ESTIMATION OF SHALLOW S-WAVE VELOCITY STRUCTURES FROM PHASE VELOCITIES OF LOVE- AND RAYLEIGH- WAVES IN MICROTREMORS

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SUMMARY

An algorithm for identification of the surface waves, Love- and Rayleigh-waves, in microtremors has already been developed to direct a new exploration technique which can determine geologic structure with respect to S-wave velocity. Based on the algorithm, a practical use of the technique was designed and was also examined at three experimental sites in an urban area, Morioka city in northern Honshu, Japan where usual seismic exploration methods are difficult to apply. The technique involves the measurement of the dispersion of both surface waves in microtremors for which used was a specially designed circular seismic array consisting of more than three three-component seismometers equally spaced on a circle and one at the circular center.

The array observations in the present study were carried out at grounds of Nioh elementary school, Iwate University and Morioka Technical high school of Morioka city as experimental sites. The seismic array consists of seven sensors with double circles with a sensor spacing in the range of 20 to 100 m. In determination of phase velocities of both surface waves, the newly modified spatial auto-correlation method was positively used, as the method can theoretically provide not only the dispersion of Rayleigh waves, but also that of Love waves directly convertible to the S-wave velocity structure.

Observed phase velocities of Rayleigh wave at three sites were in the range of 1500 to 200 m/s corresponding to the frequency range of 1 to 10 Hz. Observed phase velocities of Love wave were in the range of 700 to 180 m/s corresponding to the same frequency range. The S-wave velocity models under the experimental sites were derived from resulting phase velocities of Rayleigh and Love waves. The S-wave velocities of the basements at three sites were 1000 to 2300 m/s at depth of 65 to 130 m. Observed phase velocities at three experimental sites were in good agreement with those calculated for the structure models. These results show that the use of both Rayleigh and Love wave phase velocities in microtremors is practical to conventional exploration technique in an urban area.

INTRODUCTION

Recently, a conventional exploration method using microtremors has been developed and applied for estimating underground structure, especially S-wave velocity structure, in urban area [e.g. Horike, 1985; Matsushima and Okada, 1990]. The method utilizes the dispersion relation of phase velocities of surface waves in microtremors observed with a seismometer array. Rayleigh wave had been used to estimate structure from the dispersion relation of surface waves because it was detectable from vertical component of microtremors. However, the dispersion of Rayleigh wave depends on not only S-wave velocity structure but also P-wave velocity structure. The dispersion of Love waves is directly convertible to the S-wave velocity structure. If an exploration method not only using Rayleigh waves but also using Love waves in microtremors is developed, the method is useful to determine S-wave velocity structure precisely. However, it was difficult to detect the phase velocities of Love

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wave from microtremors because the horizontal component of microtremors contains both Rayleigh and Love waves.

This study carried out three-component microtremor array observations for estimating S-wave velocity structure from phase velocities of Love- and Rayleigh- waves at three experimental sites in Morioka City in the northern Honshu, Japan. The purpose of this study is to show the possibility of three-component microtremor array observation survey using the dispersions of both Rayleigh- and Love- waves. Phase velocities of Rayleigh wave were estimated from vertical components of microtremor and those of Love wave from horizontal components using spatial auto-correlation method. This study positively used an algorithm of spatial auto-correlation method to estimate phase velocities of Love wave in microtremors observed with a horizontal component seismometer array. The basic concept of spatial auto-correlation method was proposed by Aki (1957). Okada and Matsushima (1989) developed the theory to determine phase velocities of Love wave using horizontal component microtremor array observation.

2 AN ALGORITHM OF MODIFIED SPATIAL AUTO-CORRELATION METHOD

Spatial auto-correlation method needs a special designed array for microtremor observation. Based on the Aki's algorithms, Okada and Matsushima (1989) proposed the formula that horizontal components of spatial auto-correlation coefficients of microtremors were written as functions of Rayleigh- and Love- wave wavenumbers.

$$\rho_v(\omega, r) = J_0(rk^R) . \quad (1)$$

$$\rho_r = \{J_0(rk^R) - J_2(rk^R)\}\left(h^R(\omega)/H(\omega)\right) + \{J_0(rk^L) + J_2(rk^L)\}\left(h^L(\omega)/H(\omega)\right). \quad (2)$$

$$\rho_\theta = \{J_0(rk^R) + J_2(rk^R)\}\left(h^R(\omega)/H(\omega)\right) + \{J_0(rk^L) - J_2(rk^L)\}\left(h^L(\omega)/H(\omega)\right). \quad (3)$$

$$h^R(\omega)/H(\omega) + h^L(\omega)/H(\omega) = 1 \quad . \quad (4)$$

$$c^R = \omega / k^R, \quad c^L = \omega / k^L \quad . \quad (5)$$

ρ_v defined by eq. (1) is a vertical component of spatial auto-correlation coefficient estimated from vertical components of microtremors. ω is angular frequency. r is a correlation distance, namely, seismometer spacing distance. The spatial auto-correlation coefficient is defined by azimuthal average of auto-correlation coefficients between microtremor data at the center point and at one point on a circle. ρ_r defined by eq. (2) and ρ_θ defined by eq. (3) are radial and tangential components of spatial auto-correlation coefficients estimated from horizontal components of microtremors, respectively. J_0 and J_2 are zeroth- and 2nd order Bessel functions, respectively. $h^R(\omega)$ and $h^L(\omega)$ are powers of Rayleigh and Love waves in microtremors, respectively. $H(\omega)$ is total power of microtremors. Rayleigh power fraction is defined as a function of angular frequency by $h^R(\omega)/H(\omega)$. Love power fraction is defined by $h^L(\omega)/H(\omega)$. We assume that total power of microtremors is sum of power of Rayleigh and Love waves as shown in eq. (4). k^R and k^L are wavenumbers of Rayleigh and Love waves, respectively. c^R and c^L are phase velocities of Rayleigh and Love waves, respectively.

As the formula shows, using eq. (1) phase velocities of Rayleigh wave are identified from vertical auto-correlation coefficients of microtremors observed with a circular array of radius r. However, not only phase velocities of Love wave identified from horizontal auto-correlation coefficients of microtremors. We must identify Rayleigh or Love power fractions.

To estimate phase velocities and power fraction of Love wave in microtremors, Yamamoto (1998) modified spatial auto-correlation method. By the use of many correlation distances, namely, the use of many combinations of seismometers, we estimated both values of phase velocity and power fraction of Love wave by least squares technique in the particular frequency ω. To minimize misfit function for vertical spatial auto-correlation coefficients, we obtain the phase velocity of Rayleigh wave for angular frequency ω. We can use correlation coefficients of microtremor data observed with different-size array at different time using above technique (Ling, 1993). To minimize the sum of radial- and tangential- misfit functions, we obtain the phase velocity and the power fraction of Love wave for angular frequency ω using eqs. (2) and (3). The power fraction of Rayleigh wave is calculated by eq. (4). Although we can obtain the phase velocity of Rayleigh wave using above equations, we use the estimated value from vertical components for horizontal computation. In computation for horizontal components, we used a grid search technique as two parameters. The fitting computation is done with frequency interval of 0.1 Hz. We obtain the phase velocities of Love waves as a function of frequency, namely, as the dispersion relation [Yamamoto, 1998].

3 MICROTREMOR ARRAY OBSERVATION

Three array observations of microtremors were carried out at grounds of Nioh elementary school, Iwate University and Morioka technical high school in Morioka City in northern Honshu, Japan. Figure 1 shows the location map of the three experimental sites. Microtremor vibration levels at the sites if Nioh elementary school and Iwate University are relatively high because two sites were in an urban area. At the site of Morioka Technical high school one is relatively low because the site was not in an urban area. The experiment was carried out at night to avoid direct traffic noise.

Figure 2 shows array configuration. We regard that a triangle array is same as a circular array. We used seven seismometers in one array. The array consists of three three-component seismometers equally spaced on each circle and one at the circular center. The radial and tangential components of microtremors were calculated from EW- and NS- components. We used two or three arrays of different sizes in order to obtain wide-range correlation distances. In the case of double triangle array as shown in Fig. 2, the number of correlation distances obtained from combination of seismometers is five. The location of center point in each array is same. After a measurement was finished with one array, next measurement was carried out soon. A natural frequency of the used seismometer is 1 Hz. Each data of microtremors was recorded with data-logger. Sampling interval is 20 msec. Time calibration was carried out by GPS. Recording time in one array was 30 minutes.

4 ESTIMATION OF PHASE VELOCITIES

First, we estimate phase velocities of Rayleigh wave from vertical components of microtremors. Figure 3 shows the estimated values of phase velocities of Rayleigh wave at the Nioh site as a function of frequency from the vertical component of microtremors by the modified spatial auto-correlation method using eq. (1). We could use 10 kinds of correlation distances from two different-size arrays, namely, R=50m and R=20m arrays. Observed phase velocities of Rayleigh wave were obtained in the range of 1500 to 200 m/s corresponding to the frequency range of 3 to 10 Hz. Figure 3 shows the normal dispersion relation that phase velocities are smoothly decreasing as frequency is increasing.

Second, we estimate phase velocities and power fraction of Love wave from horizontal components of microtremors using eqs. (2) - (4) and the observed values of phase velocities of Rayleigh wave as shown in Fig. 3. Therefore, we can compute the phase velocity and power fraction of Love wave in the maximum frequency range of 3 to 10 Hz.

Figure 4 shows radial- and tangential- components of spatial auto-correlation coefficients as a function of frequency which are calculated from horizontal components of microtremor data observed with R=20m array. In one array with seven seismometers, five kinds of correlation distances were obtained. We finally obtained 10 kinds of correlation distance from R=50m and R=20m arrays for phase velocity estimation. Phase velocities of Love wave were obtained from these correlation coefficients by fitting observed values to calculated values as a function of correlation distance..

Figure 5 shows the comparison with observed values of correlation coefficients and calculated values at a frequency of 4 Hz. Open circles mean radial components of observed correlation coefficients and solid circles mean tangential components of observed correlation coefficients. Dashed line means radial components of calculated correlation coefficients and solid line means tangential components of calculated correlation coefficients. Calculated curves shown in Fig. 5 were obtained at a Love phase velocity of 400 m/s at a Love power fraction of 78 % at a frequency of 4 Hz using eqs. (2) and (3). Theoretical values satisfied observed values of both radial and tangential components.

To estimate phase velocities and power fraction of Love wave as a function of frequency, we calculated parameters fitting in the frequency range of 3 to 10 Hz sequentially. Figure 6 shows the dispersion curve of phase velocities of Love wave. Observed phase velocities of Love wave were obtained in the range of 550 to 180 m/s. Love wave dispersion shows the normal dispersion relation that phase velocities are smoothly decreasing as frequency is increasing. Figure 6 also shows the power fraction of Love wave in microtremors as a function of frequency. Estimated power fractions were obtained in the range of 40 to 85 %. and varied in frequency. At other sites, power fraction show different values, however, more than 50 %. Therefore, Love wave power at a site in an urban area was much than Rayleigh wave power.

5 ESTIMATION OF S-WAVE VELOCITY STRUCTURE

Using the dispersion relations of phase velocities of Rayleigh- and Love- waves in microtremors, we estimate S-wave velocity structure beneath the observation sites. For computation of dispersion, we used matrix method for multilayer model [Haskell, 1953]. Four parameters of P-wave velocity, S-wave velocity, density and layer thickness are necessary for Haskell's method. However, in the present study P-wave velocity and density were calculated from S-wave velocity. By forward modeling, we computed the dispersion curve of phase velocities of Rayleigh- and Love- waves while calculated values stratified observed values of both waves. Estimated parameters of three experimental sites were shown in Table 1.

Figure 7 shows the comparison with observed values of phase velocities and theoretical values at the Nioh site. Theoretical phase velocities were calculated from S-wave velocity structure shown in Table 1. Observed phase velocities were in good agreement with calculated velocities for both Rayleigh and Love waves. Seven layers model was obtained for the Nioh site. The estimated S-wave velocity of the first layer was 107 m/s, the second layer 262 m/s, the third layer 429 m/s, the fourth layer 668 m/s, the fifth layer 901 m/s, the sixth layer 1249 m/s, the seventh layer 1740 m/s and that of the basement was 2240 m/s. This structure implies not layered structure but gradually velocity gradient structure. Similarly, five layers model was obtained for the Iwate University site, six layers model for Morioka technical high school site.

Bore-hole data without P- and S- wave velocity data had been obtained at the observation site. According to the bore-hole data, weathered granite was found at a depth of about 50 m for the Iwate University site. The depth of basement of estimated structure model was 80m. We can think that estimated basement consisted of fresh granite because of S-wave velocity of the layer.

Figure 8 shows the comparison with observed values of phase velocities and theoretical values at the three experimental sites. Triangles mean observed phase velocities of Rayleigh wave and circles mean observed phase velocities of Love wave. Dashed line means theoretical phase velocities of Raleigh wave and solid line means theoretical phase velocities of Love wave. Theoretical phase velocities were calculated from velocity structure model shown in Table 1. Observed phase velocities of Rayleigh wave at three sites were in the range of 1500 to 200 m/s corresponding to the frequency range of 1 to 10 Hz. Observed phase velocities of Love wave were in the range of 700 to 180 m/s corresponding to the same frequency range. Observed phase velocities were in good agreement with those calculated for the structure model for all sites.

Figure 9 shows S-wave velocity structure models at the three experimental sites as a function of depth. The velocities of basements of models were 1000 to 2300 m/s at depth of 65 to 130 m. It is shown that the exploration method using microtremors was useful for different geology sites. These results show that the use of both Rayliegh and Love wave phase velocities in microtremors is practical to conventional exploration technique in an urban area.

5 CONCLUSION

We carried out the three-component microtremor array observation at grounds of Nioh elementary school, Iwate University and Morioka technical high school in Morioka, Japan. Then we estimated the S-wave velocity structure models above the basement depth of 65 m to 130m from the both dispersion relations of Rayleigh- and Love- waves in microtremors using the modified spatial auto-correlation method. These results show that the use of both Rayliegh and Love wave phase velocities in microtremors is practical to conventional exploration technique in an urban area.

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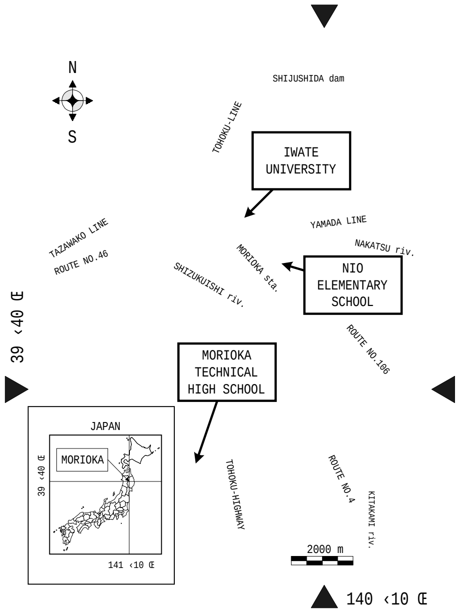

Figure 1: Location map of three experimental sites for microtremor array observation at Morioka City, Iwate Prefecture, at the northern Honshu, Japan. We carried out array observations at grounds of Nioh elementary school, Iwate University and Morioka technical high school.

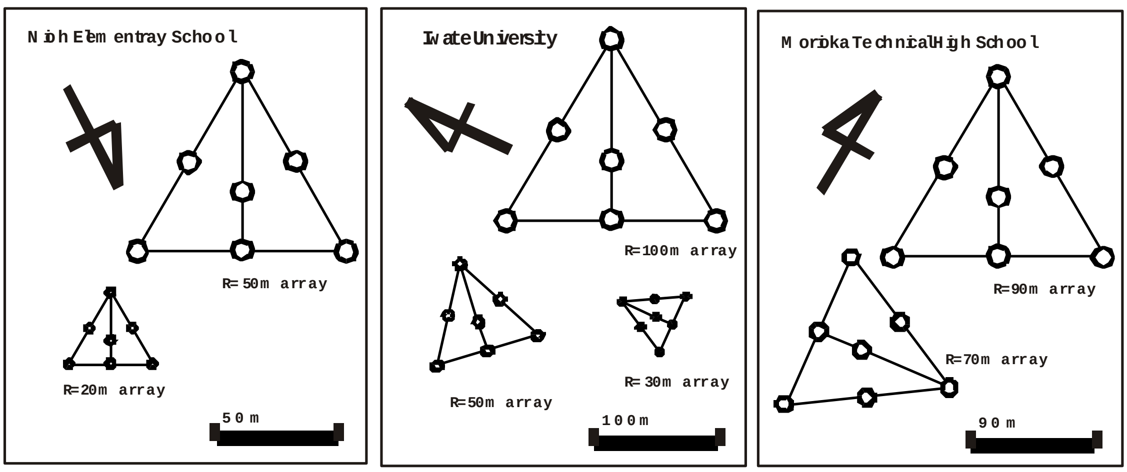

Figure 2: Array configuration for three experimental sites. Open circles mean the locations of seismometer. The array consists of seven three-component seismometers. Three seismometers are equally spaced on each circle and one at the circular center. Maximum radius is 50 m at large array of the Nioh elementary school site, 20m at small array. Maximum radius is 100 m at large array of the Iwate University site, 50m at middle array, 30m at small array. Maximum radius is 90 m at large array of the Morioka technical high school site, 70m at small array. The location of center point in each array is same.

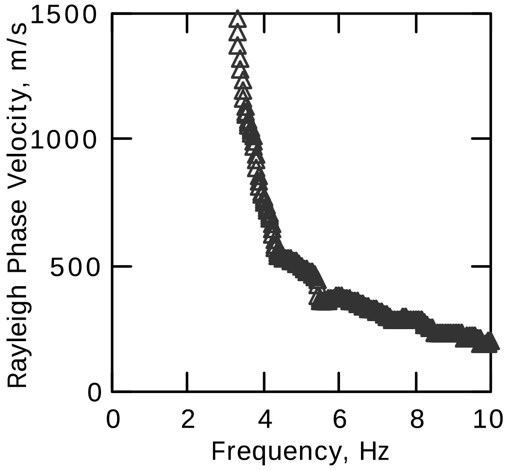

Figure 3: Estimated phase velocities of Rayleigh wave from vertical components of microtremors at the site of Nioh elementary school. The Rayleigh wave phase velocities are used to estimate Love wave phase velocities from horizontal components of microtremors using spatial auto-correlation method.

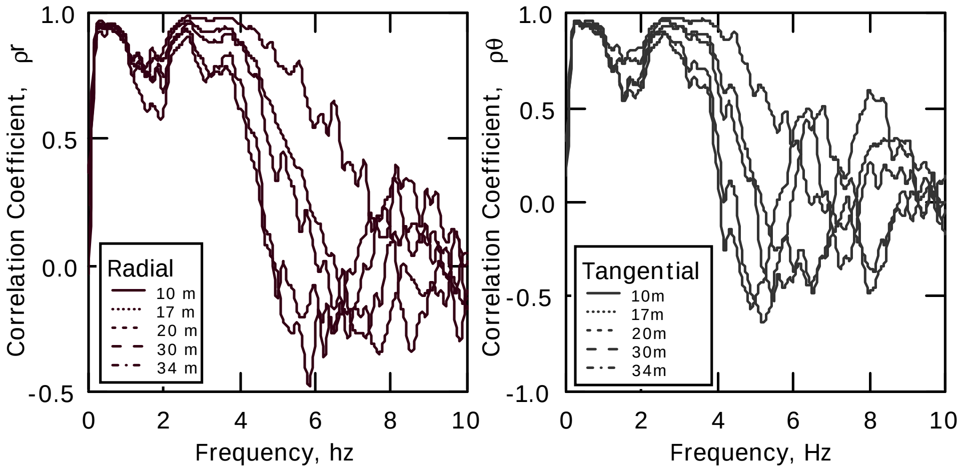

Figure 4: Radial components of spatial auto-correlation coefficients as a function of frequency calculated from horizontal microtremor data of R=20m array of Nioh site (left). Legend means correlation distances. From one array observation, we can five kinds of correlation distances. Tangential components of spatial auto-correlation coefficients as a function of frequency calculated from horizontal microtremor data of array of the same site (right).

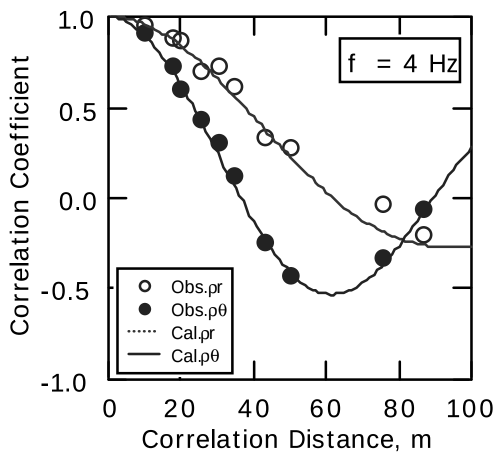

Figure 5: Comparison with observed values of correlation coefficients and calculated values for the Nioh site at a frequency of 4 Hz. Open circles mean radial components of observed correlation coefficients and solid circles mean tangential components of observed correlation coefficients. Dashed line means radial components of calculated correlation coefficients and solid line means tangential components of calculated correlation coefficients.

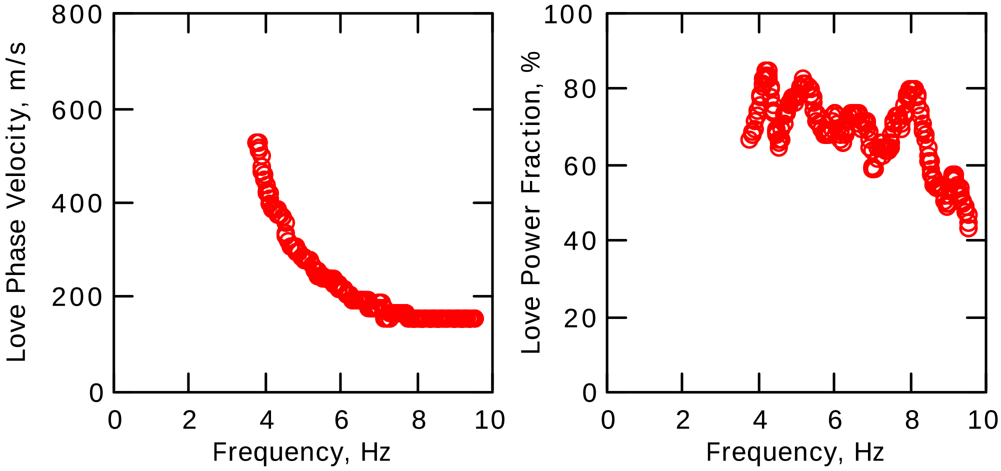

Figure 6: Estimated phase velocities of Love wave from horizontal components of microtremors using phase velocities of Rayleigh wave shown in Fig. 3 (left). Estimated power fraction of Love wave in microtremors (right). The power fraction of Love wave is defined as the ratio of Love wave power and total microtremor power. (4).

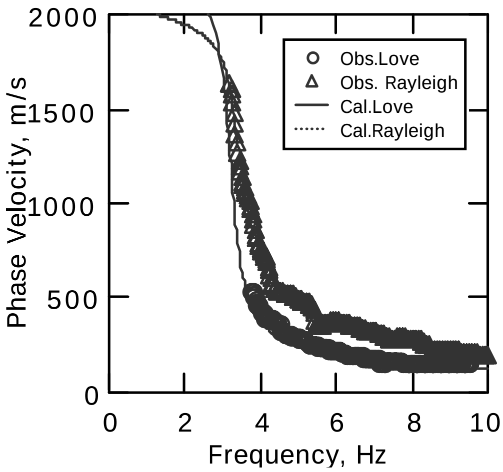

Figure 7: Comparison with observed values of phase velocities and theoretical values at the Nioh site. Triangles mean observed phase velocities of Rayleigh wave and circles mean observed phase velocities of Love wave. Dashed line means theoretical phase velocities of Raleigh wave and solid line means theoretical phase velocities of Love wave. Theoretical phase velocities were calculated from S-wave velocity structure shown in Table 1.

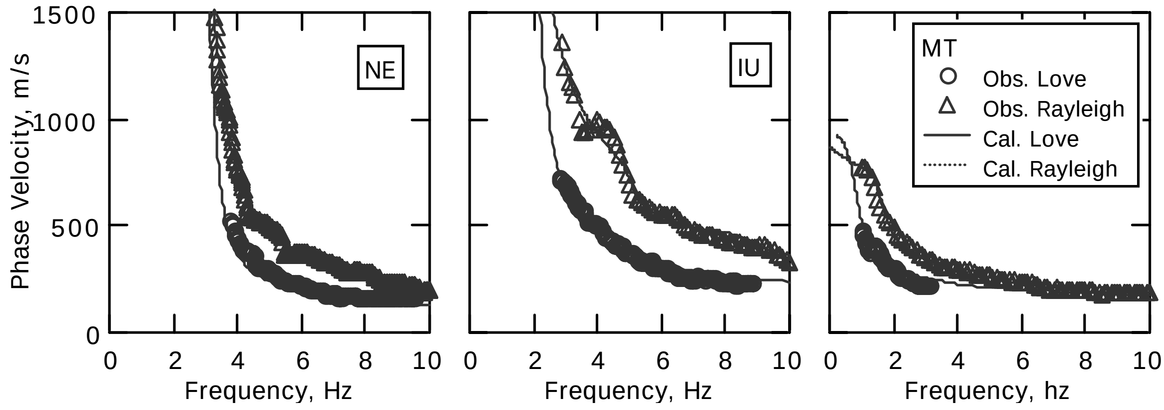

Figure 8: Comparison with observed values of phase velocities and theoretical values for three experimental sites. NE is Nioh elementary school site, IU Iwate University site and MT Morioka technical high school site. See also the caption of Fig. 7. Theoretical phase velocities were calculated from S-wave velocity structure shown in Table 1.

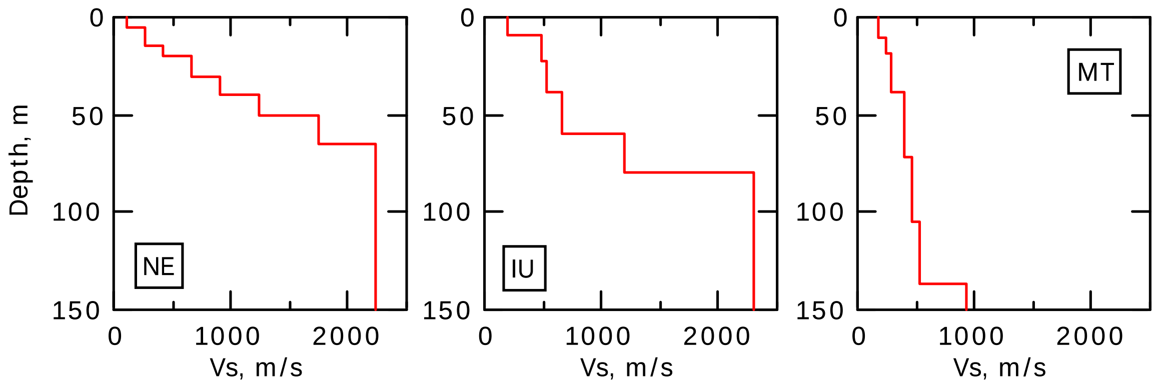

Figure 9: Estimated S-wave velocity structure models at three experimental sites at a function of depth. See the caption of Fig. 8.

Table 1: Estimated S-wave velocity structure models for three experimental sites.

NE		IU		MT	
Thickness(m)	Vs(m/s)	Thickness(m)	Vs(m/s)	Thickness(m)	Vs(m/s)
4.5	107	9	203	10	171
10	262	14	490	8	243
5	429	16	531	21	297
10	668	21	655	33	401
10	901	20	1190	33	470
10	1249	-	2300	32	539
15	1740			-	934
-	2240				

Vs; S-wave velocity (m/s),

NE; Nioh elementary school site, IU; Iwate University site, MT; Morioka technical school site.