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ESTIMATION OF SHALLOW S-WAVE VELOCITY STRUCTURE BY USING HIGH PRECISION SURFACE WAVE PROSPECTING AND MICROTREMOR SURVEY METHOD

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SUMMARY

The high precision surface wave prospecting method is a technique in which we observe surface waves generated by artificial shock with one-dimension array of seismometers and estimate S-wave velocity structures by means of inversion of the phase velocity. Using the high precision surface wave prospecting method, we can estimate underground S-wave velocity structures up to about 30 meters in depth. The microtremors survey method is a technique in which we observe microtremors with two-dimension array of seismometers and estimate underground S-wave velocity structures by means of inversion of the phase velocity. Using the microtremors survey method, we can estimate underground S-wave velocity structures from several meters to several thousand meters in depth.

In this paper, the high precision surface wave prospecting method is used to estimate underground S-wave velocity structures shallower than 30 meters, and the microtremors survey method is used to estimate underground S-wave velocity structures about from 20 to 100 meters in depth. The S-wave velocity structures obtained from these two methods are compared with those of well log. The results make clear not only that these two survey methods can be performed with lower cost and but also that they are effective to estimate underground S-wave velocity structures.

INTRODUCTION

In order to survey shallow geological structure up to about 20 or 30 meters as well as deep geological structure, refraction survey and reflection survey are usually used. But it is rather difficult to estimate S-wave velocity structure by using these survey methods. The high precision surface wave prospecting method (an abbreviated designation is SWS, i.e. Surface Wave System) (e.g. Liu et al., 1996, Liu et al., 1997, Horita et al., 1999, Konno et al., 2000, and Ling et al., 2003) is an effective survey method to estimate geological structure shallower than about 20 meters. On the other hand, the microtremor survey method (Okada, 2003) has been applied mostly in Japan to the determination of S-wave velocity structures from several ten meters to several thousand meters in depth.

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In this paper, we estimate geological structures by combining S-wave structures obtained by the high precision surface wave prospecting method for shallower depths and by the microtremor survey method for deeper depths.

HIGH PRECISION SURFACE WAVE PROSPECTING METHOD

An outline of the high precision surface wave prospecting method

The high precision surface wave prospecting method is a technique in which the surface waves are observed by using artificial shock in one dimension array, and the S-wave velocity structures are estimated by means of inversion of the phase velocity. The device of high precision surface wave prospecting method (SWS) being used in this study is a portable multi-channel unit (size: 400*250*400mm^3, weight: 14kg), which is developed by Beijing Shuidian Research Institute of Geophysical Surveying. In a briefly summary, the high precision surface wave prospecting system has particular two characteristics.

(a) The method of surveying – multi-channel

In this system, a method of multi-channel surveying with 12 or 24 channels is adopted, so that the surface waves can be extracted correctly by means of a window in which surface waves are selected only.

(b) The method of data processing – On site

A series of software for acquiring data, calculating dispersion curve of surface wave and estimating S-wave velocity structures is built in a control unit with display and keyboard, so that the recording data can be confirmed and analyzed on site.

1) The method of surveying: In practice, shocks are made by using an iron hummer of about 9 kg to strike a metal plate that is set on the ground. Recorded seismic waves are composed of body waves (direct wave, reflected wave and refraction wave) and surface waves. According to elastic wave theory, about 70% of energy of wave motion is contained in the surface waves. Amplitude of the surface waves is far bigger than that of body waves, therefore the quantity of information on underground structures which surface waves bring to observer is larger than from body waves.

For the high precision surface wave prospecting method, the multi-channel surveying method, which 12 or 24 seismometers are set in a linear arrangement, is adapted (see also Fig.1). The seismometers are set as vertical component and can be chosen as either 4Hz or 10Hz (natural frequency) depending on the purpose of survey. The interval of seismometers can also be changed from several centimeters to two meters according to the depth of prospect. The shot point is placed in extension of seismometer arrangement, and hammer, firework ball or weight-drop is used to make a shock.

Fig.2 shows an example of 12-channel record, where the horizontal axis indicates distance and the vertical axis indicates time.

2) The method of data processing: The first, to select a window including surface wave part of surveyed waves and to apply frequency wavenumber method (f-k method) to these data to calculate dispersion curve (depth [=half wavelength] - phase velocity) of surface waves; the second, to estimate S-wave velocity structure below the point of the surveying by means of inversion technique.

Data and results

To estimate shallow S-wave velocity structure, we applied high precision surface wave prospecting method to a test site. The prospecting outline is follows.

The site of prospecting: the Nobi Plain, Japan.

The number of profile: one profile.

The resources of shocking: an iron hummer of about 9 kg to strike a metal plate (size: 30cm*30cm*1cm, weight: 7kg).

The number of seismometer: 12 (natural frequency: 4Hz)

The interval between seismometers and offset: interval =1 meter, offset = 10 meters.

Fig.2 shows observed waveform that includes surface waves. We applied frequency wavenumber method (f-k method) to a record window including surface waves to calculate dispersion curve of Rayleigh waves. Fig.3 shows the f-k amplitude spectrum of the waveforms shown in Fig. 2, in which x-axis represents wavenumber (k) and y-axis represents frequency (f). Searching maximum value of f-k spectrum for each frequency and connecting them, we can obtain a dispersion curve of Rayleigh waves shown in Fig.4, in which x-axis represents velocity of Rayleigh waves and y-axis represents depth (= half wavelength).

Next, we did trial and error to estimate S-wave velocity structures. Fig.5 shows a dispersion curve of Rayleigh waves (blue circles), S-wave velocity structures (solid line) and a theoretical dispersion curve. The S-wave velocity structures (Vs, thickness, depth) are shown in Table 1.

Table 1 S-wave velocity structures estimated by high precision surface wave prospecting method

No.	Vs(m/s)	Thickness (m)	Depth (m)
1	103	3.3	0.00
2	153	5.0	3.3
3	210	5.9	8.3
4	372	16.6	14.2
5	632	---	30.8

MICROTREMOR SURVEY METHOD

An outline of microtremors survey method

Micrometors are very weak vibration existing on the surface of the earth nationally. An array observation of microtremors for determining S-wave velocity structure has mostly been applied in Japan. To extract surface waves from microtremors by array observations, two methods are available; they are frequency wavenumber power spectral density method (F-K method) (e.g. Capon, 1969; Lacoss et al., 1969; Matsushima and Okada, 1990) and the spatial autocorrelation method (SPAC method). Aki (1957) gave a theoretical basis of the SPAC coefficient defined for microtremors and developed a method to estimate the phase velocity dispersion of the surface waves contained in microtremors using specially designed circular array. Henstridge (1979) also introduced a licit expression of the relationship between the spatial autocorrelation coefficient and the phase velocity of fundamental-mode Rayleigh waves. Okada et al. (1990), Ling and Okada (1993), and Ling (1994) extended it to an exploration method that is currently called the SPAC method. The SPAC method cannot separate plural modes of dispersive surface waves as well as body waves; the method only requires fewer stations (practically three or four stations as a minimum requirement). Kudo et al. (2002) applied recently the SPAC method to the damaged area due to the 1999 Kocaeli, Turkey earthquake, and confirmed the usefulness of the method for site characterization even in urban area.

Data and results

We carried out array observation of microtremors at a test site. Array sizes (radius in meters) are 5, 10, 20 and 40 meters from small circular to large circular, respectively (Fig.6). Because only seven stations are used for one measurement, the circular of 5 and 10 meters is called small array (or S-array) and the circular of 20 and 40 meters is called large array (or L-array). The measurements of microtremors were carried out during 60 minutes for small and large array. The portable seismographs are used in this study.

It is composed of a vertical-component seismometer (its natural period is 1 second and is developed for 5 or 7 second; Shindou-Giken Co. Ltd.), and a data logger (16 bits digitizer, 20 megabytes flash memory, and GPS time synchronization; Hakusan-Kogyo Co. Ltd.).

Two examples of array records of microtremors are shown in Fig.7 (observed at large array) and Fig.9 (observed at small array). We can clearly see high coherent waves least at low frequency microtremors. Similarly, two examples of power spectra of of microtremors are shown in Fig.8 (observed at large array) and Fig.10 (observed at small array). We can clearly see high coherent power spectra from 0.3Hz to about 10Hz.

We used vertical motions for obtaining SPAC coefficients aiming to extract Rayleigh waves included in microtremors. SPAC coefficients were obtained by averaging the results of 80 blocks, in which an analysis of one block was for 40.96 seconds time window. Fig.11 shows the observed phase velocity dispersions of Rayleigh waves at large array (triangles), small array (circles) and their average (solid line).

Next, we used forking genetic algorithm (fGA) (e.g. Cho et al., 1999) to find a theoretical dispersion curve or a S-wave velocity structure that fits observed phase velocity dispersion data. It is known that the fGA generally gives a solution with less dependent to an initial model in the surface waves inversion. In this study, the upper layers of initial model is set based on the results of the high precision surface wave prospecting method and the underlying layers of initial model is set based on the geological structures in the area. Fig.12 shows the result of inversion. On the left panel of Fig.11, circles and a solid line show the observations and the computed dispersion for the S-wave velocity structure respectively, and on the right panel of the figure, a solid line and dashed lines show estimated S-wave velocity structure and search limits in fGA inversion of phase velocities, respectively. P-wave velocities and densities are assumed corresponding to S-waves using the empirical relation by Ludwig et al. (1970).

Table 2 S-wave velocity structures estimated by Microtremors survey method

No.	Vs(m/s)	Thickness (m)	Depth (m)
1	179	13	0
2	332	11	13
3	374	109	24
4	652	204	133
5	1002	---	337

CONCLUSION

In order to estimate the S-wave velocity structures from several meters to several hundred meters in depth, two methods, the high precision surface wave prospecting method and the microtremors survey method, were used in this study. We obtained the S-wave velocity structure up to about 30 meters in depth by means of the high precision surface wave prospecting method and up to about 300 meters in depth by means of microtremors survey method. We can also see that S-wave velocities estimated by two methods shallower than 30 meters in depth are quite agreeable.

The S-wave velocity structures obtained from these two methods are compared with those of well log. The results make clear not only that these two survey methods can be performed with lower cost and but also that they are effective to estimate underground S-wave velocity structures.

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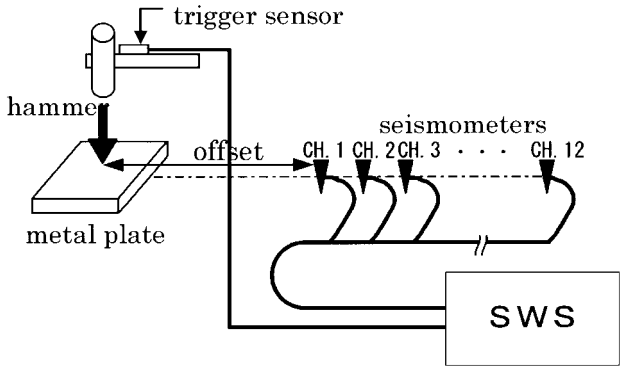

Fig.1 The image figure of high precision surface wave prospecting method (12 channels)

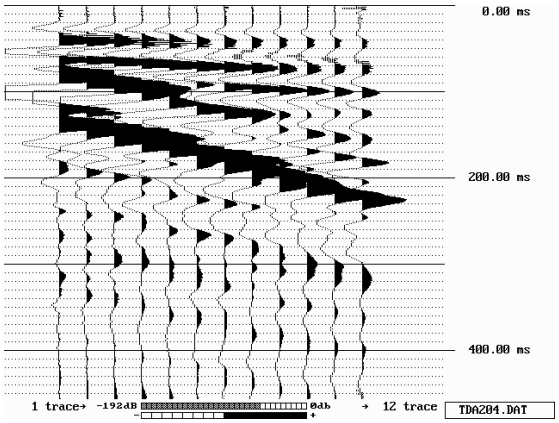

Fig.2 An example of waveform of high precision surface wave prospecting method (12 channels)

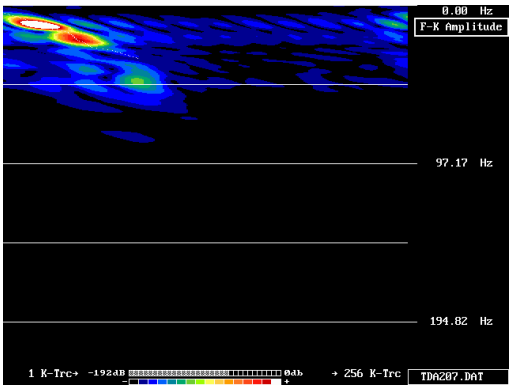

Fig.3 f-k amplitude spectrum (the horizontal axis indicates wavenumber (k) and the vertical axis indicates frequency(f)) of the waveforms shown in Fig. 2.

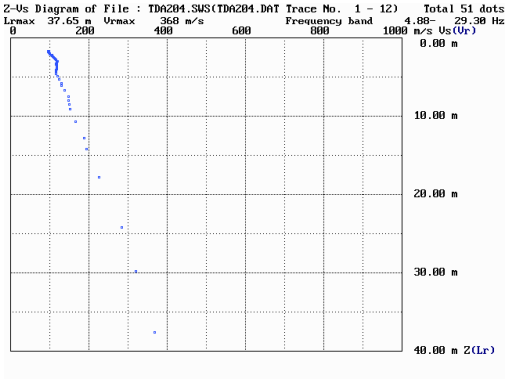

Fig.4 The dispersion curve of Rayleigh waves.

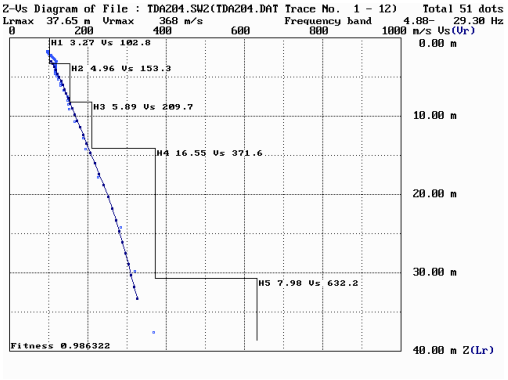

Fig.5 The dispersion curve of Rayleigh waves and S-wave velocity structure.

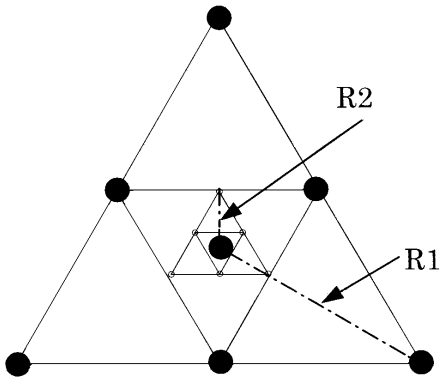

Fig6. Arrangement of microtremors array observation
(R1=40m, R2=10m)

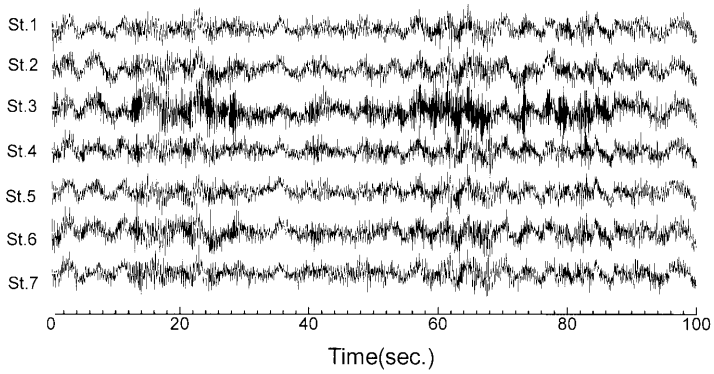

Fig.7 Example of array record of microtremors observed at large array (ground velocity time history).

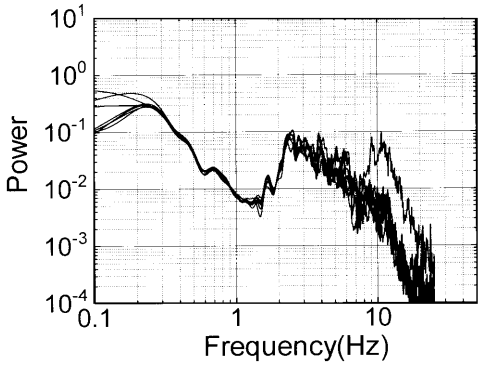

Fig.8 Power spectra of microtremors at large array

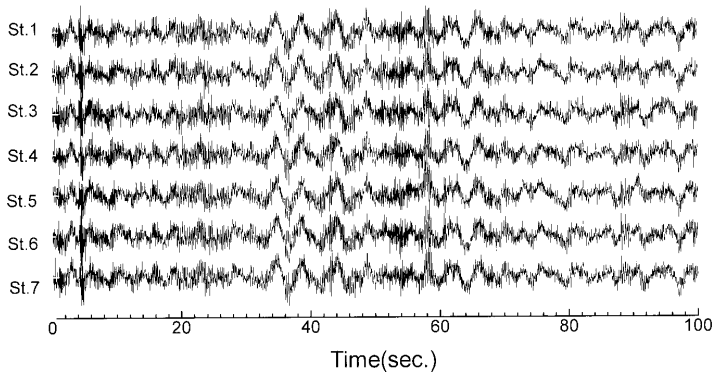

Fig.9 Example of array record of microtremors observed at small array (ground velocity time history).

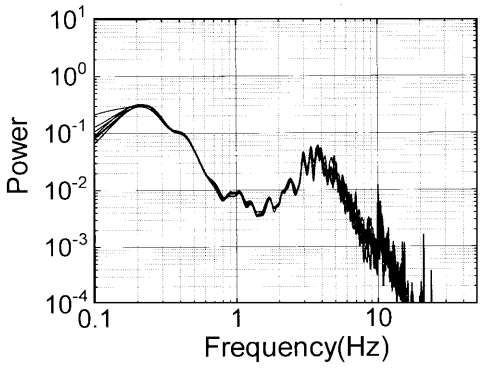

Fig.10 Power spectra of microtremors at small array

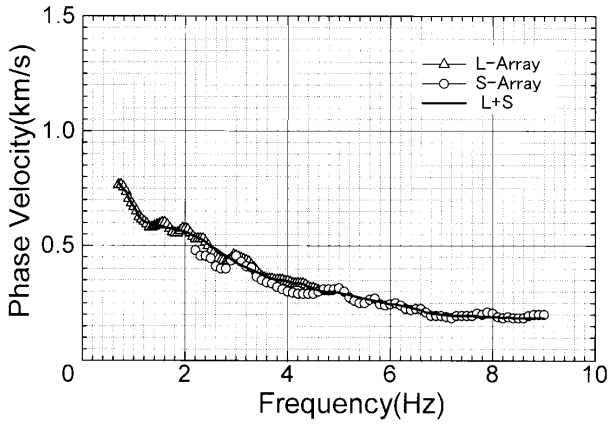

Fig.11 Phase velocity dispersion curve of Rayleigh waves at large array, small array and their average value.

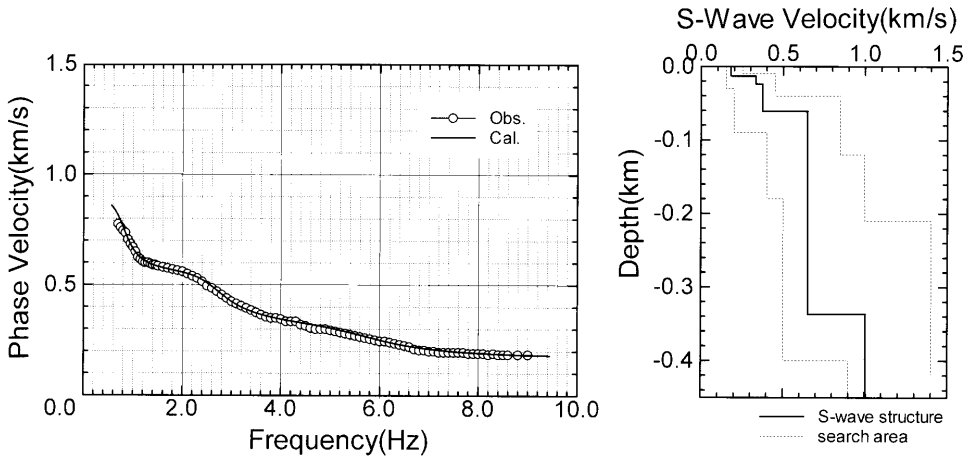

Fig.12 Phase velocity dispersion curve of Rayleigh waves (left) and estimated S-wave velocity structure (right). Circles and a solid line on the left panel show the observations and the computed dispersion for the S-wave velocity structure. Dashed lines on the right panel show search limits in fGA inversion of phase velocities.