of in situ rock masses is presented. It is based on the minimization of an error function representing the difference between microtremor measurements performed on the rock mass and the corresponding data obtained by a numerical analysis subjected to known external actions. The method requires the formulation of the elasticity inverse problem and is based on the least square minimization procedure. As an example the approach has been applied to the identification of the dynamic properties and the predominant characteristics of the rock mass underlying a deep excavated quarry in west of Shanghai city. The inverted rock mass characteristics are compared with the PS logs at the sites and show consistency, confirming that the proposed inversion is promising.

1. Introduction

Dynamic properties of the rock mass, such as shear wave velocity (v_s) and predominant period (T_p or characteristic site period) are important input parameters in dynamic analysis of rock mass that includes seismic stability. For the discontinuity such as faults, joints, cracks in the rock mass, the composition of geological materials and their constitution become very complicated. Field tests to determine elastic parameter directly are time consuming, expensive and the reliability of the results of these tests is sometimes questionable (Carvalho, 2004; Hoeka and Diederichs, 2006). Consequently, several researchers have proposed empirical relationships for estimating the value of the isotropic rock mass deformation modulus on the basis of classification schemes (Palmstrom and Singh, 2001; Sonmez et al., 2004; Zhang and Einstein, 2004). Almost all of the identification method assumes that the rock mass is homogeneous and isotropic. Obviously there are situations, such as foundations on schistose rock masses, where the variation of modulus with loading direction is important. We consider that it is necessary to investigate the in situ test methods and the interpretation of the results of in situ tests.

The reliable methods to determine the shear modulus of soil and rock are continuously conducted in the field because testing of undisturbed soil or rock samples in laboratory is often subjected to errors due to sample disturbance. Even if the disturbance is minor using advanced technique of sampling, time and expense might be substantial (Henke and Henke, 1993; Imai and Tonouchi, 1982). In the last decades, some geophysical methods and techniques (active and microtremor), surface wave ones, were mainly developed (Motamed et al., 2007; Stokoe et al., 1994; Tokimatsu et al., 1991). Dynamic properties of the soil or rock mass, especially the shear wave velocity, are measurable in the field by several practical means which include borehole seismic tests (down-hole, up-hole, and cross-hole test) and surface geophysics tests (reflection, refraction survey). Recently microtremor observation techniques have been evolved as a kind of more practical technique for exploration of site characteristics; both shear wave velocity and predominant period of the site. These techniques apply to explore site characteristics used to evaluate ground motion. The single point microtremor measurement with Horizontal-to-Vertical spectral ratio (H/V) method (Nakamura, 1989) is applied to estimate the predominant period, and the technique of array microtremor measurement is applied for exploration of phase velocity characteristics and the subsequent shear wave velocity profile from inversion analysis (Okada, 2003; Yokoi, 2005). These methods, however, can improve by using geological information and new processing techniques for archive geophysical data.

In geophysics and seismology, the inversion method is widely used for grasping of the physical properties of the earth, and the main theoretical aspects are based on a least-squares local optimization

* Corresponding author.
E-mail address: alche@sjtu.edu.cn (A. Che).

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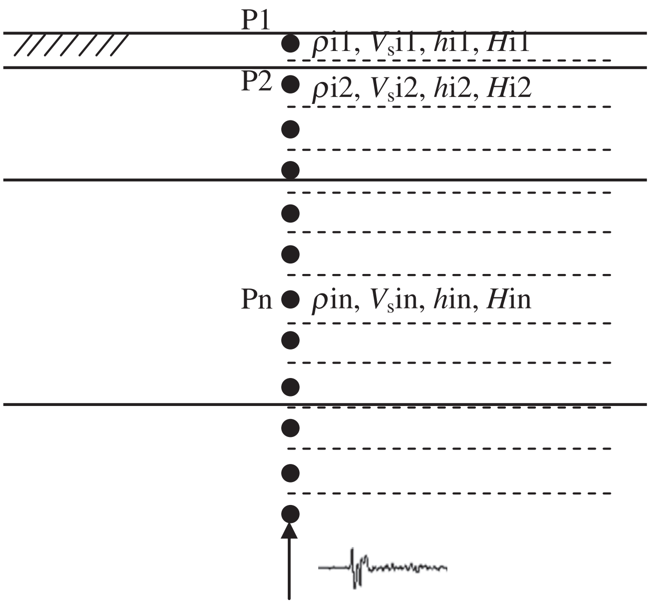

Fig. 1. Rock mass model for identification method.

approach. The actual physical parameters are matched by some iterative approaches utilizing the amplitude, frequency and phase of measured waveforms comprehensively (Pratt, 1999; Pratt et al., 1998). In recent years and in connection with the development of data acquisitions technique, inversion method has become important to investigate underground structure. Grechka and Linbin had successfully reached the anisotropy parameters of soil medium by combining the P wave and P_SV wave inversion (Grechka et al., 2004). Inversion involves iteratively improving an initial model of the subsurface by matching the measured seismic data with modeled data. The inversion algorithm is designed to minimize the misfit between the recorded and modeled data, usually measured by a least-squares error criterion. As the model described by a simple model with a limited number of parameters (e.g., a stack of horizontal homogeneous layers), Newtonian algorithms might be used (Dahl and Ursin, 1991; Lambaré et al., 1992; Pan et al., 1988). All these derivatives (Jacobian) can be computed numerically at the cost of one modeling per parameter (Amundsen and Ursin, 1991; Huasheng et al., 1994). When the model is more complicated (e.g., generally inhomogeneous), the number of parameters is usually so large that the numerical computation of the Jacobian is intractable (Amundsen et al., 1993; Lailly, 1983; Mittet et al., 1997). Problems of such type are usually solved by means of a finite-element (FE) method or a finite-difference (FD) method (Tsili and Sheng, 2001; Weiss and Newman, 2002).

Microtremor can be measured with multi-point in multi-direction in the boring hole of intact rock mass. The predominant characteristics of the rock mass with different depth can be obtained. The ground can be modeled as a multi-layered model and the multiple reflection theory to S-wave propagation are applied to calculate the ground motions. According to the geological data investigated by borehole, sampling, geophysical exploration tests and laboratory experiments; an initial geological model which can reflect rock mass characteristics is established. The ground response, i.e., velocity and Fourier spectrum at the measured points are calculated from the assumed rock

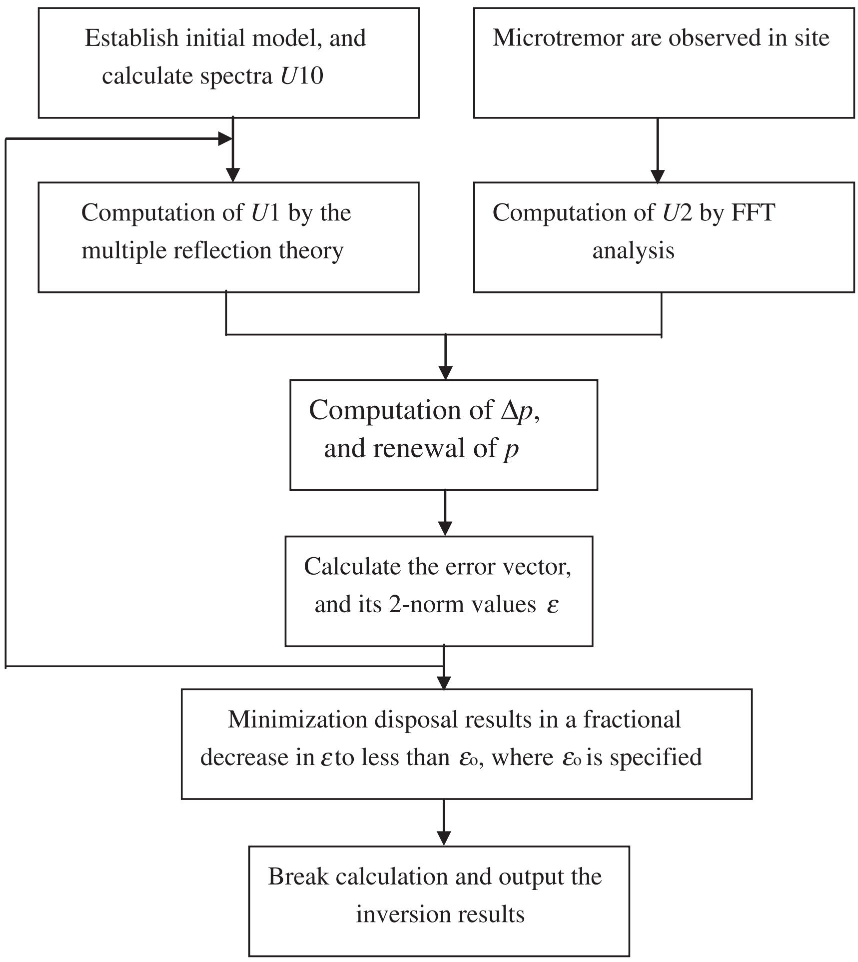

Fig. 2. Flow chart of identification analysis.

Fig. 3. Location of research area.

parameters by using the multiple reflection theory. The objective function minimizes the sum of squared differences between Fourier amplitude spectra of observed and calculated. Least squares method is effectively used in this optimization problem as a numerical procedure. Since the microtremor observation in the boring hole can be carried out easily and fast, the proposed method should make a contribution to improvement of the supplement of geophysical data.

2. Identification method based on spectra characteristics

An identification method is developed to identify the dynamic characteristics of rock mass in this paper, where the ground constants, including density (ρ/kN/m^3), shear wave velocity (V_s/m/s) and damping constant (h) and thickness of the rock layer (H/m) are identified using microtremor observation data in the boring hole. An observed boring hole can be simplified to an n numbers of degrees of freedom system according to the measurement points (P1, P2, and Pn), as shown in Fig. 1. Even if microtremor at each points (P1, P2, and Pn) measures at different time, the epicenter of each incident wave in the boring hole is considered as the same for the source of microtremor from deep of the earth. Accordingly, on the assumption that the deconvoluted incident waves and the spectrum of the boring hole agree with each other, the physical constants of the rock mass can be identified as follows.

(1) This study applied the multiple reflection theory to S-wave propagation. The method is employed in one dimensional wave propagation through horizontally layered strata. For a stratified medium model, incident wave u, which is a function of ground constant, is a solution of the differential Eq. (1).

$$\frac{\partial^2 u(z,t)}{\partial t^2} = c^2 \frac{\partial^2 u(z,t)}{\partial z^2} \tag{1}$$

where t is time, z is the coordinate of the vertical direction and c is velocity.

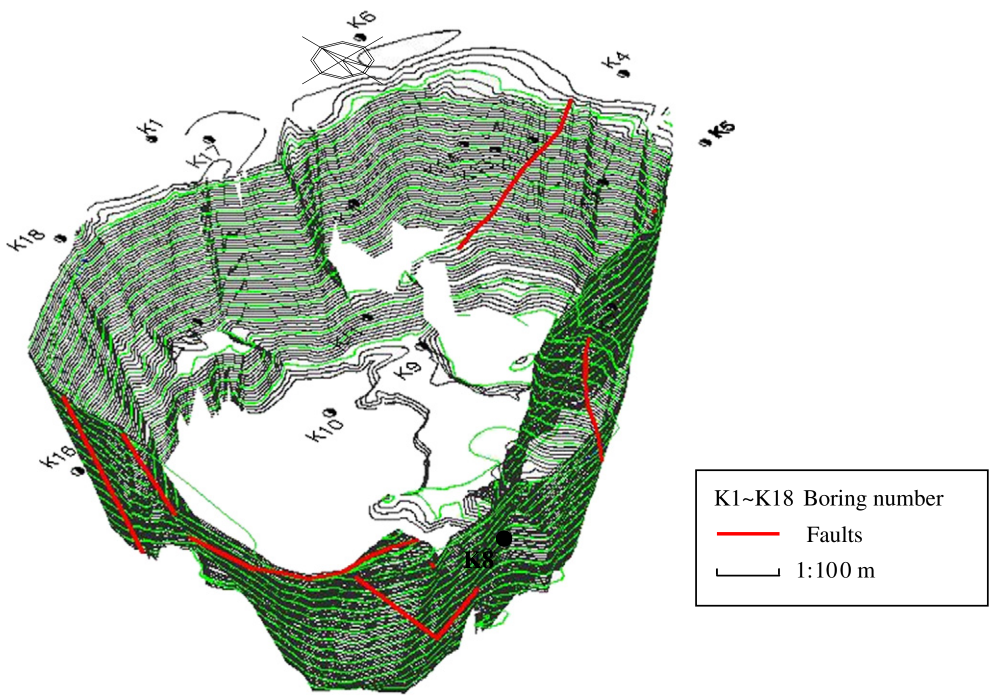

Fig. 4. Sketch of deep excavated quarry.

Table 1
Physical and mechanical properties of rock.

Name	Weathering type	Density (g/cm^3)	Static triaxial test		Static elastic modulus E (GPa)	Static Poisson's ratio μ	Dynamic elastic modulus E_d (GPa)	Dynamic Poisson's ratio γ_d
			c (MPa)	φ (°)				
Andesite	In the weathered	2.47	9.3	33.1	41.1	0.24	46	0.23
	Weathered	2.58	11.2	31.4	43.9	0.22	56.2	0.20

(2) Based on elastic wave Eq. (1), the dynamic response of ground at each ground layer can be calculated by using the shear modulus, the thickness, damping ratio, rock density at each layer and input acceleration record in the multiple reflection theory. Its spectra processed by means of fast Fourier transform (FFT) analysis are considered as a vector $\boldsymbol{f}$. Meanwhile the spectra at corresponding points can be recorded by microtremor, which is considered as a vector $\boldsymbol{f_{obs}}$. The difference between $\boldsymbol{f_{obs}}$ and $\boldsymbol{f}$ is defined as an error vector as $\boldsymbol{\varepsilon} = \boldsymbol{f_{obs}} - \boldsymbol{f}$ as an objective function for the optimization in the inverse analysis. To let the objective functions converge, Fourier amplitude spectra between recorded and calculated velocities are smoothed with Parzen's window.

(3) In the spectra data processing, the peak identification directly affects the accuracy of exploration. Recently, peak amplitude method, first derivative method and second derivative method are commonly used (Griessre and Richner, 1998; Maples, 2003; Merritt, 1995). The existing peak identification methods are still unable to accurately identify complex peak shape due to the fact that microtremor spectrum signal is complex. It is difficult to find a threshold value to apply variety of peak shapes. In order to accurately find dynamic properties of rock mass, the spectral data was processed as follows. The peak frequency and amplitude are read using peak amplitude method for numerical calculation. With range of ± 0.1 Hz of calculated peak frequency, peak frequency and amplitude for microtremor observation data are searched using peak amplitude method.

(4) The sum of squared differences between Fourier amplitude spectra of observed and calculated horizontal velocities is minimized. The objective function is represented as the Eq. (2).

$$\varepsilon = \sum_j \left| U1\left(\omega_{j-1}\right) - U2\left(\omega_{j-1}\right) \right|^2 = \sum_j \left| U10\left(\omega_{j-1}\right) + \sum_k \frac{\partial U1\left(\omega_{j-1}\right)}{\partial p_{1k}} \Delta p_{1k} - U2\left(\omega_{j-1}\right) \right|^2 \qquad (2)$$

where ε is objective function for horizontal component, $U1$ is spectra of the incident wave u in Eq. (1) by calculation and $U2$ is observation result at the measurement point, $U10$ is spectra for the initial values of the ground constant p_0, j denotes angular frequency ω_{j-1}, and k is considered to be the number of ground constants. Δp is the quantity of infinitesimal change for the nonlinear parameter p, which is related to peak value of spectra. Objective function ε depends on Δp. Optimum ground constants are provided by Δp and minimizes the objective function ε. A necessary iterative terminal condition as follow for ε to be at a minimum is,

$$\frac{\partial \varepsilon}{\partial \Delta p_{sk}} = 0 \qquad (s = 1, 2\ , k = 1, 2, 3, \ldots) \qquad (3)$$

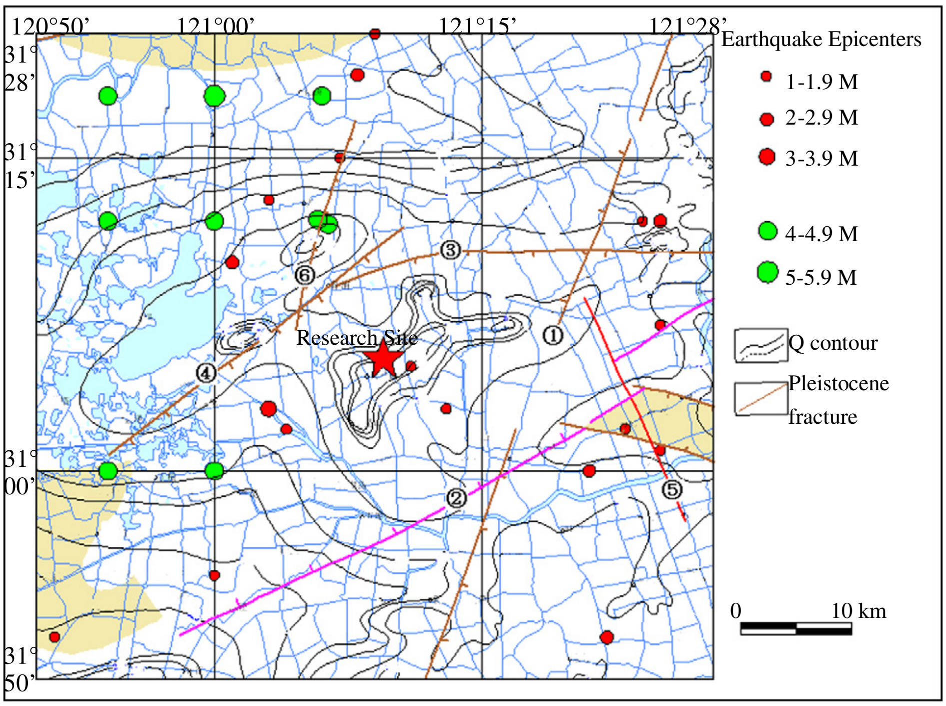

Fig. 5. Seismotectonic of the site.

(5) Optimum ground constants are calculated by the least squares method. When the iterative terminal condition is satisfied according Eq. (3), Δp is found and the ground constants are renewed. It is not easy to obtain the optimized value, because of the high nonlinearity in the objective function. The peak frequency and amplitude are used in calculation. The flow chart of identification analysis is shown as Fig. 2.

3. Study area

A high rock slope site in west of Shanghai city, about 30 km away from Shanghai city center and the only exposed bedrock in Shanghai (Fig. 3), is discussed in detail using the laboratory test and other investigation methods. There are dense river networks, water facilities around the area. The site is located on the leading edge of southeast of the Yangtze River Delta, which is the type of erosion residual hill edge landscape of Tian-ma Mountain, and the surface layer is lagoon marsh landforms. The average elevation of around ground is 2.80–3.50 m (Wusong elevation); that of bottom is −48.33 to −70.53 m. There is a deep excavated quarry which is engaged as stone mining from 1950 and closed in 2000. The quarry shows oval shape, narrow in North–South, wide in East–West, the slope angle is about 80°. The area of the quarry is about 36,800 m^2, with 80 m depth, 240 m length, and 160 m width (Fig. 4). The distribution and the physical and mechanical properties of rock and soil in the surrounding area are investigated by borehole, sampling, geophysical exploration tests and laboratory experiments. Physical and mechanical properties of rock from static triaxial tests and dynamic triaxial tests are shown Table 1.

As shown in Fig. 5, the earthquake activity has occurred near the site in past and current. The form of seismic structure in the site mainly shows as tectonic, arc structure and the active fault. There are a number of active faults after Quaternary, which have sizes that are overall small and do not produce surface rupture damage. The small seismic activity is relatively concentrated in the near tectonic site and it is with a 4–5 magnitude earthquake occurred in the conditions.

The rock properties in site is quite simple, it is composed of Jurassic acidic igneous rocks, which is $J3h^3$ Andesite. According to engineering geological exploration results (Fig. 4), the degree of rock weathering from surface ground to bedrock sequentially is completely weathered Andesite, strongly weathered Andesite, Andesite in the weathered, weathered Andesite. The engineering geologic profile is shown in Fig. 6. There is a main structural plane of the slope in the west side of the slope. And the rock joint fracture is generally developed on the surface of the slope.

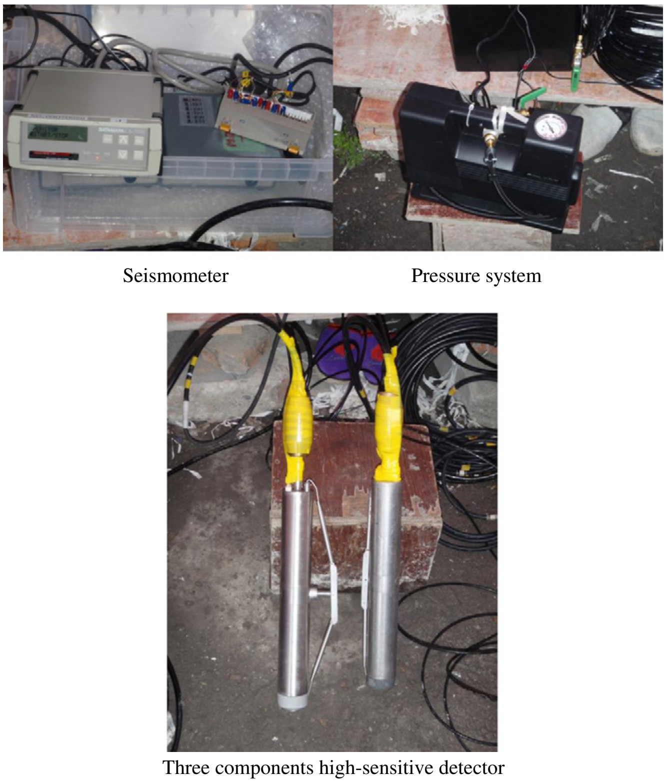

Fig. 7. Observation system.

4. Microtremor observations

In natural conditions, there is always vibration on the earth's surface, in which the amplitude is approximately 10^{-8} cm on the bedrock in the quiet mountain and 10^{-4} cm in the city, the period is 0.05–10 s, called microtremor. It is generally considered that the micro-causes are transportation, machinery operation and other human activities, or from deep formations, weather changes, river, lake, ocean waves and other natural excitation. It has been expected that the period of microtremor has a reasonable relationship with the nature of local soil deposit and dynamic characteristics of subsoil (Kanai and Tanaka, 1961; Tokimatsu et al., 1992a,b). Microtremor can be recorded by convenient portable instruments. The recording, however, is easily disturbed by

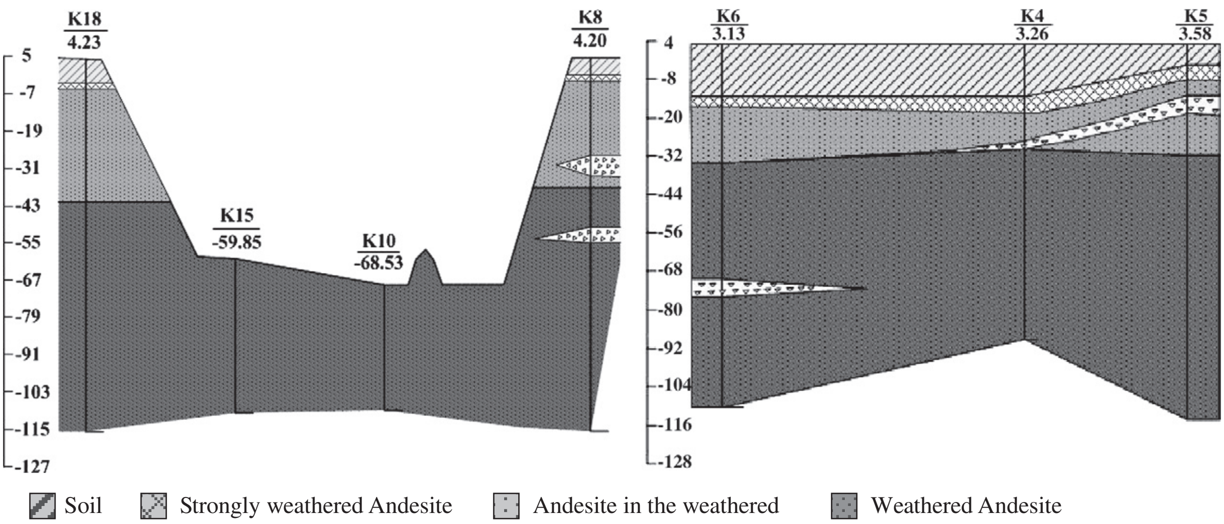

Fig. 6. Engineering geologic profiles.

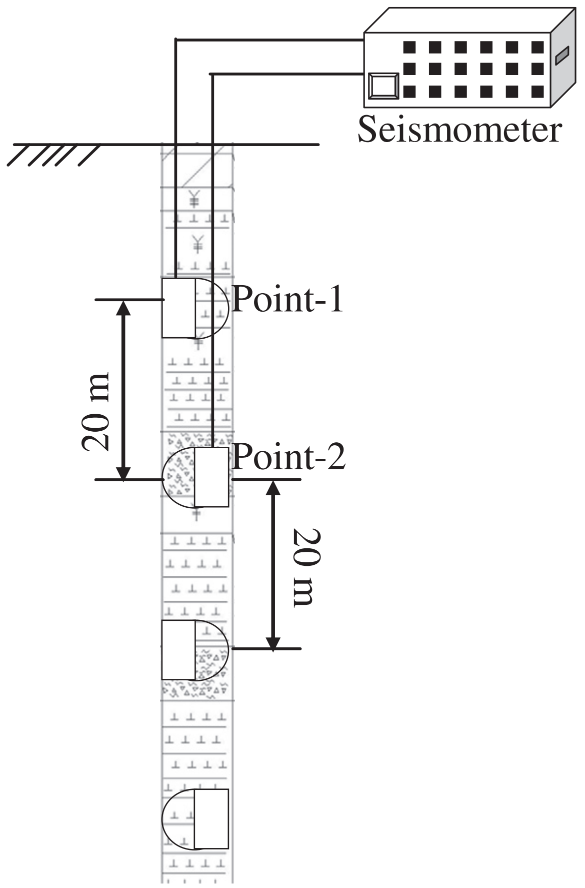

Fig. 8. Observation points.

environmental noise such as those caused by traffics and construction works. It is therefore desirable to conduct it during quiet times.

4.1. Observations

The observation system consists of a portable data acquisition with 16 bit A/D converter (LS-7000, made by Japan Hakusan Corp. frequency range is between 0 and 70 Hz, and channel number is 6), a three component, moving coil type, high-sensitive velocity detector (MBPU-4.5 M, Servo velocity type and natural period >1 s, made by Japan Buttan Service Co., Ltd) and a pressure system, as shown in Fig. 7. The pressure system is used to fix the sensor in the constant depth. And the measurement direction is controlled by compass. The detectors are connected to the data acquisition unit through cables. Before conducting measurement in each point, huddle test is performed for coherency and phase differences among the detectors. The applicable range of frequency is identified as from 0.1 to 20 Hz.

The interference of human activities should be avoided during investigation and the borehole should be smooth and non-blocking. Two sets of detectors (three components) are placed in the borehole with 20 m interval at the same time, and every observation moves 20 m, as shown in Fig. 8. The records of two horizontal components (EW and

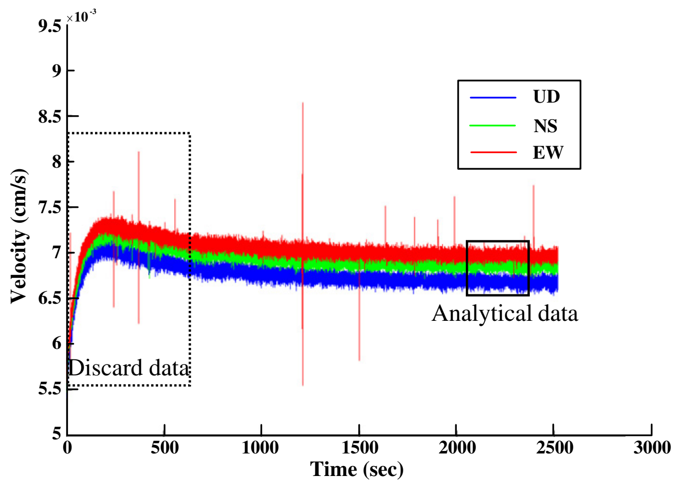

Fig. 9. Sample of recorded data.

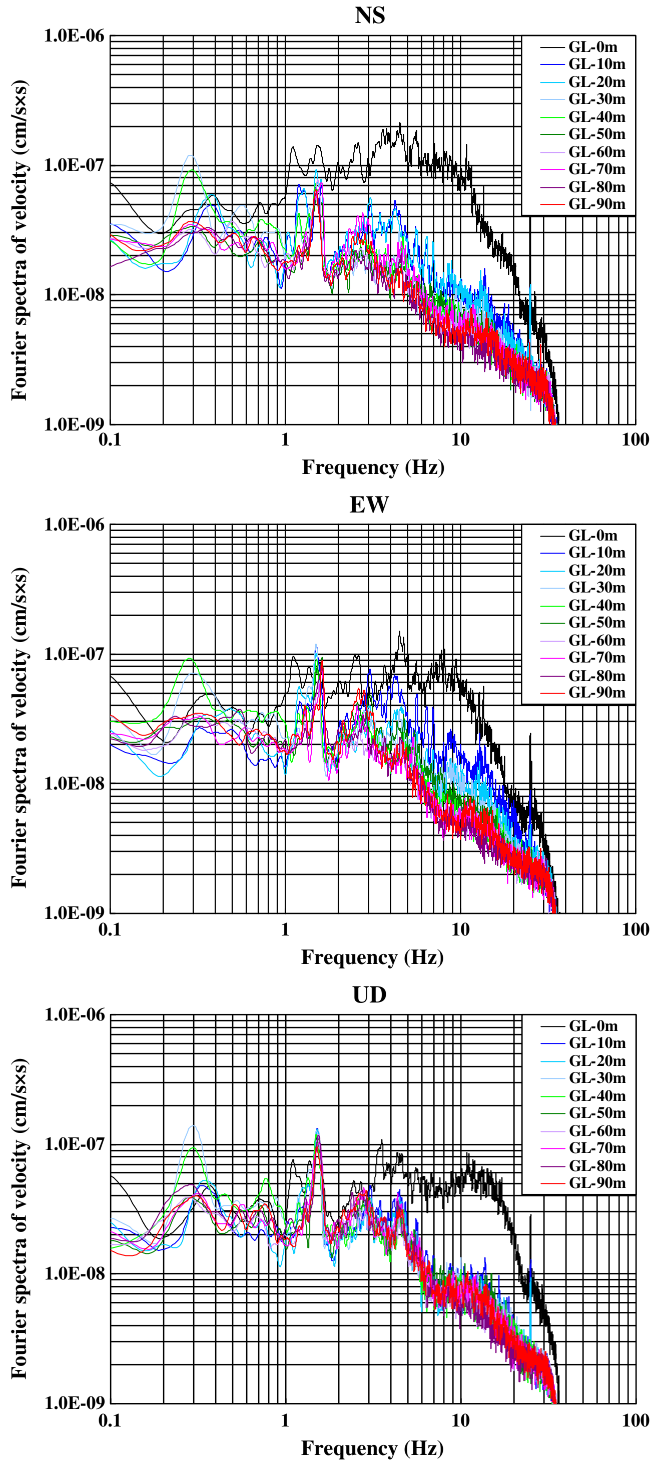

Fig. 10. Velocity Fourier spectra of microtremor from the borehole K8.

Table 2
Identified rock mass model for K8.

Litholog	Density ρ (kN/m^3)	Depth H (m)	Shear velocity V_s (m/s)		Damping h	
			Initial	Identified	Initial	Identified
Dark green–grass yellow clay	19	4.7	450	140	0.03	0.05
Weathered bedrock	21	9.6	450	250	0.03	0.05
In the weathered bedrock	28	16.7	2500	2200	0.03	0.03
Fault	20	7.0	2500	600	0.03	0.049
In the weathered bedrock	28	4.0	2500	2650	0.03	0.03
Weakly weathered bedrock	28	12.2	2500	3009	0.03	0.019
Fault	20	5.9	2500	600	0.03	0.049
Weakly weathered bedrock	28	1000.0	3000	3009	0.03	0.019

NS) and a vertical one (UD) with short-period microtremors are obtained. At each record, data is recorded for 1 h with sampling frequency of 200 Hz, and a total of 720,000 values are recorded for each point. Fig. 9 indicates the recording sample of microtremor. Care is certainly needed to avoid disturbance in the signal due to ambient heavy traffic or construction noise. These are shown to cause very small intensity of motion and the associating rock strain.

4.2. Data analysis

The spectral components (two horizontal spectrum and the vertical one) of the recorded motions are obtained by fast Fourier transform (FFT). Though the detector is so called portable, it still needs several minutes to stabilize itself. For data processing, we discard the first 10 min of data firstly in no condition. Then, we use a 327.68 s long time window to cut the remained data into time segments, as shown in Fig. 9. Average amplitude and deviation of each segment are analyzed and all the noisy segments, such as machinery, vehicles traffic or pedestrians, are discarded. The time window with a 10% smooth taper is finely designed to reduce its effect to the spectrum estimated. The spectrum of each segment is calculated by FFT and smoothed by a 0.05 Hz Parzen spectrum window.

Fig. 10 shows calculated Fourier spectrum of velocity in three directions with different depth of the K8 borehole. The plots show clear similarities among the different observation points of the spectra. The spectra always have dominant maxima at low frequencies (<3.0 Hz) that correspond to the main peak in Fourier spectrum of velocity. Furthermore, the general decay of Fourier spectrum of velocity toward high frequencies (>3.0 Hz) is also visible in the spectra. The main peak of the obtained spectra is at around 0.2 to 0.4 Hz and 1.0 to 2.0 Hz. Those frequencies are considered to be the natural (resonance) frequency under small shear strain and are closely related with the nature of rock mass.

5. Identification of ground constants

5.1. Forward calculation

According to the borehole data of K8, a numerical horizontally homogeneous stratified initial model with eight layers is established as shown in Table 2. In the model, each layer is characterized by its thickness H, density ρ, damping h, and S-wave velocity v_s. Physical property parameters of density ρ and thickness H in the model are known, while the inversion target is the ground constants (v_s, h).

The elastic wave analysis of the ground model is carried out. In the analysis, the observed microtremor data in NS and EW components from 2000 s to 2327.68 s in the borehole are used as the input motions. The spectra at each ground layers are deconvoluted using the initial ground constants.

Fig. 11 shows spectra of theoretical calculation response of initial K8 model. Spectra of SH waves due to vibration build up corresponding to the geological section is well consistent with spectral curve derived from microtremor analysis at each ground layers. Main peak of the spectra at each points are 0.32 Hz and 1.55 Hz, respectively, is in the range of 0.2 to 2.0 Hz from microtremor analysis.

5.2. Inversion analysis

Based on the microtremor peak frequencies and the sensitivity of the microtremor spectrum, the following assumptions are made for the inversion: (1) the model consists of an eight-layered half-space, (2) the v_s values of the ground layers are calculated from the results of borehole tests at the sites, (3) density ρ and depth H in the model are known, ground constants (v_s, h) are unknown, and (4) the main peak of microtremor is artificial read. By input the pretreated waveform into computation program of inversion method and set as observation vectors $\boldsymbol{f}_{\mathbf{obs}}$, the inversion computation is carried out. After a total of

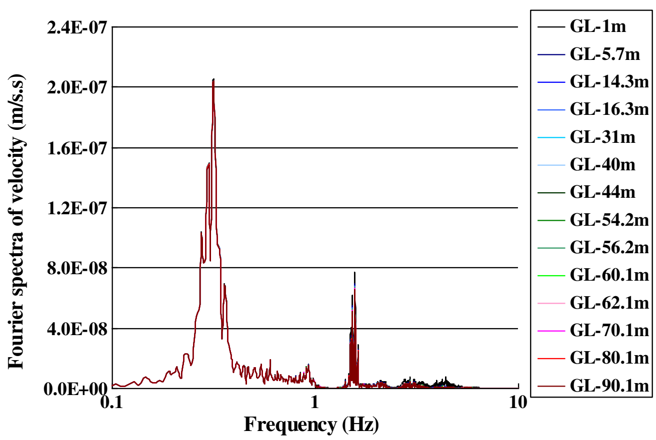

Fig. 11. Spectra of the calculation response of initial K8 model.

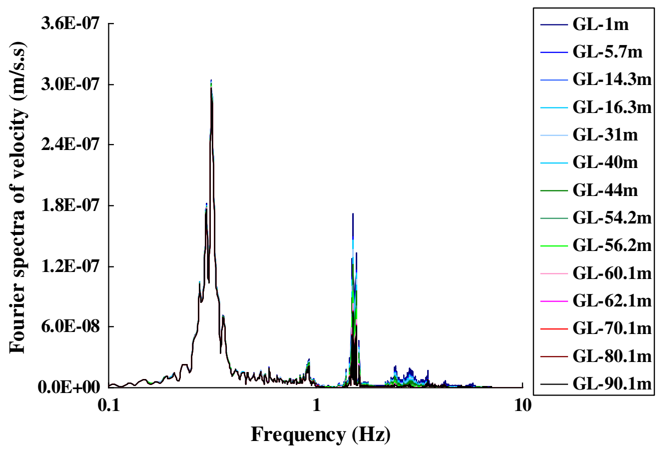

Fig. 12. Spectra of incident waves of K8.

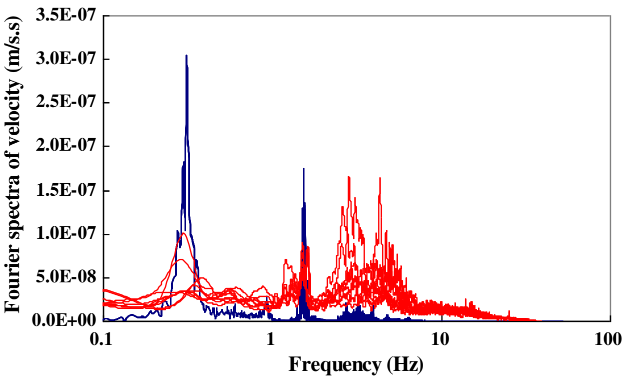

Fig. 13. Comparison between identified and observed spectra at K8.

twelve iterations, the terminal condition is satisfied, and the final results are output as Table 2.

The spectra of each identified incident waves of K8 are shown in Fig. 12. Comparison between identified (blue-line) and observed (red-line) velocity spectra at typical points are shown in Fig. 13. It is found that the calculated velocity spectra agree well with the observed ones.

In the above inversion, the variation of structure of rock mass layers is sought, given the ground constants (v_s, h) of the corresponding layers. To confirm whether the converse is true, a similar analyses is carried out for the other four boring hole data, compared with the boring hole data as shown in Fig. 6 and found that the results hold almost the same reliability and accuracy. Thus, it is concluded that the proposed inversion of microtremor spectra is promising for estimating the dynamic characteristics of surface ground.

6. Conclusions

We proposed a methodology for estimating rock mass characteristics based on microtremor spectra, which can be obtained from a conventional measurement using only one three-component sensor in the boring hole.

The inverse analysis by combining least square method with the multiple reflection theory is presented. And the most suitable dynamic rock parameters (V_s, h) are evaluated by using the down-hole microtremor data.

The application of the method is performed to actual engineering project at five boring holes. The mean values in those cases are estimated to be very close to the PS logs at the sites. The advantages of the proposed method are primarily its simplicity and flexibility.

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