A study on practical use of estimation of S wave velocity structure using Love wave phase velocity by three component microtremor array exploration

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Abstract

In this study, for the purpose of a practical use of microtremor array exploration using phase velocities of Love waves, three components microtremors were observed with relatively large size arrays in the Aoyama and Motomiya districts of Morioka City, Iwate Prefecture, located in the Tohoku region of Japan. We examined an applicability of the method in an urban area where there were a lot of noises, such as traffic or human activity noises, and we tried to estimate the S-wave velocity structure in the deep part using a long period range. The results obtained in this study are shown as follows: First, in a case of an analysis with a single sensor, microtremor H / V spectral ratios were calculated and the peak period distribution was grasped, so that the outline of the a velocity structure of the observation area could be grasped. The tendency was consistent with that of the basement depth of the finally obtained S wave velocity structures. Next, as an analysis with an array, phase velocities of Rayleigh wave and Love wave were successfully detected by using two types of methods, called the spatial autocorrelation method and the frequency wavenumber analysis method, even in urban areas where there are limited places and there are noisy observation conditions such as automobile traffic. In our previous study, 10 sensors were required. However, in this study, this method could be applied to 4 sensors. This can be applied to a small number of sensors by trial and error by changing the interval used for analysis for each experiment when using the SPAC and FK methods. We set that the array radii were 30m, 100m, 400m, and 1000m. The phase velocity dispersion curves of Rayleigh waves and Love waves could be obtained even with a large array radius of 100m. However, there was a large difference in the dispersion curve at 400m and 1000m, which is thought to be due to the spatial change of the velocity structure in the Aoyama and Motomiya districts. The S wave velocity structures were estimated from the obtained phase velocities. When the S wave velocity structure was estimated from only Rayleigh wave using vertical microtremor records, there was a trade-off between the layer thicknesses and the S wave velocities, and we could not determine the S wave velocity structures uniquely. In this study, however, the S-wave velocity structure was estimated from Love waves and Rayleigh waves and H/V spectral ratios using three-component microtremor data, so that the decision conditions increased and the S-wave velocity structure could be estimated uniquely.

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Keywords: Love wave, phase velocity, frequency wavenumber method, spatial autocorrelation method, Morioka City

1. Introduction

Microtremor array exploration technique is often used to examine shallow S-wave velocity structures (Okada, 2003). Microtremor array exploration is a method of simultaneously observing microtremors in an array consisting of more than three seismometer on a circle and one at a center, calculating the phase velocity of surface waves contained in the microtremors, and performing an inverse analysis of the subsurface S-wave velocity structure that satisfies the dispersion relation. Generally Frequency - wave number analysis (Capon, 1969) and spatial autocorrelation analysis(Aki, 1957) were used to estimate phase velocities of Rayleigh waves from vertical components of microtremors. It can be said that microtremor array exploration technique using vertical components has been practically used. In the microtremor array exploration, the vertical components of microtremor has been often used (Okada, 2003), however, the horizontal components of microtremors were rarely used for microtremor array explorations. This is because the S-wave velocity structure is obtained by using the dispersion relation of Rayleigh waves included in the vertical microtremors. Love waves included in horizontal components of microtremors are not easy to identify and so they had been not used in microtremor explorations in practical levels. However, Rayleigh waves are affected not only by the S-wave velocity of the ground but also by the P-wave velocity, therefore if the exploration technique of use of Love waves that are purely affected by only the S-wave velocity becomes practical, an improvement in accuracy for estimating S wave velocity structures is expected. It is also expected to reduce the uncertainty in the inverse analysis on Vs structure estimation.

Recent technological advances in observation equipment have made it easier to observe three-component microtremors with an array, and many researchers and engineers have been able to obtained not only vertical tremor data but also horizontal tremor data. In the analysis of horizontal microtremors, there is a method by Saito (2007) which applied frequency wavenumber analysis to horizontal microtremors. This method does not depend on the vertical component analysis and can estimate phase velocities of the wave propagating in the radial and transverse directions from purely two horizontal components, namely EW and NS ones. However, there are few research reports on three-component microtremors due to the limitation of the number of microtremors (e.g. Fujine et al., 2014). Fujine et al. (2014) tried to estimate phase velocities of Love wave by Saito(2007) method, but they did not successed because of and the number of sensors and surroundings artificial noises and so on. Therefore, the number of examples of an observation and an analysis has to be increased to improve the equipment arrangement method and analysis method. There is also a method by Tsuchida et al. (2016) for frequency wave number analysis of horizontal microtremors, and they have shown that a lobe of estimated FK spectra is improved. However, the method of Tsuchida et al. (2016) requires a loop calculation of the wave number in the analysis program, which may increase the calculation time and calculation memory. In this study, we adopt the method of Saito (2007), which requires a small amount of calculation for each frequency. However, there are few research reports on three-component microtremors due to the limitation of the number of microtremors, and there are many cases where the results obtained are not good (e.g. Sakaguchi et al., 2018). At present, it is thought that it is at the stage where the number of observation and analysis cases is increased, and the equipment placement method and analysis method need to be improved.

In our previous research, we observed microtremor data on the premises of Iwate University using a triple triangular array configuration (Yamamoto et al., 2019), and Saito (2007) frequency wave number analysis method (FK method) and three-component spatial autocorrelation method (SPAC). Method) (Yamamoto, 2000), the horizontal motion was analyzed, and the phase velocity estimation ability of the two methods was compared. As a result, the effectiveness of the microtremor array exploration using the phase velocity of the Love wave using the horizontal motion FK of Saito (2007) was shown. However, in the study of Yamamoto et al. (2019), favorable conditions were established for microtremor array exploration as follows:

(1) There was no restriction of freedom of the location of an sensor point because microtremor observation were carried out within a school ground,

(2) Simultaneous observations were carried out using 10 microtremors that we are able to borrow fortunately,

(3)Roads with heavy traffic were not adjacent to each other and were observed under low noise conditions.

In addition, in order to study on the applicability under more severe observation conditions, the horizontal motion was analyzed in the same manner using the microtremor data (Sakaguchi et al., 2018) with array of various shapes observed at Iwate Prefectural Sports Park, Morioka City. We calculated the phase velocity of the Love wave and examined the applicability of the method. We also compared whether the detection accuracy of the Love wave phase velocity differs depending on the arrangement of the seismometer array. As a result, the effectiveness of the microtremor array exploration using the phase velocity of the Love wave using the horizontal motion FK of Saito (2007) was shown. In addition, it was shown that the phase velocity can be detected with the same accuracy not only in the shape of a triangular array but also in a T-shaped, L-shaped, or linear array.

In this study, an equilateral triangular array exploration was performed in Aoyama and Motomiya districts of Morioka city. The purposes of this study are as following three points:

(1) To examine the applicability of the method in urban areas where there is a lot of noise such as traffic noise due to location restrictions,

(2) To estimate S-wave velocity structure with higher reliability by using three-component tremor data,

(3) To estimate the deep structures using long period microtremors with large size arrays because the interval between the sensors was short in previous studies.

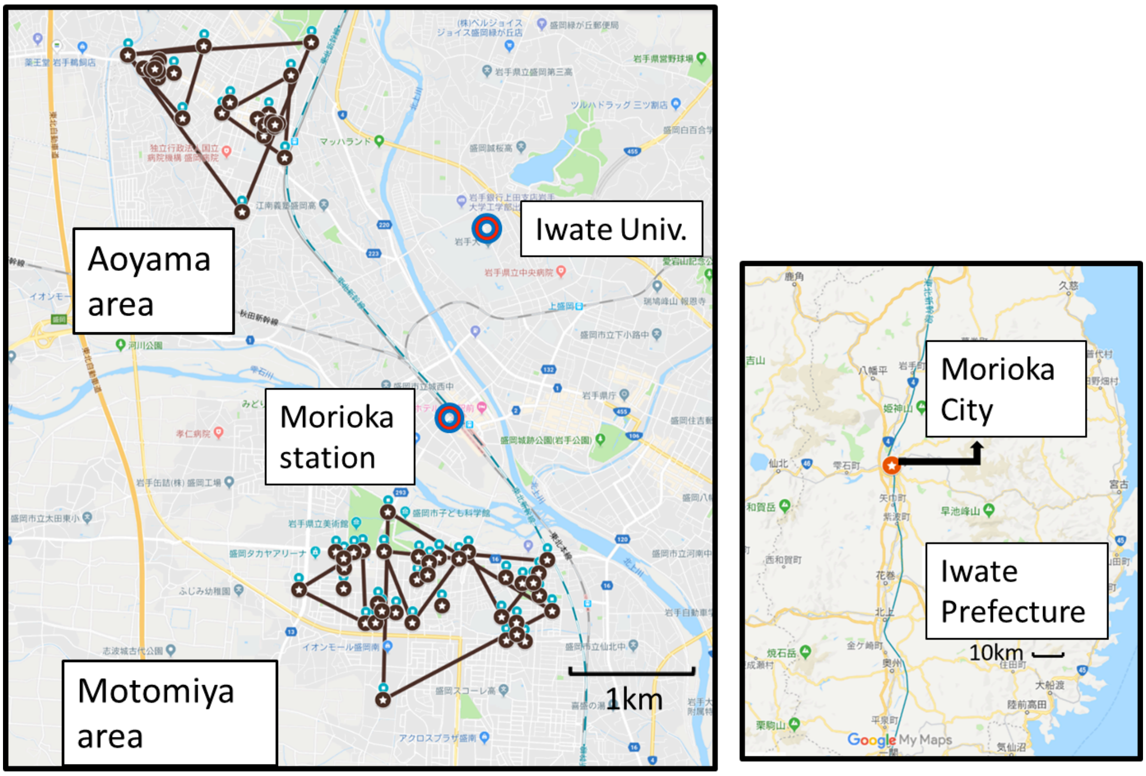

Fig. 1 Microtremor array observation locations. Circles in the figure indicate the sensor locations where microtremors were observed. Microtremor data were observed in equilateral triangle arrays with array radii of 30m, 100m, 400m, and 1000m, respectively in Aoyama and Motomiya areas of Morioka City.

2. Three component microtremor array observation

Microtremor array observation is a method of simultaneously observing microtremors in a sensor array set in a plane, calculating phase velocities of surface waves in microtremors, and estimating the subsurface S-wave velocity structure that satisfies dispersion relations of surface waves. In a microtremor observation, there are two methods: a method of two times observing with two triangular arrays of different radii using four tremors, and a method of once observing with a double triangular array using seven tremors. In this study, we carried microtremor observations out four times at the same point with equilateral triangle arrays with different array sizes consisting of four sensors. One array consists of three sensors on a circle and one at a center. The array radii were set to be 30m, 100m, 400m, and 1000m, respectively. The tremor data used were observed in the Aoyama and Motomiya districts of Morioka City. A maximum of 60 minutes of observation was performed between October and December, 2018. The three-component velocity-meter (Lennartz LE-3D/5s) with a natural period of 5 seconds by Lennartz Electronics was used for a microtremor sensor. The sensitivity of the sensor is 400 V/(m/s). The LS-8800 made by Hakusan Industry Co., Ltd was used for a data logger. The sampling frequency was 100 Hz, the amplification factor of the logger was 16 times, the minimum delay type filter was used. The time was synchronized by GPS.

Figure 1 shows microtremor array observation locations. The circles in the figure indicate the sensor locations. The analyzed data are microtremor data observed in equilateral triangle arrays with array radii of 30m, 100m, 400m, and 1000m, respectively, and were observed in Aoyama and Motomiya districts of Morioka City. The recording time is from 30 minutes to 60 minutes. When the array size was smaller than 400m, recording time was less than 60 minutes. Table 1 shows names, sizes, dates and recording times of microtremor arrays.

Table 1 – List of microtremor array observations

Site name and Radius	Date	Recording time
Aoyama-East 30m	2018/11/26	11:41-12:11(60min)
Aoyama-East 100m	2018/11/26	10:36-11:21(45min)
Aoyama-East 400m	2018/10/16	11:15-12:30(45min)
Aoyama-West 30m	2018/12/5	11:13-11:43(30min)
Aoyama-West 100m	2018/12/5	11:54-12:39(45min)
Aoyama-West 400m	2018/10/19	12:50-13:50(60min)
Aoyama 1000m	2018/10/19	11:16-12:16(60min)
Motomiya-East 100m	2018/10/31	11:20-12:05(45min)
Motomiya-East 400m	2018/10/17	13:03-14:03(60min)
Motomiya-Center 100m	2018/10/31	12:32-13:17(45min)
Motomiya-Center 400m	2018/10/18	10:35-11:35(60min)
Motomiya-West 100m	2018/10/31	14:00-14:30(30min)
Motomiya-West 400m	2018/10/26	11:12-12:12(60min)
Motomiya 1000m	2018/10/17	10:50-11:50(60min)

3. Peak period of H / V ratio of fine movement

First, in order to estimate the outline of the base structure, the H / V ratio of the tremor for each point was calculated from the tremor records observed by the array, and the peak period was read. The H/V spectral ratios were calculated by the ratio of horizontal and vertical spectra of microtremors. The results are shown in Fig. 2 and Fig. 3. In the Aoyama area, the peak period is generally about 0.2 to 1.5 seconds from east to west. Also in the Motomiya area, the peak period shows longer from about 0.4 to 1.4 seconds from east to west. Therefore, we think that the depth of the basement in Aoyama area and Motomiya area increases from east toward west because the peak period of H/V is related to the basement depth.

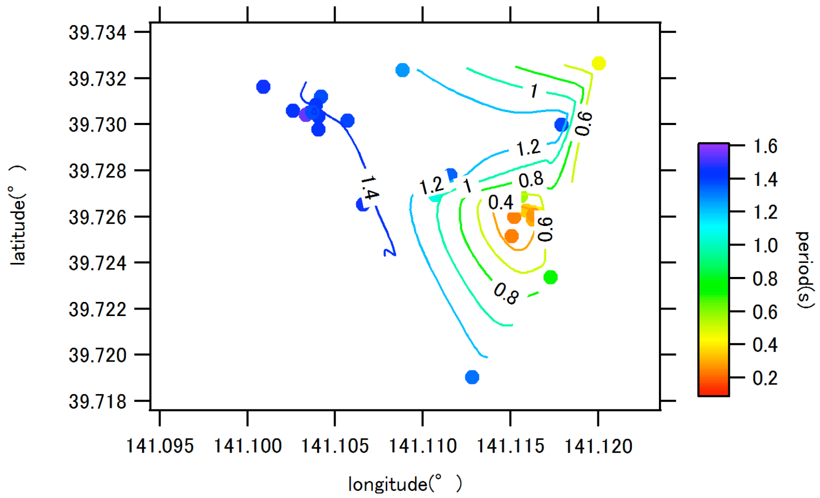

Fig. 2 Peak period of microtremor H/V spectral ratios in the Aoyama area.

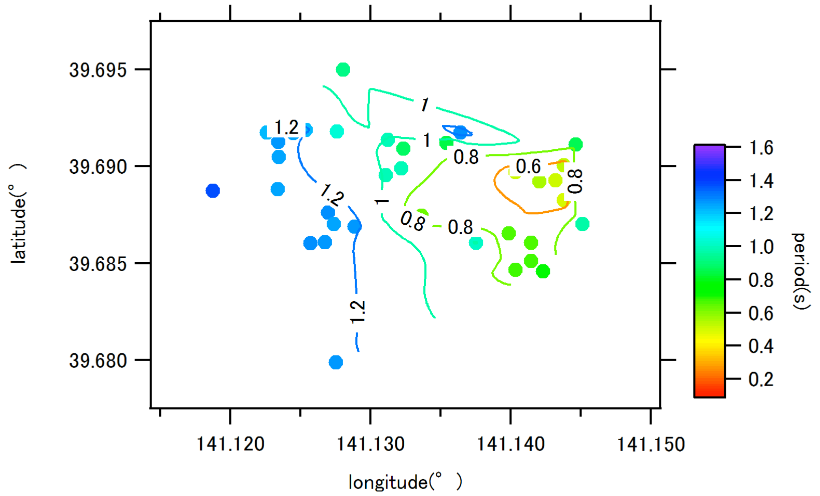

Fig. 3 Peak period of microtremor H/V spectral ratios in the Motomiya area.

4. Estimation of phase velocity

We applied to the frequency wave number analysis method of Saito (2007) to horizontal components of the observed microtremors to estimate phase velocities of transvers components, namely Love wave. Fig. 4 and Fig. 5 show the phase velocities of Love wave in Aoyama and Motomiya areas. Open circles indivcate the phase velocities obtained from the microtoremor observations, and solid lines indicate the phase velocities calculated from the finally estimated S-wave velocity structure model. Although there are some variations, it was confirmed that the phase velocities obtained from different arrays with a radius of 400 m or less were continuous. There is good agreement between the phase velocities obtained from the observations and those calculated from the model. Figures 6 and 7 show the phase velocities of Rayleigh waves. Although the deviation was slightly large, it was confirmed that the phase velocities of Rayleigh wave from arrays with a radi of 30m to 1 km were continuous.There is also good agreement between the phase velocities of Rayleigh wave obtained from the observations and those calculated from the model. The dispersion curves of the phase velocities of Rayleigh waves are calculated using also the spatial autocorrelation method for the vertical tremor obtained from each array.

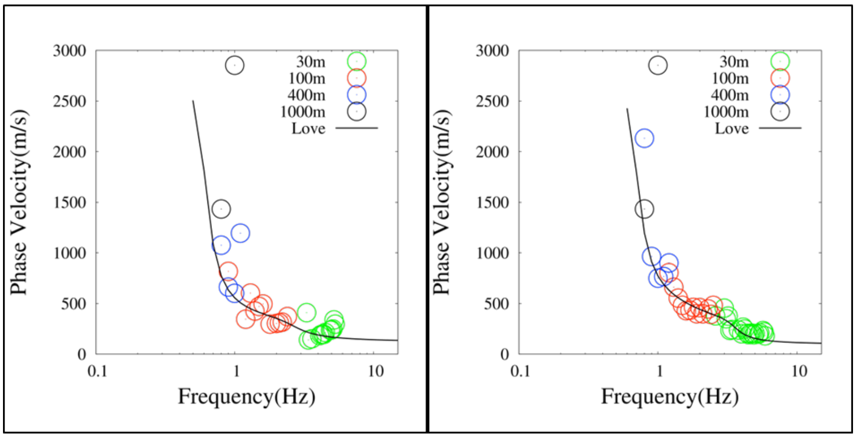

Fig. 4 Phase velocities of Love waves in Aoyama area.

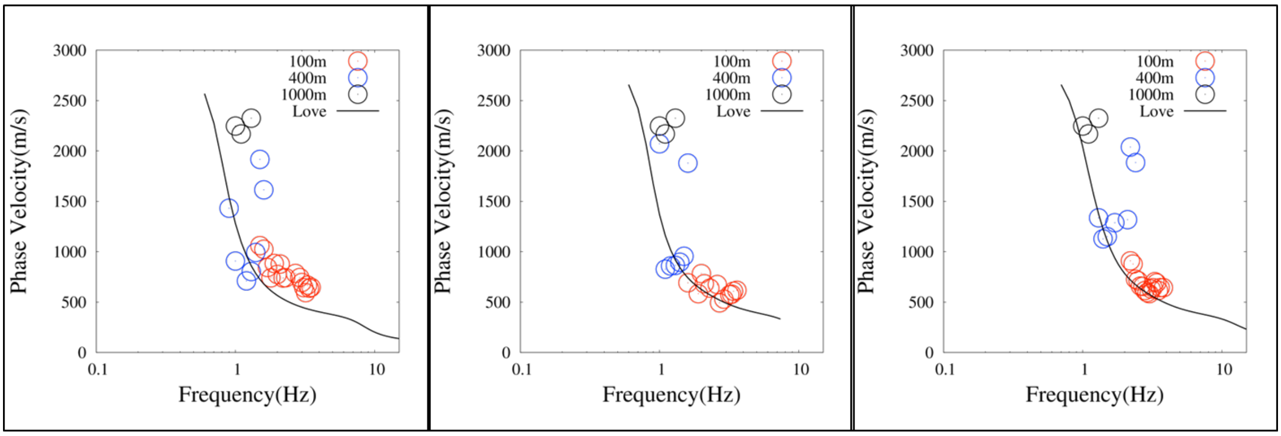

Fig. 5 Phase velocities of Love waves in Motomiya area.

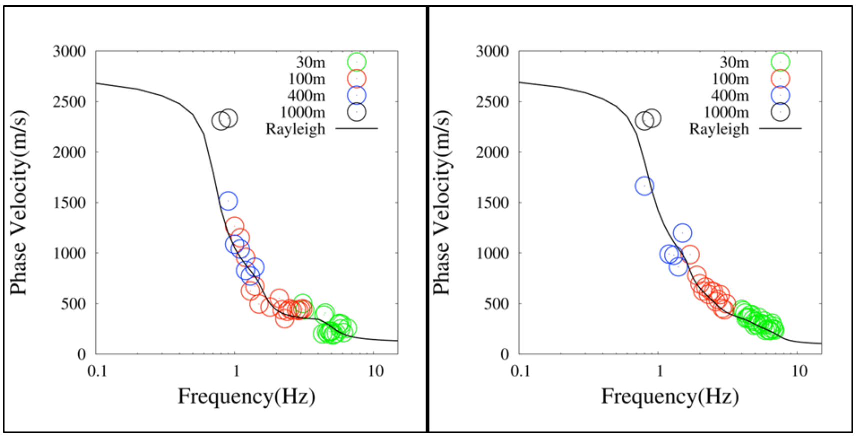

Fig. 6 Phase velocities of Rayleigh wave in Aoyama area

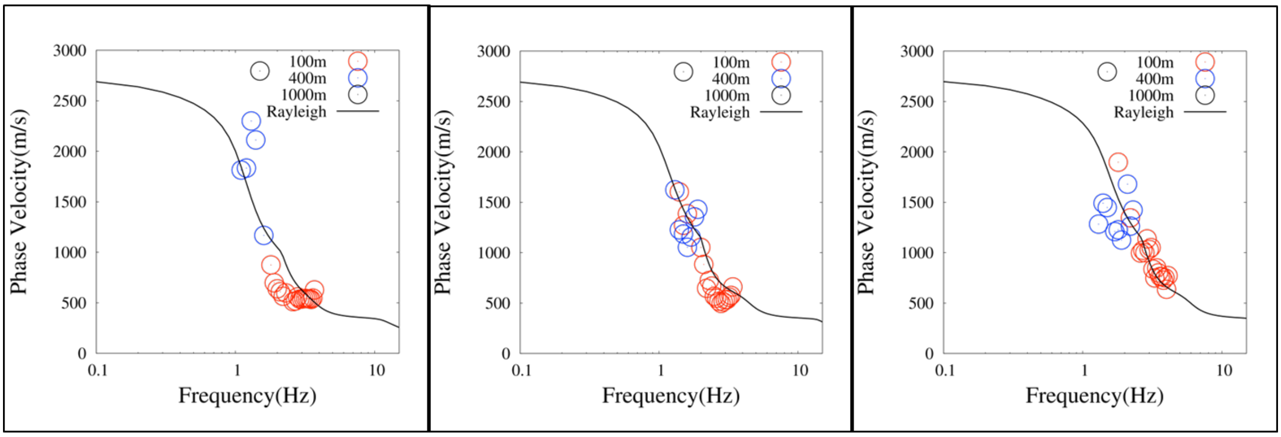

Fig. 7 Phase velocities of Rayleigh waves

5. Estimation of underground structure

We estimated underground S wave velocity structures to satisfy Rayleigh wave phase velocities obtained from the vertical component using the spatial autocorrelation method and FK method, Love wave phase velocity obtained from the transverse component using the horizontal FK method and the shape of H/V spectral ratios. The H/V ratio was compared with the ellipticity of fundamental Rayleigh waves. Figure 8 shows an example of comparison of observed values with calculated values. In each case, the calculated values satisfy the observed values. In ordinary microtremor array exploration, the S-wave velocity structure is often estimated using only vertical motion. However, in that case, if there are few existing geological or geophysical information, the S wave velocity structure model cannot be determined uniquely. It was shown that the model can be determined uniquely when the phase velocities of the two types of surface waves, namely Love and Rayleigh waves, and the microtremor H/V spectral ratios are used in a wide frequency range to some extent is used.

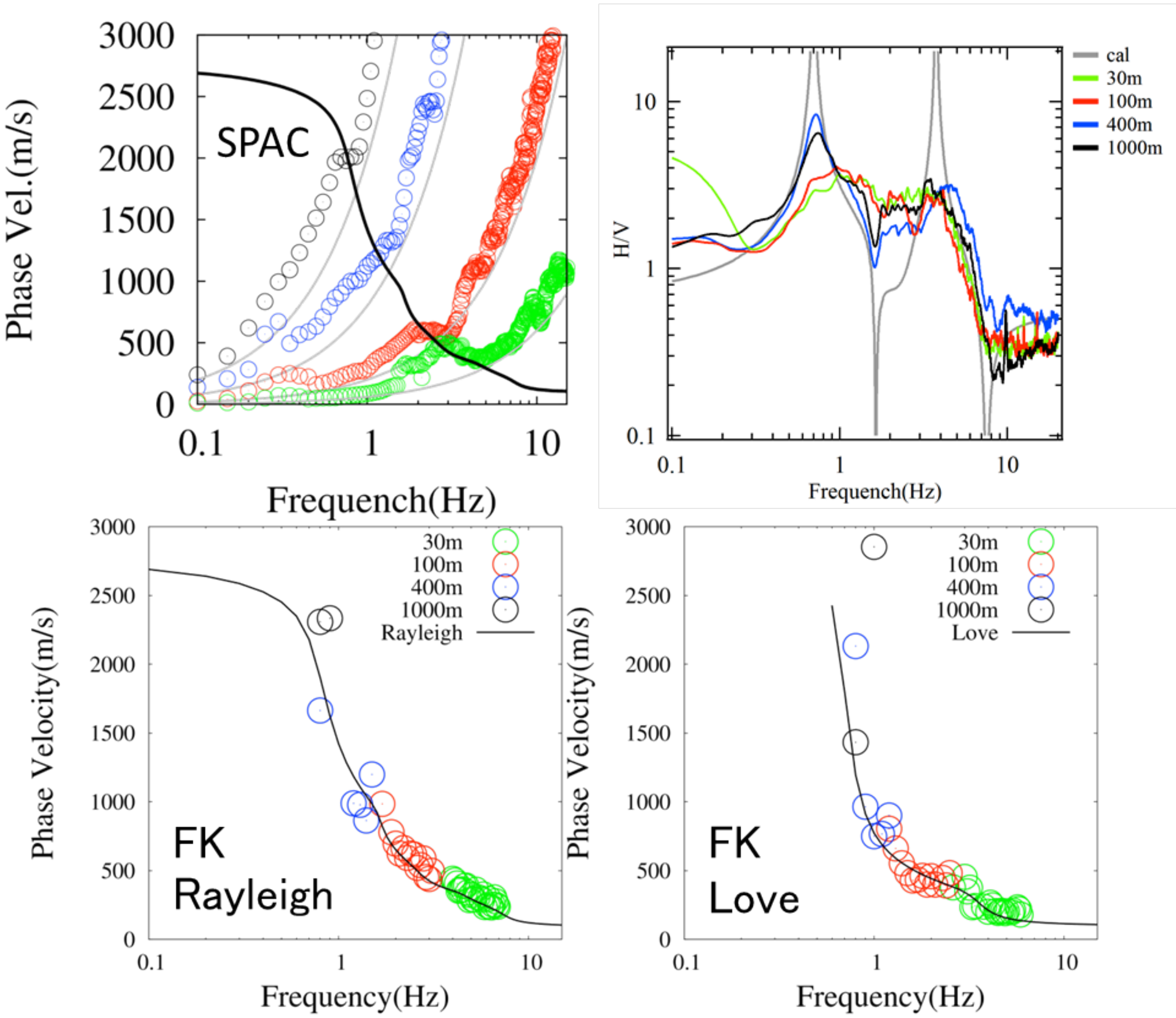

Fig. 8 Examples of comparison of observed values with calculated values. An upper left panel indicates phase velocities of Rayleigh wave obtained by SPAC method. A lower left panel indicates phase velocities of Rayleigh wave obtained by FK method. A lower right panel indicates phase velocities of Love wave obtained by FK method. An upper right panel indicates microtremor H/V spectral ratios

Figure 9 shows the S-wave velocity structures in the Aoyama area estimated by the above method, and Fig. 10 shows the results in the Motomiya area. Comparing the two structural models in the Aoyama area, it can be seen that the basement in west side is about 80 m deeper than Vs = 2100 m/s compared to the east side. This is consistent with the trend of the peak period distribution of H/V in Fig. 2. Comparing the three velocity structure models in the Motomiya area, the basement of Vs = 2100 m/s in center area is about 60 m deeper than the east and the basement in west side is about 90 m deeper than the east. It can be seen that this is consistent with the tendency of the fine motion H/V peak period distribution in Fig. 3. In both Aoyama and Motomiya areas, the estimated structures are gradually deeper from east to west, which was consistent with the tendency of the change in the basement depth obtained from peak periods of the H/V.

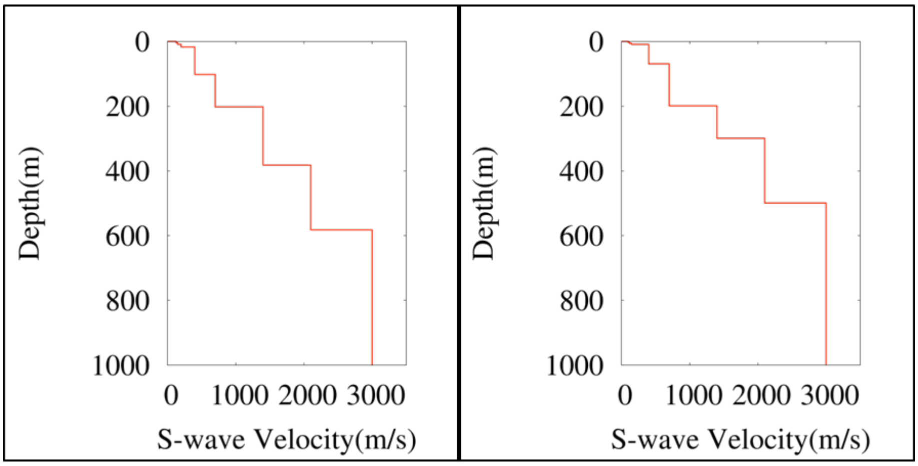

Fig. 9 Estimated S-wave velocity structurtures in Aoyama area.

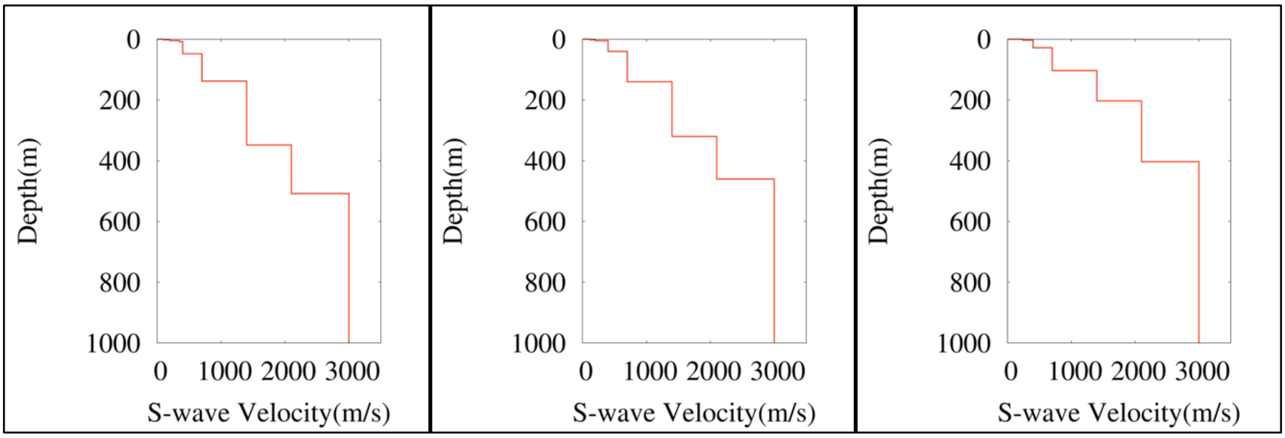

Fig. 10 Estimated S-wave velocity structures.

5. Conclusion

Microtremor array observations were performed in an urban area of Morioka city, and phase velocities of Love wave were able to detect using the FK method even in a record observed with a larger array radius of 100 m than one in past studies. In the analysis of Rayleigh waves alone, there was a trade-off between S-wave velocity and layer thickness. However, using both Rayleigh waves and Love waves by three-component microtremor array exploration made it possible to uniquely estimate the S-wave velocity structure model. The results shows that the microtremor surveys by using Love wave in urban areas with noisy conditions is able to estimate as well as in favorable conditions for microtremor observation..

6. References

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