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ESTIMATION OF S-WAVE VELOCITY STRUCTURES BY USING MICROTREMOR H/V SPECTRA TECHNIQUE BASED ON BOTH RAYLEIGH- AND LOVE- WAVES

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SUMMARY

It is important to clarify basement structures of urban areas from a viewpoint of earthquake engineering. Microtremor H/V spectra techniques had been conventionally used to estimate the basement depth based on medium responses of horizontal to vertical amplitude ratio of Rayleigh wave. It is insufficient to consider only Rayleigh wave because microtremor consists of not only Rayleigh wave but also Love wave. This study tried to estimate the velocity structures from microtremor H/V spectra based on the theory of surface wave H/V spectra [Arai and Tokimatsu [1]]. This theory needs both Rayleigh and Love waves to explain microtremor H/V spectra. But, the power ratio of Rayleigh and Love waves in microtremors had not been estimated. We apply three-component spatial auto-correlation analysis, which we have developed, to obtain the power ratio of Rayleigh to Love waves in microtremors. By using this analysis we can obtain the power ratio based on tri-axial microtremor array records empirically.

We carried out microtremor observations at three sites in Morioka City, the northern Honshu, Japan. We employ a circular seismic array with seven tri-axial sensors. The array observation aims to obtain the dispersion curve of phase velocity of Rayleigh wave and the power ratio of Rayleigh to Love wave, respectively. Estimated power ratios were around 1.0 at all sites. Therefore, we assumed that the ratios were 1.0 in order to calculate surface wave H/V spectra.

The microtremor H/V spectra were estimated from the average of spectra at all sensors. We used genetic algorithm inversion technique to determine velocity structures from microtremor H/V spectra because the inversion of structures from microtremor H/V spectra is a non-linear problem. They also agree with the structures estimated from the dispersion curves of Rayleigh phase velocity by using a classical array technique. And synthetic surface wave H/V spectra calculated from the structure are concordant with observed microtremor H/V spectra. The results suggest that the use of both Rayleigh and Love wave is necessary to estimate velocity structures using microtremor H/V spectra.

INTRODUCTION

It is important to clarify S-wave velocity structures beneath urban areas from a viewpoint of earthquake engineering. Recently, conventional exploration techniques using microtremors has been

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developed and applied to estimate underground structures at urban areas. There are two kinds of exploration techniques using microtremors. One is the method using a seismometer array for microtremor observations, and the other is the method using one tri-axial seismometer. This study utilizes horizontal to vertical (H/V) spectral ratio of microtremors observed by only one seismometer in order to estimate Vs structures.

Microtremor H/V spectra techniques had been conventionally used to estimate the basement depth based on medium responses of horizontal to vertical amplitude ratio of Rayleigh wave. It is insufficient to consider only Rayleigh wave because microtremor consists of not only Rayleigh wave but also Love wave. This study tried to estimate the velocity structures from microtremor H/V spectra based on the theory of surface wave H/V spectra [Arai and Tokimatsu [1]]. This theory needs both Rayleigh and Love waves to explain microtremor H/V spectra. But, the power ratio of Rayleigh and Love waves in microtremors had not been estimated. We apply three-component Spatial auto-correlation analysis, which we have developed, to obtain the power ratio of Rayleigh to Love waves in microtremors. By using this analysis we can obtain the power ratio based on tri-axial microtremor array records empirically.

The aim of this study is to apply the theory of the surface wave H/V ratio to estimate underground structures using microtremors. And it is also to know the real ratio of Rayleigh to Love waves in microtremors. We carried out tri-axial seismometer array observations at three sites of Morioka City of the north Honshu, Japan, and estimated S-wave velocity structures by observed microtome H/V based on the surface wave H/V ratio. When we do not know the power ratio of Rayleigh or Love waves to total microtremor power, we do not use the theory of the surface wave H/V ratio. First, we estimated the power ratio of Rayleigh or Love waves to total power from tri-axial microtremors by three-component SPAC method. Next, we estimated Vs structures from microtremor H/V based on surface wave H/V using GA inversion technique. Finally, we compared Vs structures estimated from microtremor H/V to those from Rayleigh wave dispersions.

MICROTREMOR OBSERVATIONS

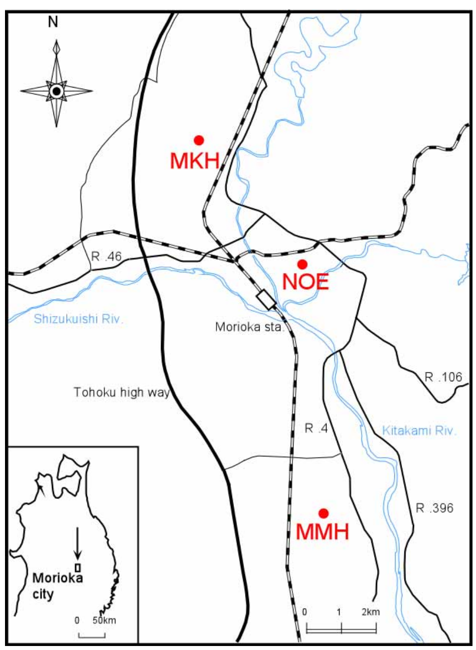

Figure1 Location map of microtremor observation sites. Microtremor observations were done at three sites of Morioka area of northern Honshu, Japan. MKH indicates Morioka-Kita High School, NOE Nioh Elementary School, and MMH Morioka-Minami High School. At each site a seismic circular array was set up using seven seismometers.

Figure 1 shows a location map of three experimental sites, which are grounds of Nioh Elementary School (NOE), Morioka-Kita High School (MKH) and Morioka-Minami High School (MMH), for tri-axial microtremor array observations. Figure 2 shows the array configuration of microtremor observation and data acquisition system. The natural period of the seismometer is 1 sec. Seven data-loggers were used for recording microtremors. Time calibrations were done using GPS within 1 msec. The shape of a seismometer array is a triangle, and the maximum radii are 10 m, 25 m and 40m. One array consists of seven seismometers.

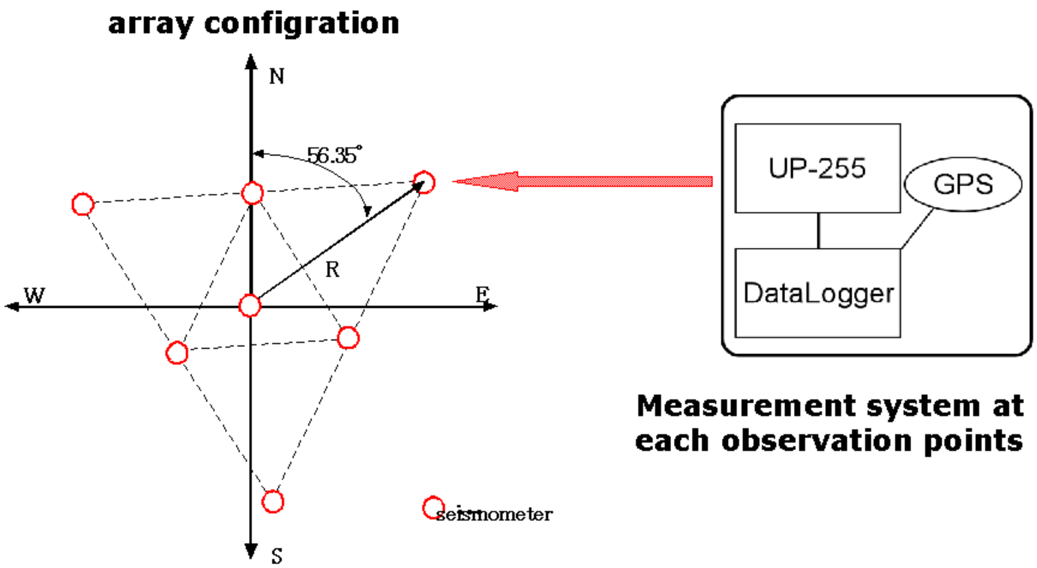

Fig. 2 Tri-axial seismometer array configuration and data acquisition system. Open circle indicates a measurement system consisting of one tri-axial seismometer and one data-logger. Before the microtremor measurement, a time calibration was carried out for all system using GPS.

DATA ANALYSIS

free surface

1	H_1, ρ_1, Vp_1, Vs_1
2	H_2, ρ_2, Vp_2, Vs_2
3	H_3, ρ_3, Vp_3, Vs_3
...	......
k	$\infty, \rho_k, Vp_k, Vs_k$

Figure 3 Geometry of subsurface layer. The subsurface model consists of several horizontal elastic layers. Each layer is characterized by thickness, density, P-wave velocity and S-wave velocity. To make a microtremor source model, it is assumed that vertical and horizontal point forces are randomly distributed on the free surface.

Microtremor H/V

We divided observed microtremor records into several sections, and calculated the average of all records and the average of each section. We adopt all the sections of smaller records than average of total record to calculated spectral analysis for microtremors. We calculated the power spectra of EW-, NS- and UD microtremors using FFT technique. The horizontal power spectra were estimated from geometrical mean of EW- and NS- power spectra. The microtremor H/V were estimated by root of horizontal to vertical power spectra.

$$(H/V)_m = \sqrt{(\sqrt{EW \times NS})/UD} \qquad (1)$$

EW indicates EW components of power spectra, NS indicates NS components of power spectra and UD indicates UD components of power spectra.

Surface wave H/V

Based on Arai and Tokimatsu [1], we explain the model. The structure model shown in figure 3 is assumed to be semi-finite elastic medium consist of N- parallel, solid, homogeneous and isotropic layers. Each layer is characterized by thickness, density, Vp and Vs. On the free surface of the structure model, horizontal or vertical point sources are randomly distributed. Then, the surface wave H/V proposed by Arai and Tokimatsu are expressed by eq. (2).

$$(H/V)_s = \sqrt{P_{HS}/P_{VS}} \qquad (2)$$

$$R/L = \sqrt{P_{HR}/P_{HL}} \qquad (3)$$

Eq. (2) shows surface wave H/V spectral ratio. P_{HS} indicates the horizontal power of microtremors; P_{VS} indicates the vertical power of microtremors. P_{HR} indicates the horizontal Rayleigh wave power of microtremors; P_{HL} indicates the horizontal Love wave power of microtremors. R/L shows the ratio of Rayleigh to Love waves. R/L were converted from the ratio of Rayleigh or Love waves of total power of microtremors, which was estimated from tri-axial seismometer array observation. And surface waves were assumed to be the fundamental mode.

Ratio of Rayleigh to Love waves

First, we determine phase velocities of Rayleigh wave by using Spatial Auto-correlation analysis from vertical microtremor array records (Aki [2]). Next, we estimate phase velocities and relative power of Love wave by using three-component SPAC analysis from horizontal microtremor array records (Okada and Matsushima [3], Yamamoto [4]). We can know the ratio of Rayleigh wave to Love wave based on microtremor array observations. Radial SPAC coefficient is represented as the combination of zeroth and second orders Bessel functions of correlation distance; r, Rayleigh wave length; k^R and Love wavelength; k^L (Eq. (4)).

$$\rho_r = \{J_0(rk^R) - J_2(rk^R)\}\frac{h^R}{H} + \{J_0(rk^L) + J_2(rk^L)\}\frac{h^L}{H} \qquad (4)$$

$$\rho_\theta = \{J_0(rk^R) + J_2(rk^R)\}\frac{h^R}{H} + \{J_0(rk^L) - J_2(rk^L)\}\frac{h^L}{H} \qquad (5)$$

$$H = h^R + h^L \qquad (6)$$

Similarly, tangential one is represented (Eq. (5)). h^R indicates Rayleigh power, h^L indicates Love power, and H indicates total power of microtremors. We assume that microtremors consist of Rayleigh and Love waves (Eq. (6)). Therefore, we can determine the power ratio of Rayleigh to Love wave as the power fraction of Love wave to total microtremor power.

RESULTS-MICROTREMOR H/V AND RATIO OF R/L-

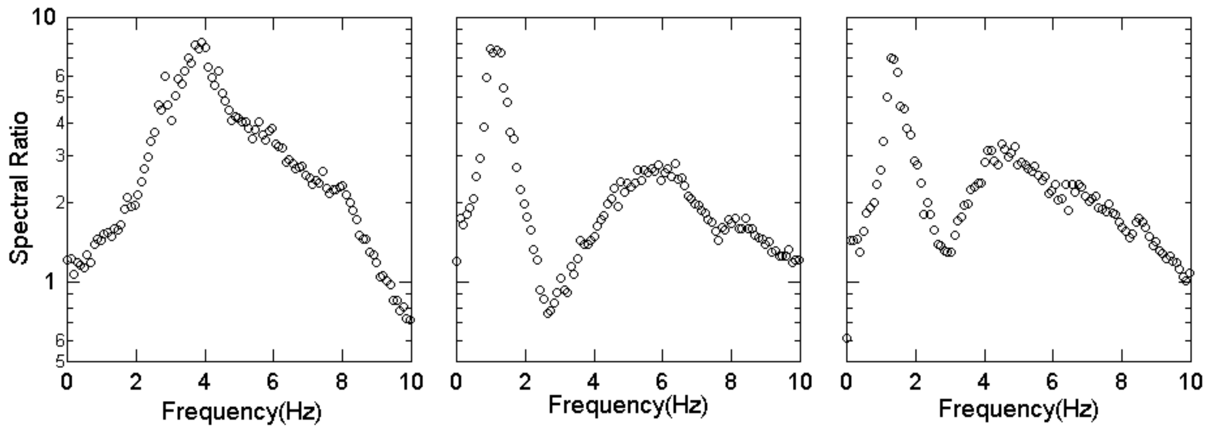

Fig. 4 Observed microtremor H/V spectra at the sites of NOE (left), MKH (center) and MMH (right). We can see characteristic frequencies of the peak of H/V spectra at three sites.

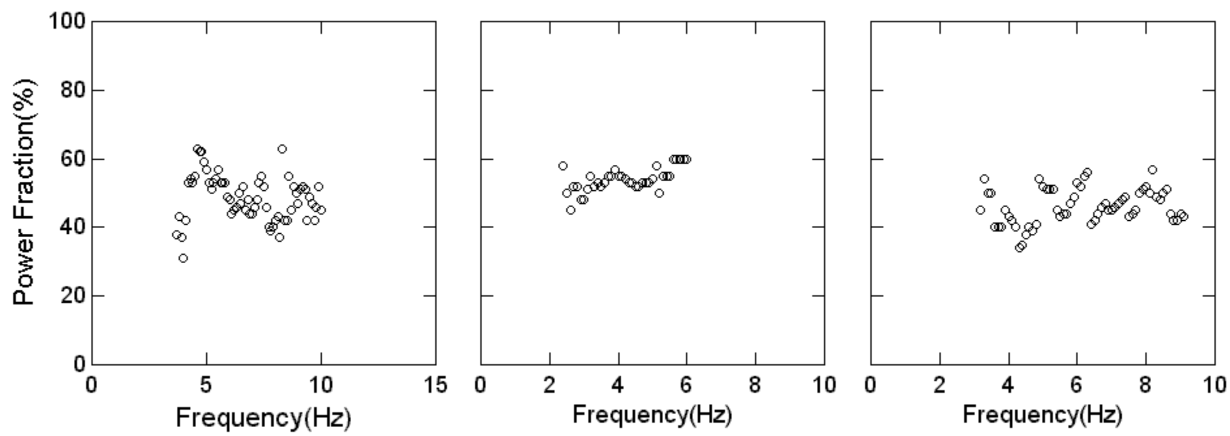

Fig. 5 Estimated power ratios of Love wave to total microtremor power which is assumed that microtremor consists of only Rayleigh and Love waves. The left figure shows the ratio at NOE, the center one at MKH and the right one at MMH. The figure shows that Love power fraction is ranging from 40% to 60 %. For computing surface wave H/V spectra, in this study it is assumed that the power ratio of Rayleigh- to Love- wave is 1 at any frequency.

Figure 4 shows observed microtremor H/V spectra at the sites of NOE, MKH and MMH. We can see characteristic frequencies of the peak of H/V spectra at three sites as follows. The peak frequency at NOE is 4 Hz. The peak frequencies are 1 and 6 Hz at MKH. The peak frequencies at MMH are 1 and 4 Hz. The trough frequencies at MKH and MMH are 3 Hz.

Figure 5 shows estimated power ratios of Love wave to total microtremor power, which is assumed that microtremors consist of only Rayleigh and Love waves. The ratio at NOE was ranging from 30% to

63 % with frequency increasing from 3.7 Hz to 10 Hz. Estimated ratios were ranging from 34% to 60 % at sites of MKH and MMH. These results shows that Love power fraction is ranging from 40% to 60 % at all frequency range at all three sites. Because the power of Rayleigh wave had been same as one of Love wave, we determine that the ratios were 1 at all frequencies to calculate surface wave H/V for estimating underground structures.

ESTIMATION OF VS STRUCTURE USING GA TECHNIQUE

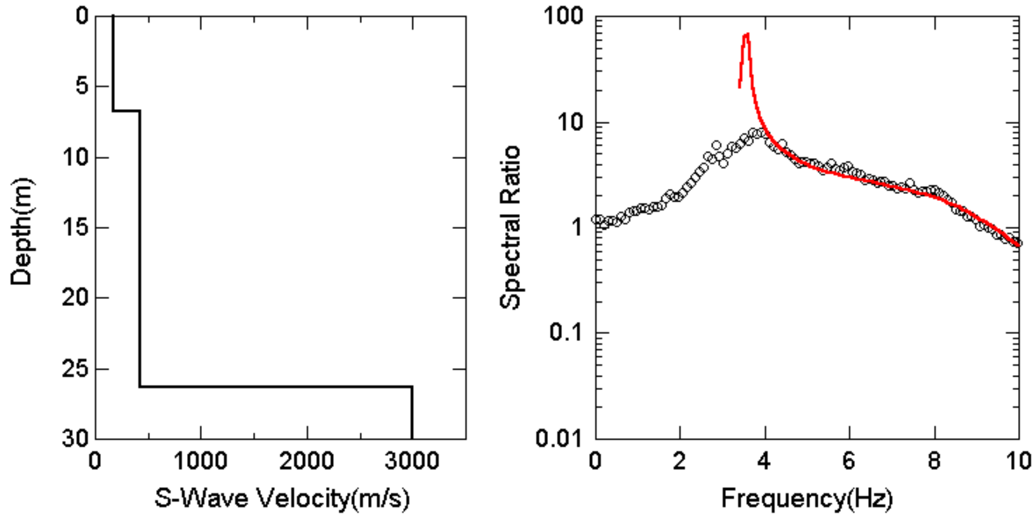

Figure 6 Estimated Vs structure at NOE (left) and relation between microtremor H/V ratio and surface wave H/V (right). Open circles indicate microtremor H/V, solid line indicates surface wave H/V. The microtremor H/V ratios are observed values, and the surface wave H/V ratios are calculated values using parameters estimated by GA inversion. We can see that the peak frequencies are 4.0 Hz for both observed and calculated ratios. The observed ratios correspond to calculated ones at larger frequencies than 4 Hz.

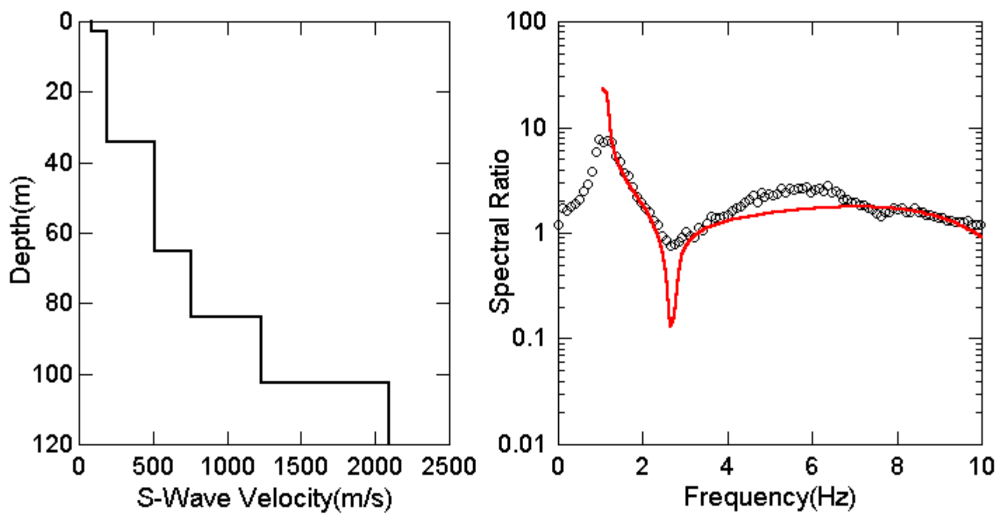

Figure 7 Estimated Vs structure at MKH (left) and relation between microtremor H/V ratio and surface wave H/V (right). Open circles indicate microtremor H/V, solid line indicates surface wave H/V. We can see that the peak frequencies are 1.0 Hz and the trough frequencies are 3.0 Hz for both observed and calculated ratios.

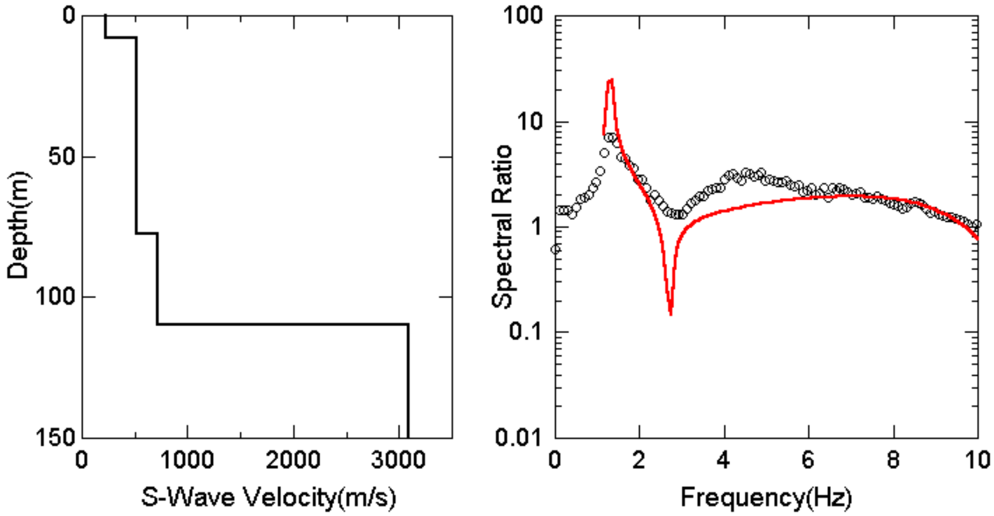

Figure 8 Estimated Vs structure at MMH (left) and relation between microtremor H/V ratio and surface wave H/V (right). Open circles indicate microtremor H/V, solid line indicates surface wave H/V. We can see that the peak frequencies are 1.0 Hz and the trough frequencies are 3.0 Hz for both observed and calculated ratios.

To assume that observed microtremor H/V was the surface wave H/V that consists of 50 % Rayleigh and 50 % Love waves, the Vs structure with parameters of S wave velocity and thickness for each layer was estimated using genetic algorithm (GA) inversion technique. The GA program was referred from the FORTRAN driver coded by Carroll [5]. By minimizing a misfit between observed microtremor H/V and calculated surface wave H/V, the Vs structures were estimated based on GA technique. For a check of exploration using surface wave H/V, we estimated also Vs structures using dispersion relations of phase velocities of Rayleigh wave from vertical microtremor array records, simultaneously. Finally, we compare two structures estimated by different methods.

Figure 6 shows estimated Vs structures at NOE. The structure with three layers was estimated at NOE. The depth of the basement was estimated to be 26.3 m. The surface wave H/V calculated from the structure model and the microtremor H/V observed at NOE were shown. We can see that the observed value of the peak frequency corresponds to the calculated value and the observed values of the H/V ratios correspond to the calculated values at the frequency range between 4 Hz and 10 Hz. Figure 7 shows estimated Vs structures at MKH. The structure with six layers was estimated. The depth of the basement was estimated to be 103 m. The surface wave H/V calculated from the structure model and the microtremor H/V observed at MKH were shown. We can also see that the observed value of the peak frequency corresponds to the calculated value and the observed values of the H/V ratios correspond to the calculated values at the frequency range between 1 Hz and 2 Hz, and between 7 Hz and 10 Hz. Figure 8 shows estimated Vs structures at MMH. The structure with four layers was estimated. The depth of the basement was estimated to be 110 m. The surface wave H/V calculated from the structure model and the microtremor H/V observed at MMH were shown. We can see that the observed value of the peak frequency corresponds to the calculated value and the observed values of the H/V ratios correspond to the calculated values at the frequency range between 6 Hz and 10 Hz.

DISCUSSIONS

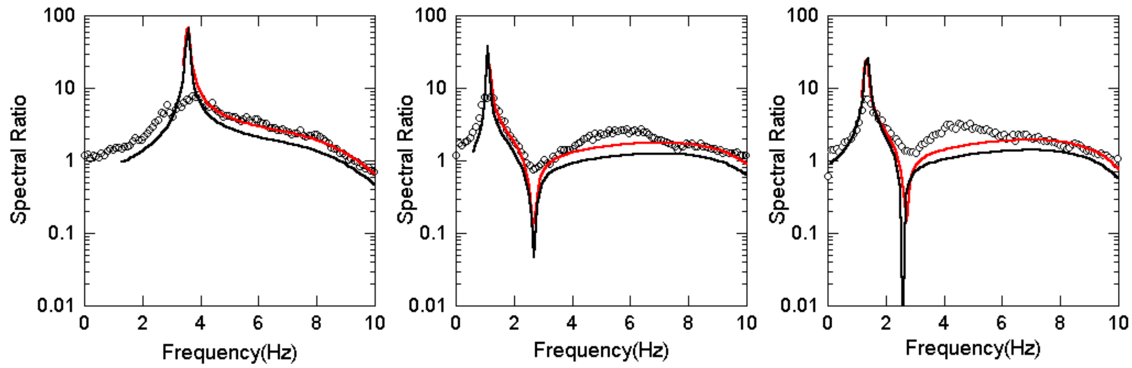

Figure 9 Comparison observed microtremor H/V of calculated Rayleigh wave H/V or calculated surface wave H/V. Open circles indicate observed microtremor H/V. Solid thick lines indicate Rayleigh wave H/V, gray lines indicate surface wave H/V consisting of Rayleigh and Love waves. We can see that observed H/V are good agreement in calculated surface wave H/V. The values of microtremor H/V were not good agreement in calculated Rayleigh wave H/V although the peak frequencies of microtremor H/V were good agreement in those of Rayleigh wave H/V.

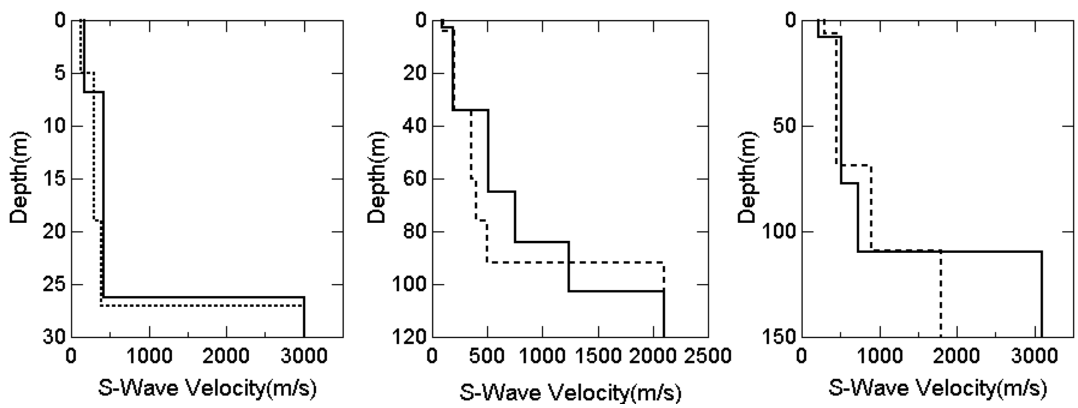

Figure 10 Comparison estimated structures using surface wave H/V technique of those using microtremor array technique at three sites. Dashed lines indicate Vs structure estimated from the dispersion of phase velocities of Rayleigh wave using array technique, and solid line indicate Vs structure estimated from microtremor H/V. We can see that Vs structures using microtremor H/V were good agreement in those using Rayleigh wave phase velocity.

Figure 9 shows observed microtremor H/V, calculated Rayleigh wave H/V and calculated surface wave H/V. Open circles indicate observed microtremor H/V. Solid thick lines indicate Rayleigh wave H/V, gray lines indicate surface wave H/V consisting of Rayleigh and Love waves. We can see that observed H/V are good agreement in calculated surface wave H/V. The values of microtremor H/V were not good agreement in calculated Rayleigh wave H/V although the peak frequencies of microtremor H/V were good agreement in those of Rayleigh wave H/V.

Figure 10 shows estimated structures using surface wave H/V technique of those using microtremor array technique at three sites. Dashed lines indicate Vs structure estimated from the dispersion of phase velocities of Rayleigh wave using array technique and solid thick line indicate Vs structure estimated from microtremor H/V spectrum using surface wave H/V technique. We can see that Vs structures using microtremor H/V were good agreement in those using Rayleigh wave phase velocity.

CONCLUSION

We carried out microtremor array observations at three sites of Morioka area to estimate the microtremor H/V and the ratio of Rayleigh wave to Love wave. By applying surface wave H/V based on Rayleigh and Love waves to observed microtremor H/V, the Vs structures were estimated using GA technique. The following conclusions were revealed.

(1) To compute the surface wave H/V spectra, the power ratio of Rayleigh- to Love- waves in microtremors was estimated from tri-axial seismometer array observations using SPAC method. The results show that the power ratio (Love wave power fraction) was ranging from 40 % to 60 %.

(2) Using the surface wave H/V model that microtremors consist of Rayleigh and Love waves, an observed microtremor H/V was compared with a calculated surface wave H/V which was assumed that Rayleigh power was same as Love power at any frequency. As a result, the observed H/V was good agreement with calculated one at all frequencies at three sites.

(3) At three sites of Morioka city, S-wave velocity structures were estimated by microtremor H/V based on surface wave H/V model using GA inversion technique. Therefore, the availability of the exploration using microtremor H/V technique was shown.

To use the values of microtremor H/V spectra for estimating subsurface structures at urban area, we need the model based on both Rayleigh and Love waves.

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