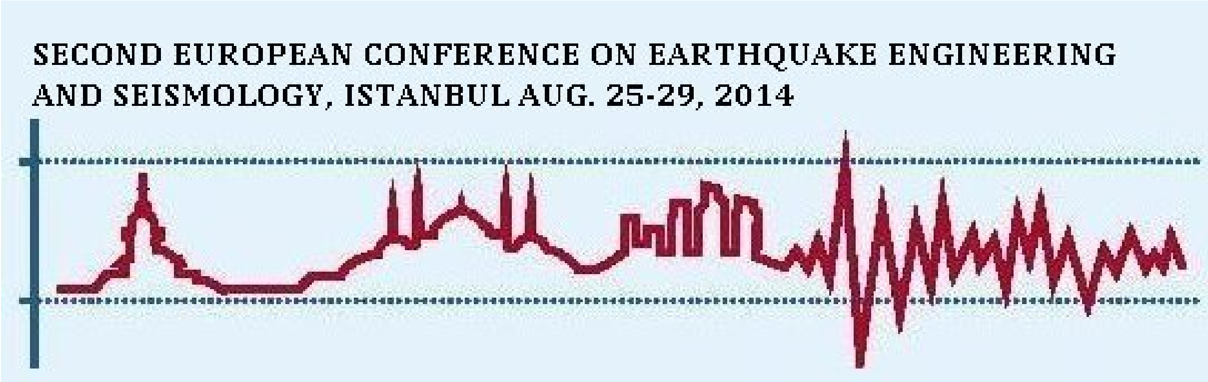

LOVE WAVE DETECTION AS WELL AS RAYLEIGH WAVE FROM MICROTREMOR ARRAY MEASUREMENTS

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ABSTRACT

Kochi city, located in southwestern Japan, is severely threatened by historically repeating large earthquakes that occur along the Nankai Trough. In a recent study (Ohori et al., 2013), to achieve more detailed seismic hazard assessment in Kochi city, we constructed a shallow underground structure model of the city covering an area 10.5 km east–west by 5.5 km north–south with a resolution of 125 m. During the study mentioned above, we deployed, in Takasu area in Kochi city, 8 sets of three-component portable seismometers to create two circular arrays with radii of 50 m and 100 m. We obtained, from the microtremor array recordings in November 2010, the dispersion characteristics of both Love waves and Rayleigh waves in a frequency range between 1.2 and 3.8 Hz. These were analyzed using two kinds of frequency-wavenumber (FK) spectral methods: Capon's technique (1969) applied to the vertical components and Saito's approach (2007) to the horizontal components. To better understand the characteristics of microtremors in the target area and to obtain surface wave dispersive characteristics in a higher frequency range (up to 6 Hz), we conducted additional measurements in March 2013 using smaller circular arrays. We used 4 sets of three-component portable seismometers with a radius varying step-by-step from 50 m to 25 m to 12.5 m. We applied the spatial autocorrelation (SPAC) method, Yamamoto's technique (2000) to the same data and compared the estimated phase velocity results with those from the FK spectral method. The SPAC analyses showed that the energy power ratio of Love-waves in horizontal components were within 40-70% in a frequency range between 1.4 to 6 Hz. In this paper, we note a short description about results derived from the first microtremor array measurements at Takasu area, and report the details about results from the second measurements.

INTRODUCTION

Subduction of the Philippine Sea plate beneath the overlying Eurasian plate has induced Magnitude 8 class mega-thrust repeating earthquakes along the Nankai trough and caused widespread damages especially in western Japan (Tsuji, 2003). The Long-Term Evaluations of the Earthquake Research Committee, The Headquarters for Earthquake Research Promotion of Japan (2012), reported high

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occurrence probability within the next 30 years (as of January 1, 2011) with 87% for the Tokai earthquake, 70% for the Tonankai earthquake, and 60% for the Nankai earthquake. Moreover, studies on histroical earthquakes revealed that these mega-thrust earthquakes might occur as a seismic linkage (Tsuji, 2003). To understand the possibility of seismic linkage and re-occurrence of these earthquakes, large-scaled research projects sponsored by Ministry of Education, Culture, Sports, Science and Technology, Japan have been continuously conducted, i.e. Special Project for Earthquake Disaster Mitigation in Urban Areas (2002-2006), Research for the Tonankai and Nankai earthquakes (2003-2007) and the Project for Seismic Linkage for Tokai, Tonankai and Nankai earthquakes (2008-2012), and so on.

Kochi City is one of representive regional-class cites in southwestern Japan (Fig.1a) and it is severely threatened by historically repeating large earthquakes that occur along the Nankai Trough. Therefore, the disaster mitigation measures against the next large earthquake must be accelerated in Kochi City. Concerned with the the Project for Seismic Linkage for Tokai, Tonankai and Nankai earthquakes (2008-2012) mentioned above, to achieve more detailed seismic hazard assessment in Kochi city, we constructed a shallow underground structure model of the city covering an area 10.5 km east–west by 5.5 km north–south with a resolution of 125 m (Ohori et al., 2013). During the study, we deployed, in Takasu area in Kochi city (Fig.1b), 8 sets of three-component portable seismometers to create two circular arrays with radii of 50 m and 100 m. We obtained, from the microtremor array recordings in November 2010, the dispersion characteristics of both Love waves and Rayleigh waves in a frequency range between 1.2 and 3.8 Hz. These were analyzed using two kinds of frequency-wavenumber (FK) spectral methods: Capon's technique (1969) applied to the vertical components and Saito's approach (2007) to the horizontal components. It should be noted that the cases in which Love-waves were successfully detected are still very few in previous studies in comparison with Rayleigh-waves.

To better understand the characteristics of microtremors in the target area and to obtain surface wave dispersive characteristics in a higher frequency range (up to 6 Hz), we conducted additional measurements in March 2013 using smaller circular arrays. We used 4 sets of three-component portable seismometers with a radius varying step-by-step from 50 m to 25 m to 12.5 m. We applied the spatial autocorrelation (SPAC) method, Yamamoto's technique (2000) to the same data and compared the estimated phase velocity results with those from the FK spectral method. In this paper, we note a short description about results derived from the first microtremor array measurements at Takasu area, and report the details about results from the second measurements.

MIRCROTREMOR ARRAY MEASUREMENTS AND ANALYSES

The 1st Measurements

In November 2010, we carried our our first microtremor array measurements in Takasu area in Kochi city (Fig1b). We deployed 8 sets of three-component portable seismometers to create two circular arrays with radii of 50 m and 100 m (as seen in Fig.2). Also, centers of two arrays had to be located at 25 m separate from each other. The target area was used as mainly agricultural land and seismomters had to be placed on agricultral roads. Fortunetely, we had no possible sources inside the array but we sometimes had unexpected vehicles, bicycles, and persons passing close to some seismometers. As seen in Fig.1b, outside the array, there were a hospital, a filtration plant, a hotel, and factories inside an industrial park, and two heavy traffic road: one running from sourth to north and the other from south-west to north-east. Each portable seismometer set used in measurements was owned by the Earthquake Research Institute, the University of Tokyo, and composed of three-component sensors of JEP-6A3 (Mitsutoyo Corp.) and a 24bit datalogger of DATAMARK LS-7000XT (Hakusan Corp.). Two array measurements were carried out simultaneously. The recording length was 30 minuntes with a sampling frequency of 100 Hz.

The procedure to calculate the cross spectrum, which was used commnly in analyses of both FK method and SPAC method, was almost the same as in Ohori e al. (2002). For analytical convenience, the data were divided into three sets, comprising thtree data sets containing 600 sec. Each data set included 60,000 data points. In calculating the cross spectrum, each data set was divided again into 10 segments of 6,000 data points (60 sec) and transformed into the frequency domain with

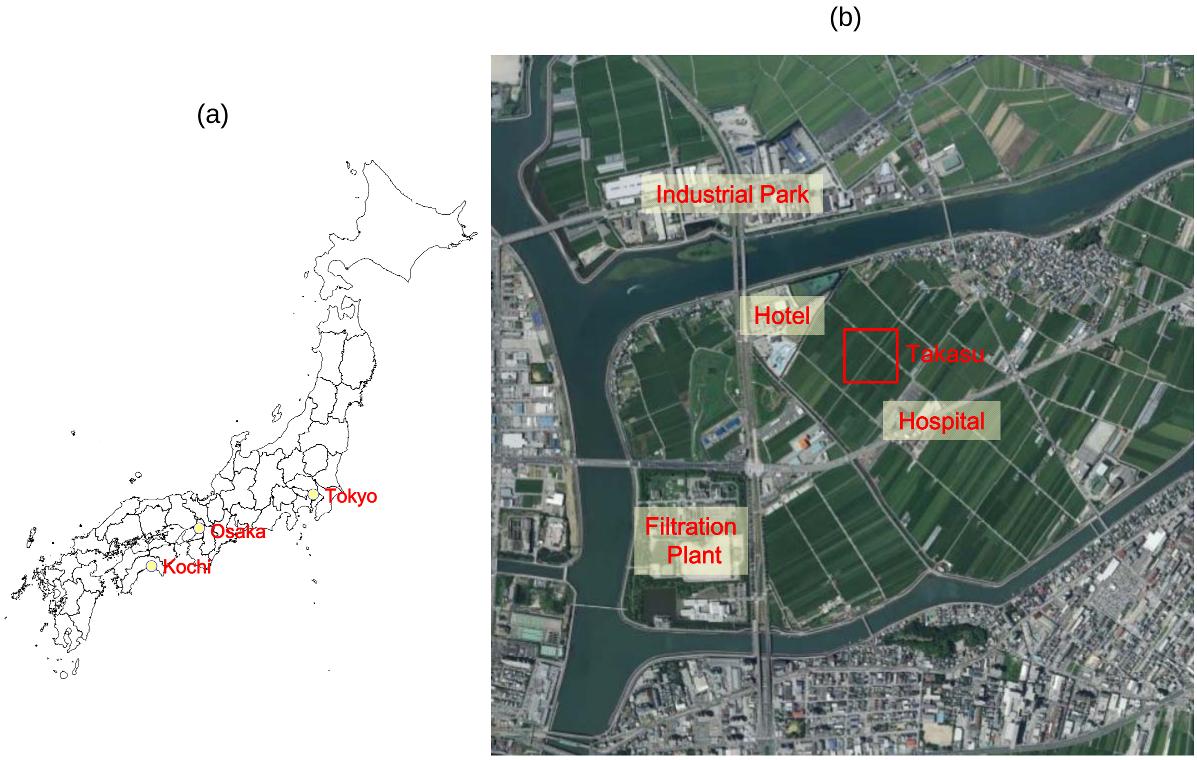

Figure 1. Map showing the location of Kochi City in Japan (a) and target area, Takasu in Kochi City and its surrounding area (b).

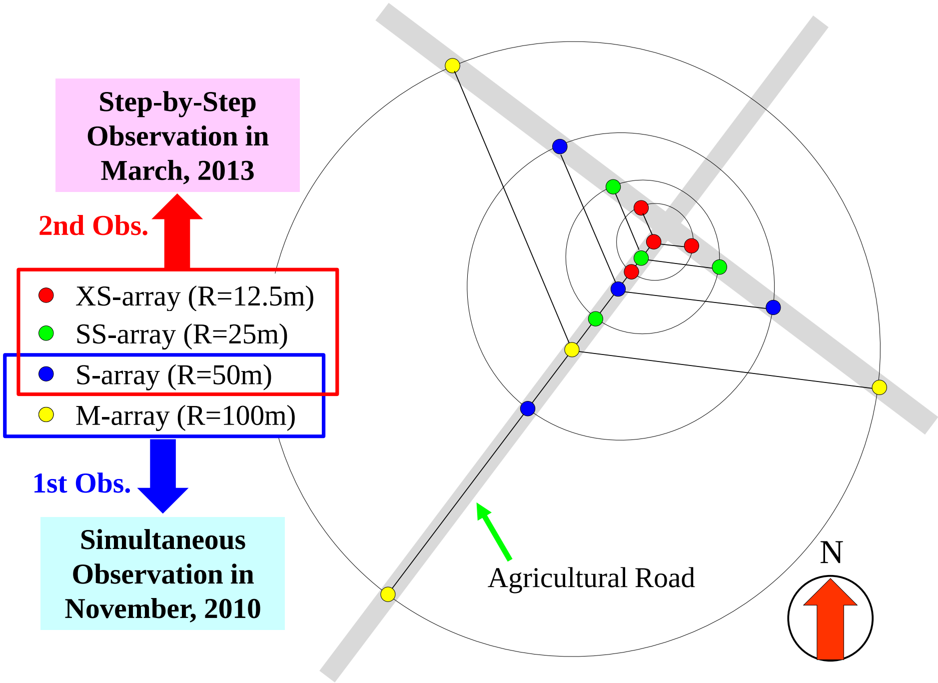

Figure. 2 Map showing sensor location of circular-array configurations. Radii of four circles are 12.5 m, 25 m, 50 m and 100 m, respectively.

the fast Fourier transform after making the total data points up to 8,192 with null data addition. The cross spectrum for each segment was obtained and smoothed by a Parzen window with a width of 0.2Hz. Then the normalized cross spectrum between the *l* th and *n* th seismometers for each data set was calculated as below:

$$S_{ln}(f) = \frac{\frac{1}{M}\sum_{m=1}^{M} {}_{m}S_{ln}(f)}{\sqrt{\frac{1}{M^2}\sum_{m=1}^{M} {}_{m}S_{ll}(f)\sum_{m=1}^{M} {}_{m}S_{nn}(f)}} \qquad (1)$$

where f is the frequency (in Hz), ${}_{m}S_{ln}(f)$ is the cross spectrum for the m th segment, and M is the total number of segments (10 segments in present study). This procedure is based on the direct segment method (Capon, 1969). Other conditions were tested, but no significant differences were found in the obtained phase velocities. Our records included some noise from different sources, such as accidentally passing vehicles, bicycles, and persons close to some seismometers, traffic noise from two surrounding heavy traffic roads in south direction and west direction from the area, and so on. As stated by Ohori et al. (2002), in the case of short period microtremors, it is difficult to recognize by sight which part of the waveform is good or bad, so we used all of the data for the phase-velocity calculation.

The surface wave dispersion charactersitics were analyzed with two kinds of the frequency-wavenumber (FK) spectral methods: Capon's technique (1969) applied to the vertical components and Saito's approach (2007) to the horizontal components. In Fig.3, phase velocities estimated from vertical components are shown with solid circles, and those from transverse-components are with solid triangles. In Fig.3b, we show only the shallower part of the S-wave velocity structure beneath the Takasu area, which was extracted from our constructed model (Ohori et al., 2003). This model was connected at the bottom with the deep velocity structure model proposed by the Central Disaster Manegement Council of Japan (2003). Using this model, we calculated theoretical phase velocities of the fundamental-mode Rayleigh-wave and Love-wave and plotted them in Fig.3a with solid lines. The minimum wavelength detected from the array is considered to be more than twice of the minimum sensor distance, and in this case it is corresponding to 50 m as shown with dotted line in Fig.3. We, therefore, considered that we obtained the dispersion characteristics of both Rayleigh-waves and Love-waves in a frequency range between 1.2 and 3.8 Hz. As shown in Fig.3a, observed results from vertical components agree well with the theoretical Rayleigh-wave phase velocities. Also, observed results from transverse components agree well with the theoretial Love-wave phase velocities.

In Fig.4, we show example FK spectra of 1.8 Hz derived from both vertical component and transverse one. Contours of the log-normalized FK spectrum [-10log(P(f,k)/P(f,kpeak))] for each spectrum are drawn in steps of 1 dB. A circle and a straight line denote the corresponding peak velocity and azimuth, respectively, for the wavenumber vector at the peak spectrum amplitude. The FK spectrum from vertical component in Fig.4a resoves the wave propagetion from south-west direction. On the other hand, the FK spectrum from transverse component in Fig.4b resolves several peaks: the largest peak found in north-west direction, and the second one in south-west. These peak directions may imply that waves propagating to the array were excited by some possible sources, such as traffic loads near road crossings along two heavy traffic roads, human activites at the hotel located in north-west direction, machinary noises from the filtration plant in south-west direction and machinary noises from the industrial park in north-west direction.

The 2nd Measurements in 2013

To better understand the characteristics of microtremors in the target area and to obtain surface wave dispersive characteristics in a higher frequency range (up to 6 Hz), we conducted the 2nd measurements in March 2013 using smaller circular arrays. We used 4 sets of three-component portable seismometers with a radius varying step-by-step from 50 m to 25 m to 12.5 m (as seen in Fig.2). Each portable seismometer set, owned by the Natioal Research Institute of Earth Science and Disaster Prevention, was composed of three-component sensors of JA-40GA04 (Japan Aviation Electronics Industry,Ltd.) and a 24bit datalogger of DATAMARK LS-7000XT mentioned above. The

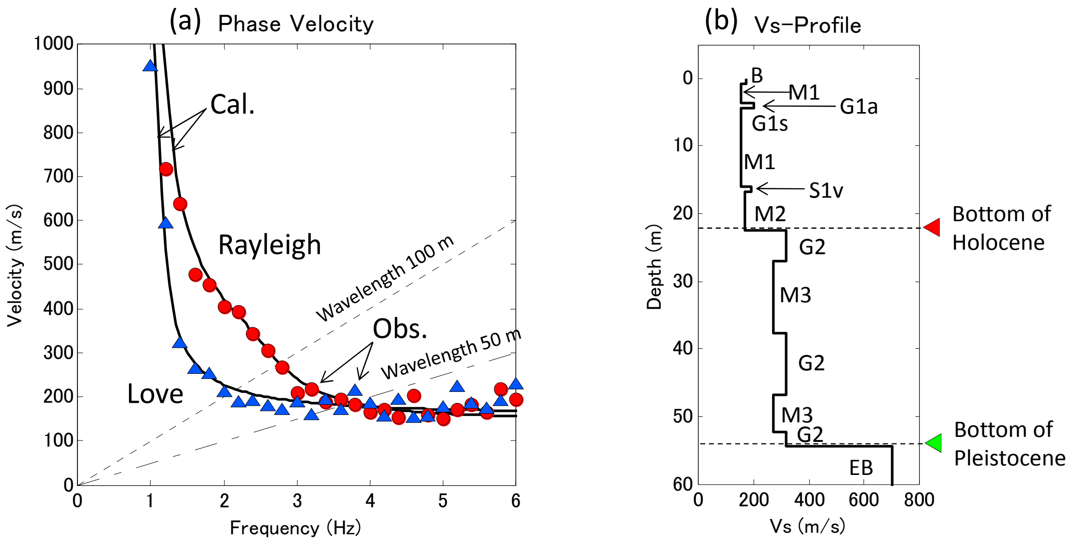

Figure. 3 Phase velocity results (a) comparing the observed data and calculated one based on the proposed S-wave velocity model (b) [After Ohori et al. (2013)]. Note that the deep strucutue model by the Central Disaster Management Council of Japan (2003) is connected with the bottom of this model.

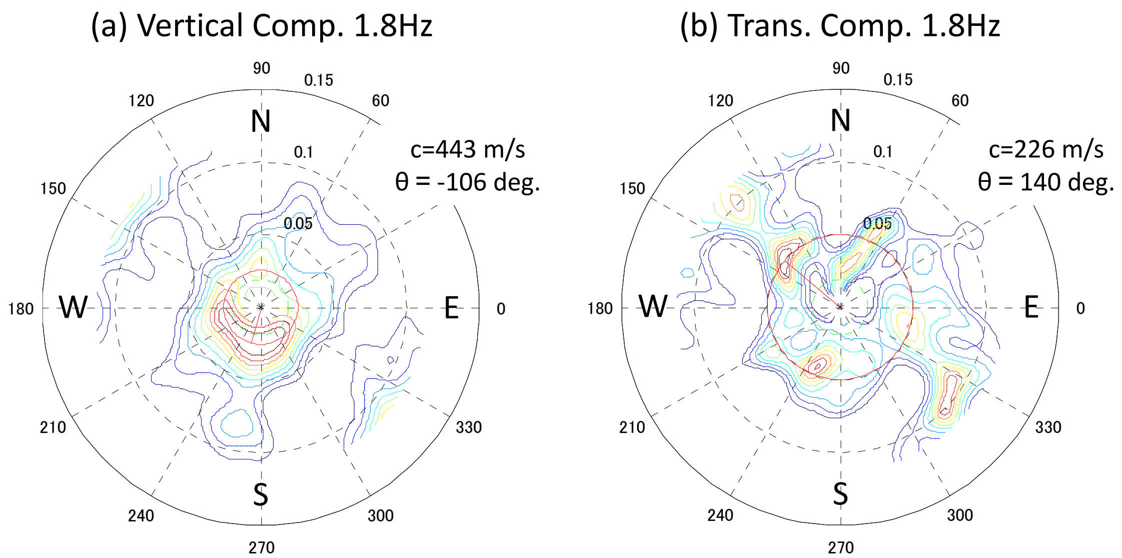

Figure. 4 Example FK spectra from vertical-component (a) and transverse-component (b) during the 1st measurements.

recording length was 30 minuntes with a sampling frequency of 100 Hz. Analytical procedure to derive the cross spectrum was the same as those for the data of the 1st measurements.

First, we analyzed the vertical componetns with the FK method of Capon (1969) to estimate the Rayleigh-wave phase velocity. In Fig.5, esitmated phase velocities and arrival directions from vertical components are plotted. Also, we analyzed the transverse componetns with the FK method of Saito (2007) to estimate the Love-wave phase velocity. In Fig.6, esitmated phase velocities and arrival directions from transverse components are plotted. In Figs. 5a and 6a, theoretical phase velocity of the Rayleigh- and Love-waves were plotted with solid lines. The minimum wavelength, which the smallest array can detect, is 25 m as plotted with dotted lines in these figures. As seen in Fig.5a, observed phase velocity results from vertical components are well coincident with the theoretical

Rayleigh-wave phase velocity. On the other hand, observed phase velocity results from transverse components are less, but to some extent they agree with the theoretical Love-wave phase velocities.

From Fig.5b, vertical components seemed to compose of waves propagating from various directions, but a cluster of arrival direction is found in south west direction between 2 and 5 Hz. From Fig.6b, a cluster of arrival direction is found in south east direction between 1.4 and 2.6 Hz. In Fig.7, we show example FK spectra of 1.8 Hz derived from both vertical component and transverse one. The FK spectrum from both components resoves the wave propagetion from south-east direction with different velocities. Compared with the FK spectra from the 1st mesurements in Fig.4, results from the 2nd measurements are different in arrival directions but comparable in phase velocities.

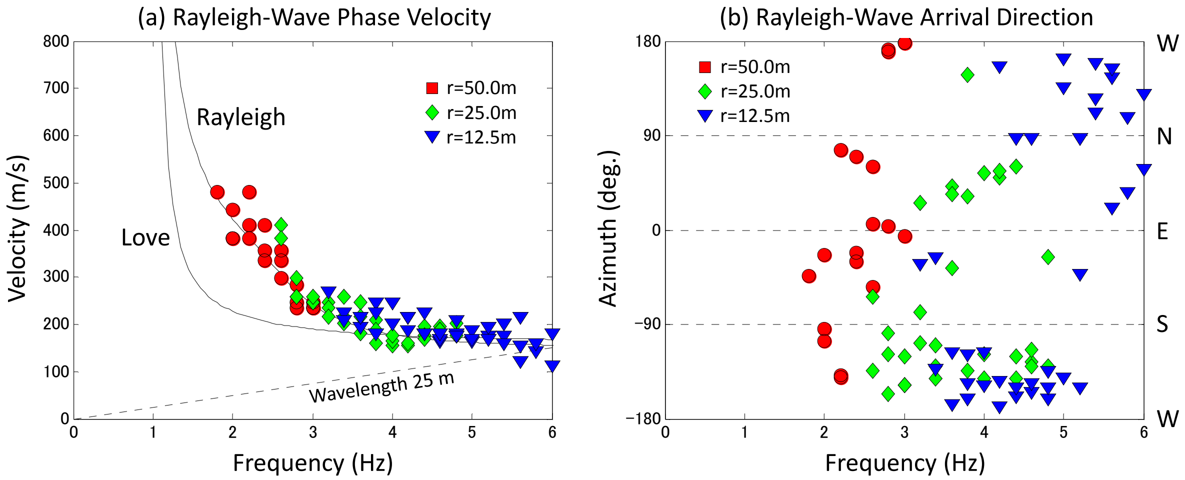

Figure. 5 Results of FK spectral method for vertical components obtained from data during the 2nd measurements. Phase velocity and arrival direction are plotted in (a) and (b), respectively.

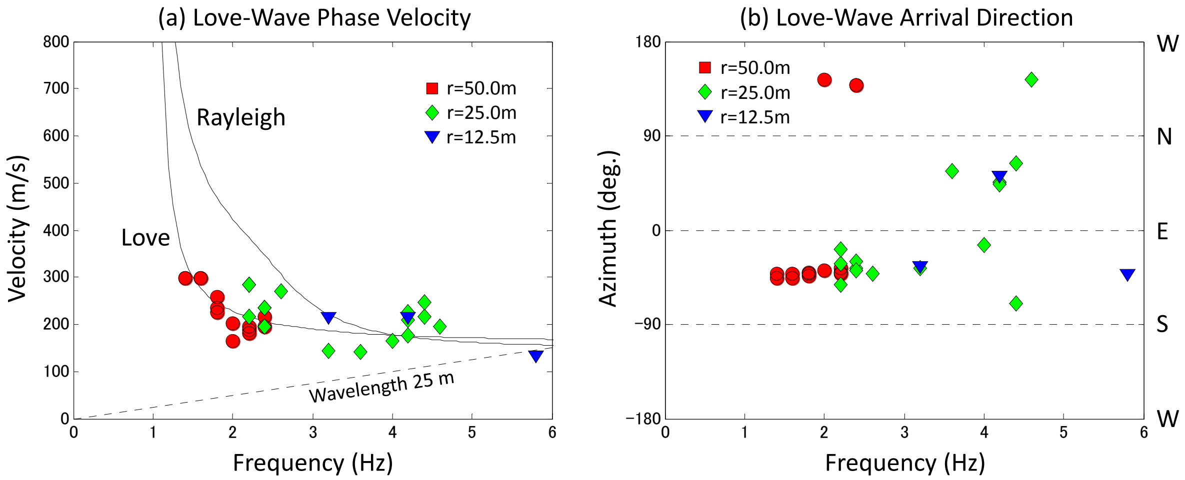

Figure. 6 The same as in Fig.5 but for transverse components.

Next, we analyzed the vertical componetns with use of the SPAC method of Yamamoto (2000) to estimate the Rayleigh-wave phase velocity. In Fig.8a, esitmated phase velocities are plotted together with theoretical ones of Rayleigh–waves. Also, we analyzed the transverse componetns with the SPAC method to estimate the Love-wave phase velocity. In Fig.8b, esitmated phase velocities are plotted together with theoretical ones of Love-waves. Figs.8a and 8b were plotted in the same manner as those in Figs.5a and 6a. As seen in Fig.8a, observed phase velocity results from vertical components are well coincident with the theoretical Rayleigh-wave phase velocities.

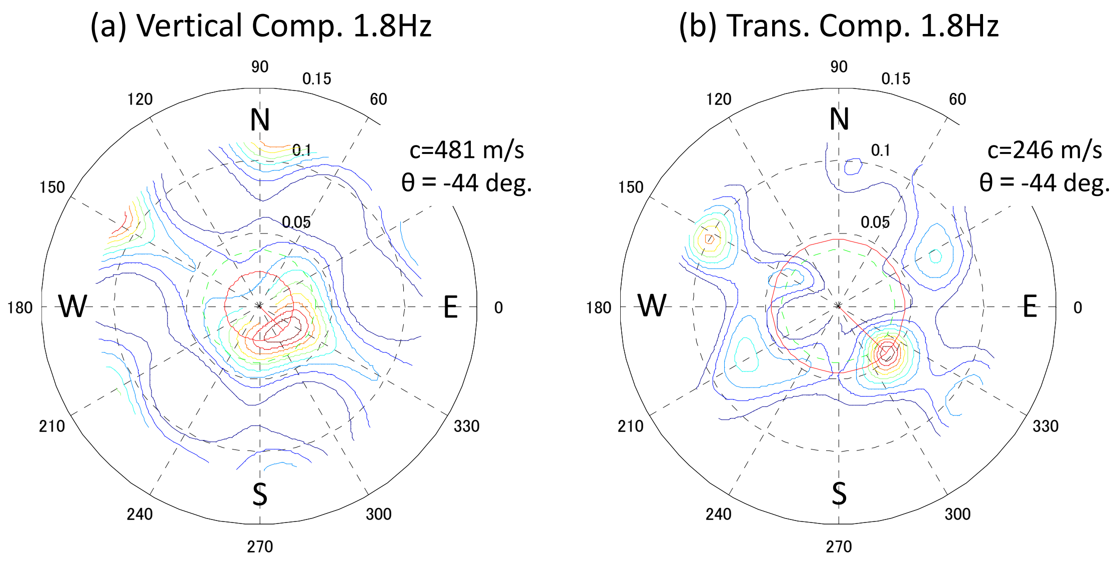

Figure. 7 Example FK spectra from vertical-component (a) and transverse-component (b) during the2nd measurements.

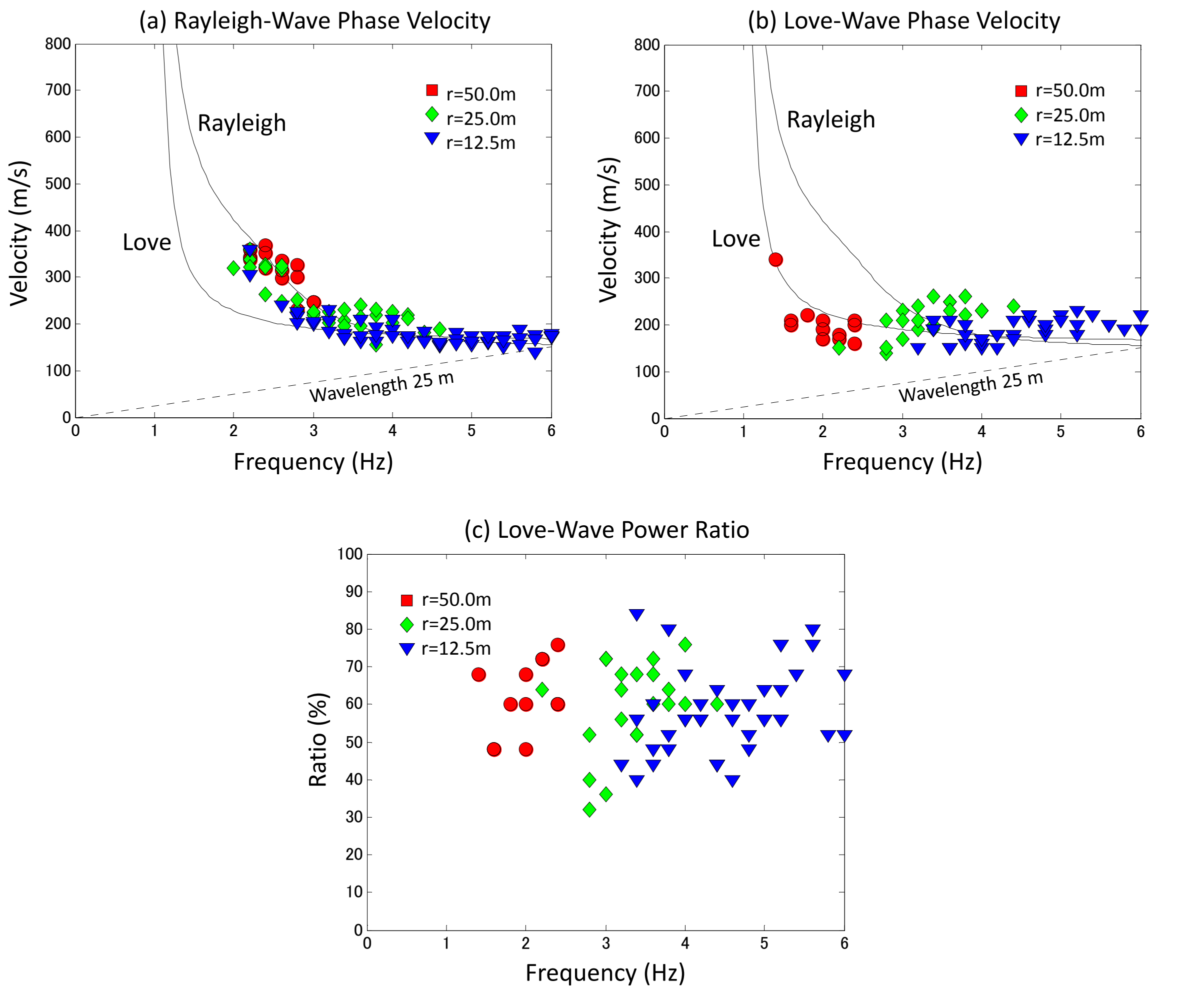

Figure. 8 Results of SPAC method from data obtained during the 2nd measurements. (a) Phase velocities from vertical components, (b) those from transverse components, and (c) Love-wave power ratio against total horizontal components.

On the other hand, observed phase velocity results from transverse components are less, and somehow heigher than theoretical Love-wave phase velocity in a frequency range between 3 and 6 Hz. Comparing the phase velocity results from the FK method in Figs.5a and 6a,and the SPAC method in Figs.8a and 8b, they look similar to each other. Also the SPAC method provides not only phase velocity but also the energy power ratio of Love-waves in horizontal components. In Fig.8c, we show the energy power ratio of Love-waves in horizontal components. Most of data seems to scatter within 40-70% in a frequency range between 1.4 to 6 Hz. This result corresponds to those in previous studies: e.g. 50- 80% in Yamamoto (2000). It may suggest the predominance of Love-waves in horizontal components compared with Rayleigh-waves.

CONCLUSIONS

In Takasu area of Kochi City, we twice conducted the microtremor array measurements and detected the Love-waves as well as the Rayleigh-waves using two representative analytical methods of the array data, the FK method (Capon, 1969; Saito, 2007) and the SPAC method (Yamamoto, 2009). Phase velocities between 1.2 and 6 Hz were derived. The FK method suggested that the the propageting waves to the array might be excited from some possible sources, such as traffic loads, human activity, and machinary noises from outside the array area. The SPAC method showed that the energy power ratio of Love-waves in horizontal components were within 40-70% in a frequency range between 1.4 to 6 Hz.

Finally, we successfuly detect the Love-waev phase velocity as well as the Rayligh-wave phase velocity. We agree that detection of Rayleigh-waves is a necessary solution for estimation of the S-wave velocity structure from microtremor array measurements. But if we detect Love-waves as well as Rayleigh-waves, we can constrain model parameters more than Rayleigh-waves only. In future work, we will try to invert the S-wave velocity with use of estimated phse velocities of both Rayleigh-waves and Love-waves and emphasize the significance of Love-waves in determination of the S-wave velocity structure.

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