USING TWO-STATION MICROTREMOR ARRAY METHOD TO ESTIMATE SHEAR-WAVE VELOCITY PROFILES IN SEATTLE AND OLYMPIA, WASHINGTON

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Abstract

We performed two-station microtremor array measurements (2ST-MAM) at several sites in Seattle and Olympia, Washington. We used three-component broad-band sensors (accelerometers) for microtremor data acquisition with variable station separations ranging from 10 to 3000 meters for each site. We recorded the microtremor data ranging from 10 minutes (for closer separations) to 1 hour (for large separations), with a total of several hours of measurements per site. We used the spatial autocorrelation (SPAC) method to calculate phase velocities from the 2ST-MAM data, and obtained clear dispersion curves between 0.2 to 30 Hz. Maximum phase velocity is about 1500m/s at the frequency of 0.2Hz at downtown of Seattle. A Genetic Algorithm and a non-linear least squares method were used for the inversion, and S-wave velocity profiles down to a depth of several kilometers were estimated in the downtown Seattle area. A low velocity layer with S-wave velocity lower than 600m/s was determined down to a depth of 10m. A velocity layer with S-wave velocity of 700m/s was determined down to a depth of 700m. Bedrock with S-wave velocity higher than 1500m/s was determined at a depth of greater than 2500m. At the Olympia downtown site, a low velocity layer with S-wave velocity less than 400m/s was determined to a depth of 90m and there is a clear velocity boundary at a depth of 90m. Bedrock with S-wave velocity higher than 1000m/s was determined at a depth of about 250m. These preliminary results have shown that using the 2ST-MAM method is applicable to deep and shallow depth-to-bedrock investigations, and provides fast, cost-effective and accurate S-wave velocity estimates.

Introduction

Active and passive surface wave methods have been increasingly getting popular in last 10 years. The passive seismic survey method or microtremor array measurements (Okada, 2003) in which ambient noise is used as surface waves, is particularly attractive because the method does not require any artificial source and the depth of investigation can be increased easily. Large scale microtremor measurements have been widely used in last 10 years in Japan for estimating S-wave velocity structure down to a depth of several kilometers. In these investigations, triangle arrays with size of several kilometers are used for calculating a phase velocity in frequency range from 0.2 to 1Hz. Most people use a spatial autocorrelation (SPAC) method (Aki, 1957) for calculating phase velocities from ambient noise and the method requires at least 4 or 7 sensors placed on center and vertices of triangles. Margaryan et al. (2009) showed that the SPAC using only two sensors yields almost identical phase velocities as one of 4 or 7 sensors on triangles. Recently, Hayashi and Underwood (2012a, 2012b) have shown that S-wave velocity profiles down to a depth of 2 to 3 km can be determined by using two sensors and the SPAC in the South Bay of the San Francisco Bay area. The SPAC using small number of sensors enables us to perform the microtremor array measurements much easily. We have performed the two-station microtremor array measurements (2ST-MAM) at several sites in Seattle and Olympia, Washington. Main

Figure 1: Sites of investigation.

purposes of measurements are evaluating the applicability of the 2ST-MAM to deep and shallow depth-to-bedrock investigations in the area.

Data Acquisition and Processing

Data acquisition

The two-station microtremor array measurements (2ST-MAM) have been performed at three sites in Seattle and two sites in Olympia. Figure 1 shows location of investigation sites. At each site, one seismograph was fixed at one place and data was acquired at that location for the entire survey. Data was acquired by a second seismograph at larger separations ranging from 10 to 3102m. Table 1 summarizes the locations and separations of seismographs for each site. In each measurement, 10 to 60 minutes ambient noise was recorded. As the separation of seismographs increased, the record length of ambient noise was increased. The sampling interval used was 10msec. Figure 2 shows an example of array configuration from the Denny Park (048) placed at the downtown Seattle. Data acquisition was performed in the night-time at the downtown Seattle and the day-time at other sites. Seismographs were placed in relatively quiet places such as in parks or residential areas.

Two seismographs (McSEIS-MT Neo), three-component accelerometers, manufactured by OYO Corporation were used for data acquisition. The seismographs include GPS clock and two seismographs were synchronized in any distance by using attached the GPS clock.

Table.1 Locations and separations of the two seismographs for each measurement site.

No.	Site name	Location (degree)		Separations (m)
		Latitude	Longitude	
048	Denny Park (Seattle)	47.619598	-122.340042	10,20,40,80,100,150,200,250,300, 400, 500,702,1116,1968,2547,3102
049	Alki (Seattle)	47.575977	-122.41642	10,20,40,80,160,320,640,968
050	Hiwatha Park (Seattle)	47.578232	-122.383667	10,20,40,80,160,344,677
051	Centennial Park (Olympia)	47.038425	-122.898415	8,16,27,54,75,128,200
052	Regional Athletic Park (Olympia)	47.044806	-122.756677	10,20,40,80,160,330,567,1060,1743

Figure 2: Example of array configuration (048 : Denny Park).

Processing

Recorded data was divided into several blocks with overwraps in data processing. Each block consists of 8192 samples with a data length of 81.92 seconds. Several blocks including nonstationary noise were rejected before following processing. If $f(i,t)$ and $g(i,t)$ are two traces of i_{th} block obtained at two receivers with separation Δx, then Fast Fourier Transform (FFT) of these two functions (wave forms) for each block can be expressed in frequency domain as $f(i,\omega)$ and $g(i,\omega)$. Therefore, complex Coherence COH for i_{th} block is calculated as

$$COH_{fg}(i,\omega) = \frac{CC_{fg}(i,\omega)}{A_f(i,\omega)A_g(i,\omega)} \tag{1}$$

where $CC_{fg}(i,\omega)$ is cross-correlation of two traces $f(i,\omega)$ and $g(i,\omega)$. $A_f(i,\omega)$ and $A_g(i,\omega)$ are autocorrelation of $f(i,\omega)$ and $g(i,\omega)$, respectively. The special autocorrelation $SPAC$ is defined as a real part of the averaged complex coherences:

$$SPAC(\Delta x,\omega) = \sum_{i=1}^{n} \mathrm{Re}\left(COH_{fg}(i,\omega)\right) \tag{2}$$

where n denotes the number of blocks. Coherence (COH) was calculated by each block then all blocks of real part were averaged as the SPAC. Ten to one hundred blocks are averaged for calculating final SPAC. If we assume that microtremor propagates all direction equally, the SPAC forms a Bessel function (Aki, 1957)

$$SPAC(\Delta x,\omega) = J_0\left(\frac{\omega}{c(\omega)}\Delta x\right). \tag{3}$$

where, $c(\omega)$ is phase velocity at angular frequency ω and J_0 is the first kind and zero order of the Bessel function. The velocity that minimize error in equation (3) can be considered as the phase velocity at the angular frequency ω.

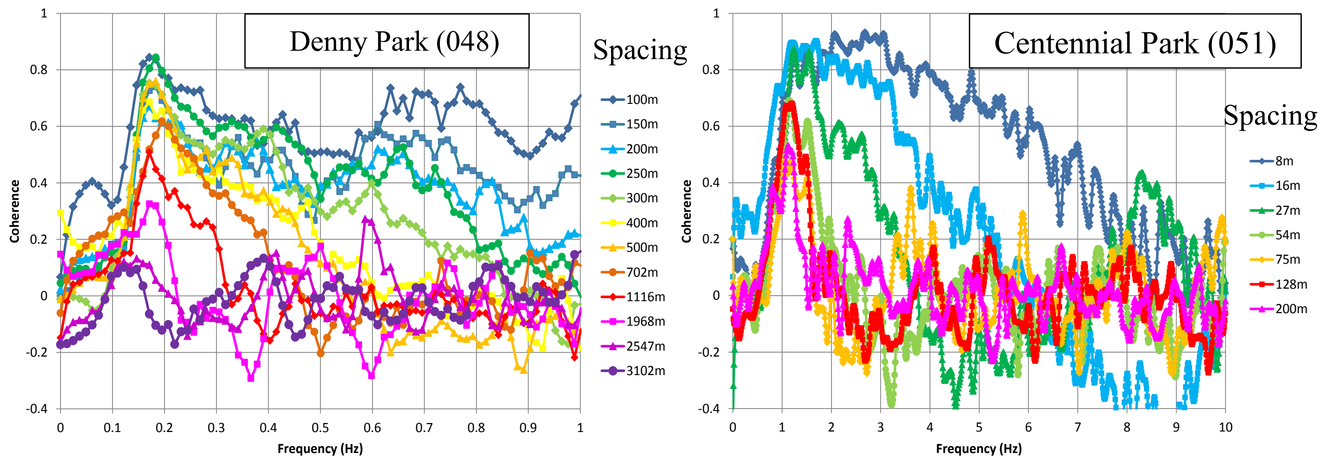
Dispersion Curves and S-wave Velocity Profiles

Example of spatial autocorrelation

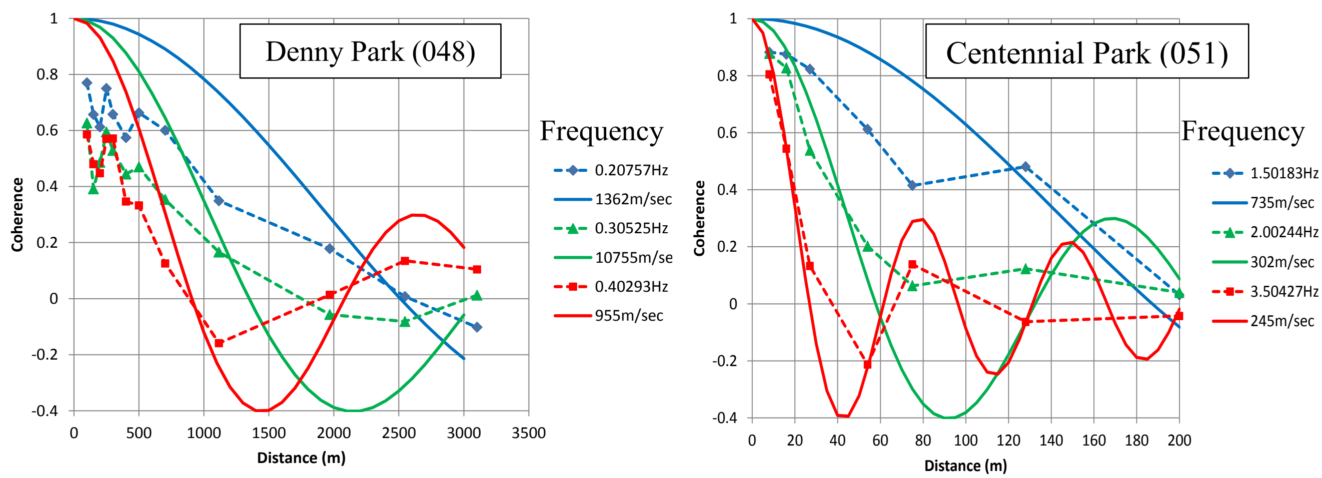
Figure 3 shows an example of spatial autocorrelations at the Denny Park (048) (downtown Seattle) and the Centennial Park (051) (downtown Olympia). The Denny Park is the example of deep (down to several kilometers) bedrock investigation, whereas Centennial Park is shallow (down to several 10s meters). Figure 3a shows frequency-dependent coherences whose spacing is larger than 100m (Denny Park) and all coherences (Centennial Park). It can be clearly seen that coherences have a clear distinction associated with the spacing of seismographs.

Figure 3b shows typical coherences as a function of distance (spacing of seismographs) with theoretical Bessel functions calculated for phase velocities that yield minimum error between the observed coherence and the theoretical Bessel function. In Figure 3b, broken lines and symbols indicate observed coherences and solid lines indicate theoretical Bessel functions. We can see that observed coherences and the theoretical Bessel functions agree well.

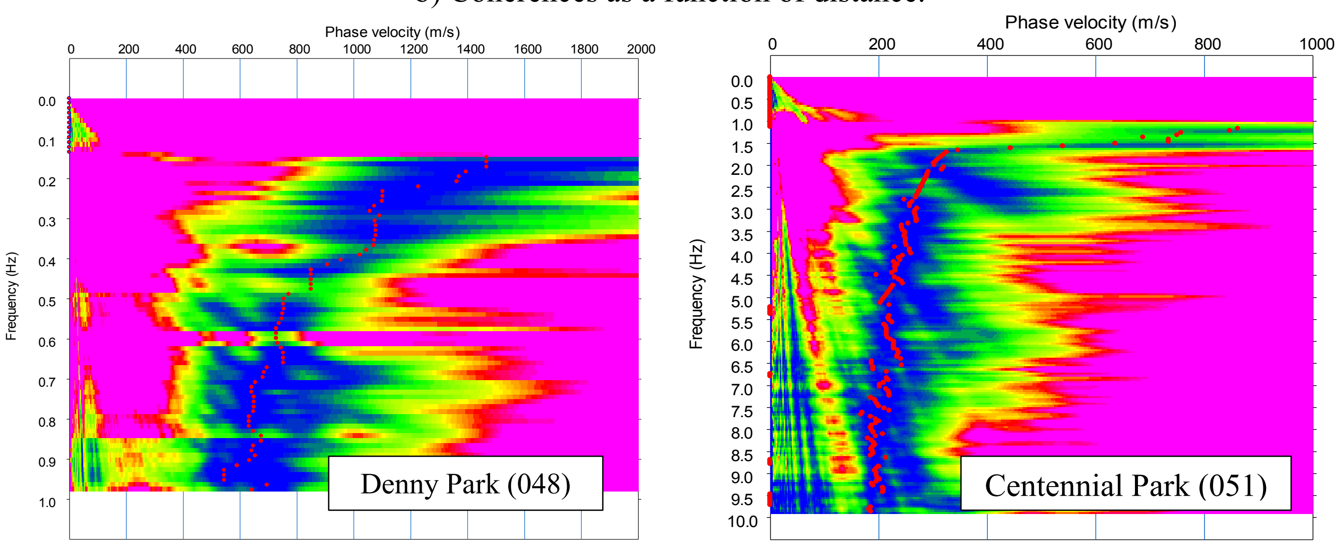
Figure 3c shows error between observed coherences and theoretical Bessel functions. The red color indicates large error and the blue color indicates small error. Red dots indicate minimum error phase velocities at each frequency and they can be considered as observed dispersion curves. Clear dispersion curves can be recognized in frequency range from 0.1 to 1.0 Hz at the Denny Park (048) and



a) Coherences as a function of frequency.



b) Coherences as a function of distance.



c) Error between observed coherences and theoretical Bessel functions.

Figure 3: Example of spatial autocorrelation (a and b) and phase velocity images (c) at the Denny Park (left) and the Centennial Park (right).

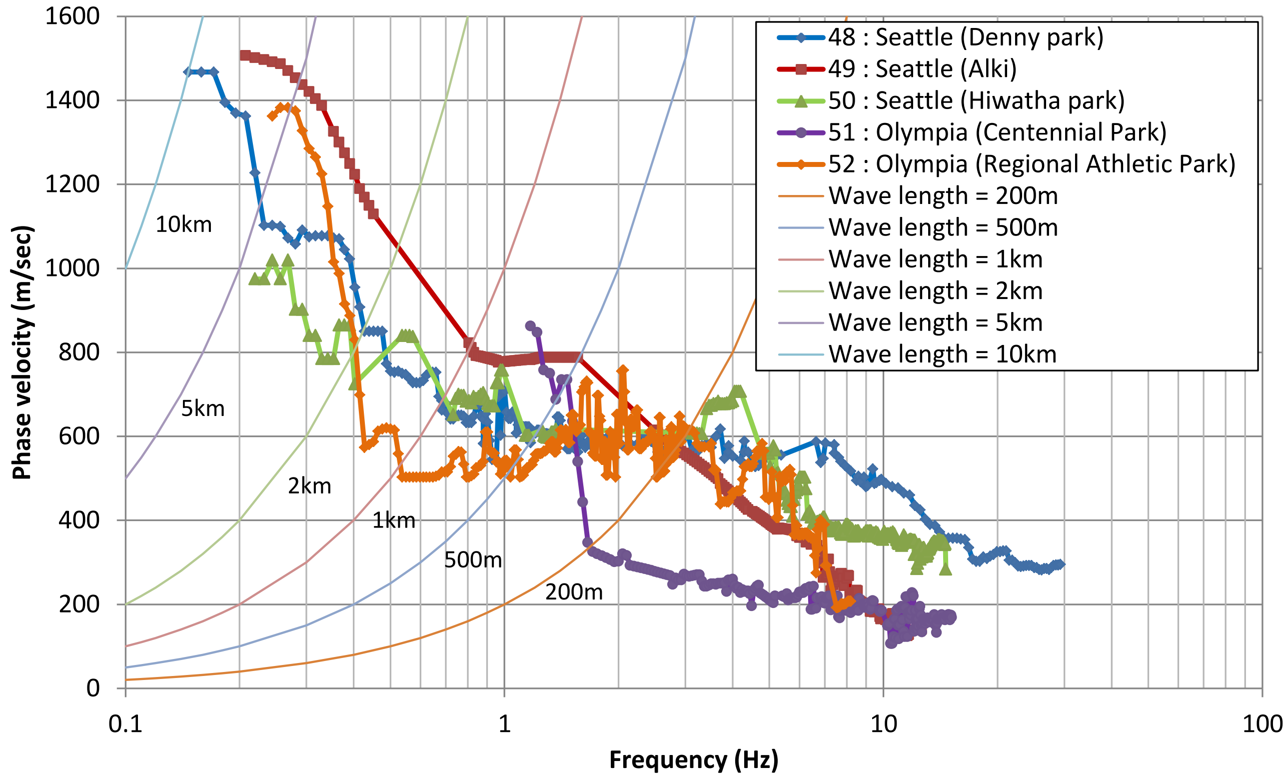


Figure 4: Comparison of observed dispersion curves.

from 1.0 to 10Hz at the Centennial Park (051) sites.

We note from Figure 3 that clear changes of coherences and phase velocities are observed in the frequency range from 0.2 to 0.5Hz at the Denny Park (048) and from 1 to 4Hz at the Centennial Park (051). These changes correspond to deep (Denny Park) and shallow (Centennial Park) bedrocks respectively. As mentioned before, the Denny Park and the Centennial Park are typical examples of deep (several kilometers) and shallow (several 10s of meters) bedrock investigations. The results imply that the applicability of the 2ST-MAM to both deep and shallow bedrock investigations.

***Dispersion Curve*s**

Figure 4 shows comparison of dispersion curves obtained by the 2ST-MAM at five sites. At all sites, phase velocities were obtained at the frequency range from 1.2 to 8Hz. We estimated phase velocities, except for Centennial Park (051) site, down to a frequency of 0.2Hz, with maximum frequencies varying from 8 to 30Hz.

At Denny Park (048), Alki (049), and Regional Athletic Park (052) sites, the longest wave lengths associated with observed phase velocities are longer than 5 km and they may include information on the S-wave velocity structures to a depth of 2 to 3km. The maximum phase velocities at these sites are about 1400m/sec and it implies that S-wave velocities at the depth of 2 to 3km are higher than 1400m/sec. In general, the longest wave length obtained through the SPAC is 2 to 4 time of receiver separation. The maximum receiver separations of these sites are 3102m, 968m and 1743m respectively. It is quite reasonable that the maximum wave lengths are 5 to 10 km at these sites.

At Hiwatha (050) and Centennial Park (051) sites, the longest wave lengths are about 4km and

700m respectively and they may include the information of S-wave velocity structure to a depth of 1km and several hundred meters, respectively.

If we pay attention to the frequency range from 0.4 to 0.8Hz, the phase velocities of the Regional Athletic Park (052) are slower than those of other sites. The frequency range from 2 to 6Hz, the phase velocities of the Centennial Park (051) are much slower than those of other sites.

Inversion

A joint inversion (Suzuki and Yamanaka, 2010) was applied to the observed dispersion curves, and S-wave velocity profiles were analyzed for five sites. In the inversion, phase velocities of the dispersion curves were used as observation data. The unknown parameters were layer thickness and S-wave velocity. A Genetic Algorithm (Yamanaka and Ishida, 1995) was used for optimization. Search area of the inversion were determined from initial velocity models created by a simple wavelength transformation in which wavelength calculated from phase velocity and frequency is divided by three and plotted at depth. Theoretical phase velocity were defined as an effective mode that generated by calculating the weighted average of the fundamental mode and higher modes (up to the 20nd mode) based on medium response. The inversion was performed based on minimization of difference between the observed and the effective mode phase velocities.

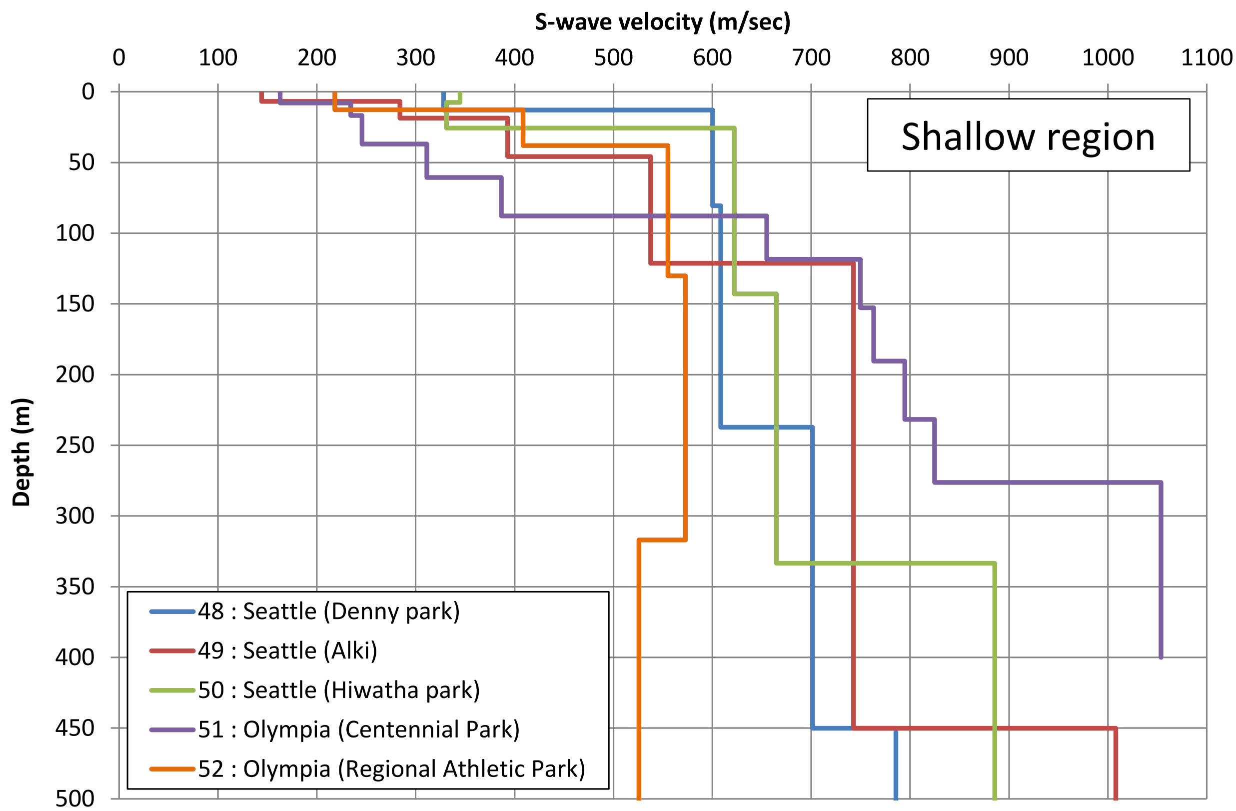
S-wave velocity profiles

Figure 5 shows comparison of S-wave velocity profiles in shallow (top) and deep (bottom) region obtained by the inversion. At the Denny Park (048), the Alki (049), and the Regional Athletic Park (052) sites, S-wave velocity profiles down to a depth greater than 2000m were determined. At the Hiwatha (050) and the Centennial Park (051) sites, S-wave velocity profiles were only determined down to depths of 1000m and 400m respectively. Shallow penetration depth of these sites is due to a lack of large separation measurement.

At the Denny Park (048) (downtown Seattle area), S-wave velocity profiles down to a 3km depth were estimated. A low velocity layer with S-wave velocity less than 600m/s was determined down to 10m. A velocity layer with S-wave velocity of 700m/s was determined down to 700m. Bedrock with S-wave velocity higher than 1500m/s was determined at depth greater than 2500m. At the Alki (049), S-wave velocity deeper than a depth of 500m is clearly higher than that of the Denny Park (048). It is well known that there is a deep tectonic basin in the downtown Seattle area (Frankel et al., 2009). The deep bedrock at the Denny Park (048) corresponds to the tectonic basin in the downtown Seattle area.

At Centennial Park (051) site located in downtown Olympia, a low velocity layer with S-wave velocity less than 400m/s was determined to a depth of 90m and there is a clear velocity boundary at a depth of 90m. S-wave velocity shallower than a depth of 90m is clearly slower compare with other four sites. This low velocity layer may correspond to a varied Quaternary channel filled with unconsolidated soils (Walsh et al, 2003). Bedrock with S-wave velocity higher than 1000m/s was determined at a depth of about 250m. At the Regional Athletic Park (052) placed at the east of the downtown Olympia, S-wave velocity at the depth range from 40 to 600m was approximately 550m/s and clearly slower than other sites in Seattle area. S-wave velocity deeper than a depth of 900m is higher than the Denny Park (048) and Alki (049) in Seattle.

Figure 6 shows examples of comparison of observed and theoretical dispersion curves. Yellow circles indicate the effective mode of theoretical phase velocities that generated by calculating the weighted average of the fundamental mode and higher modes (up to the 20th mode) based on medium



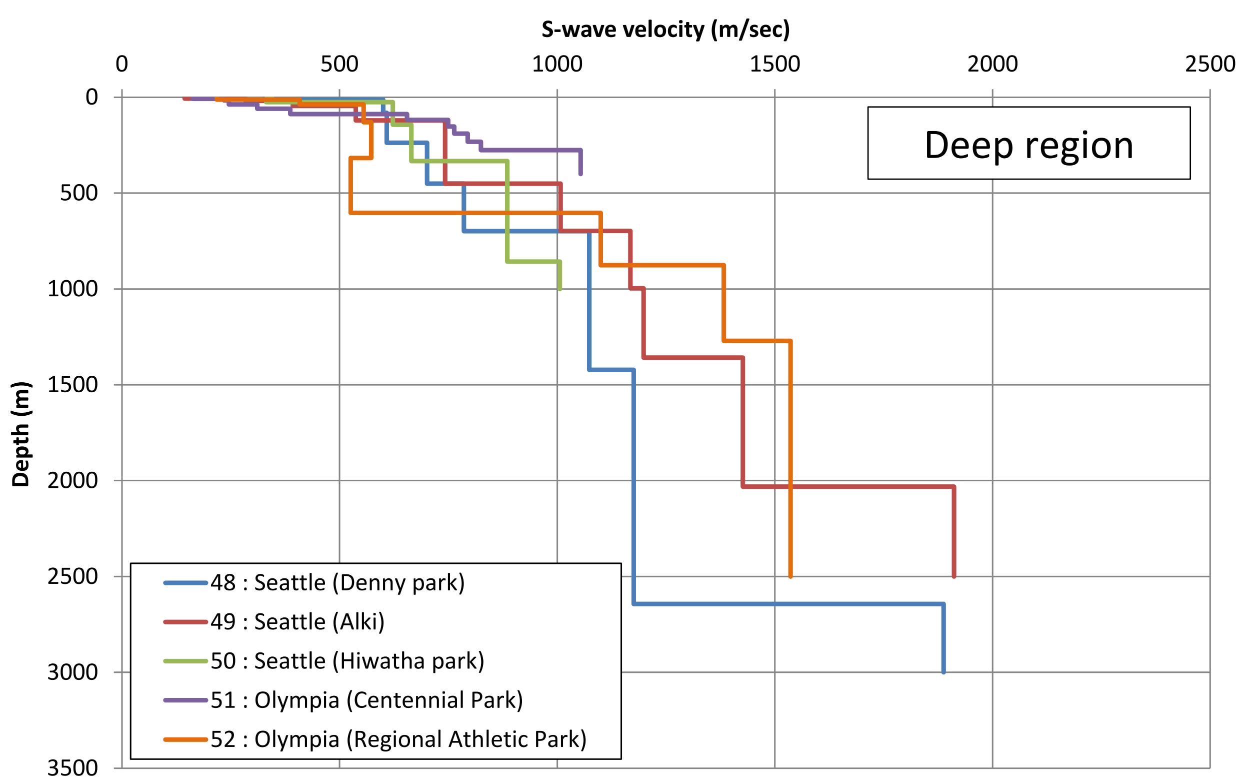
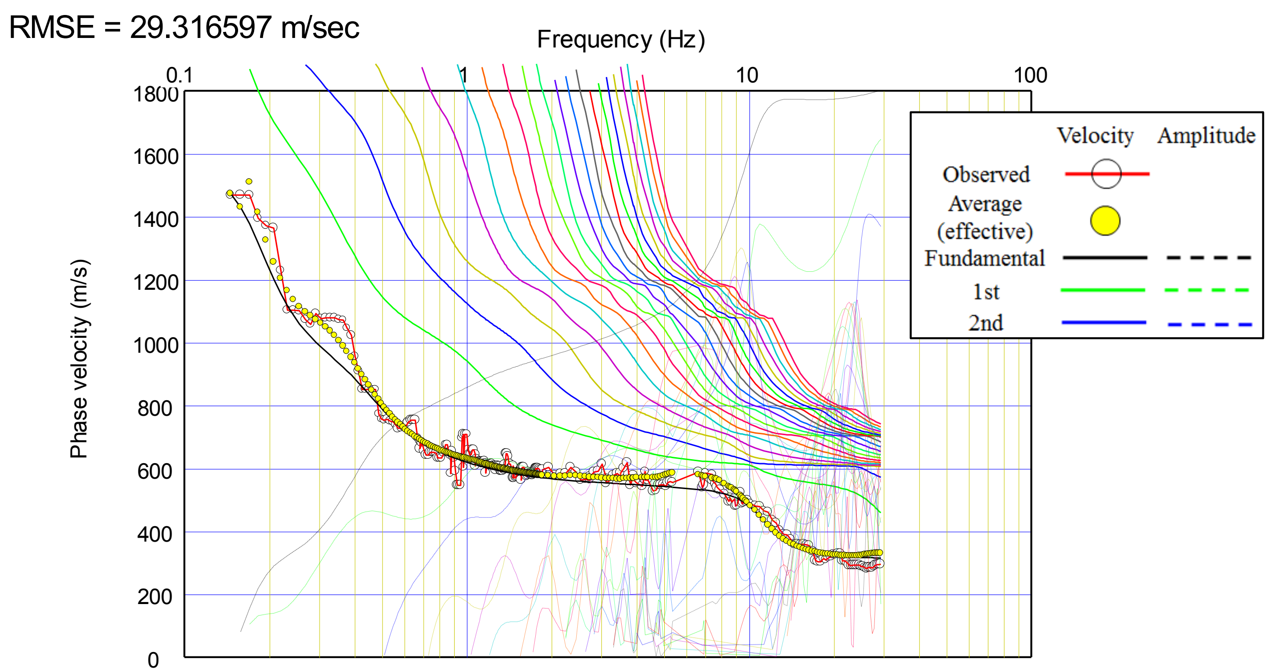
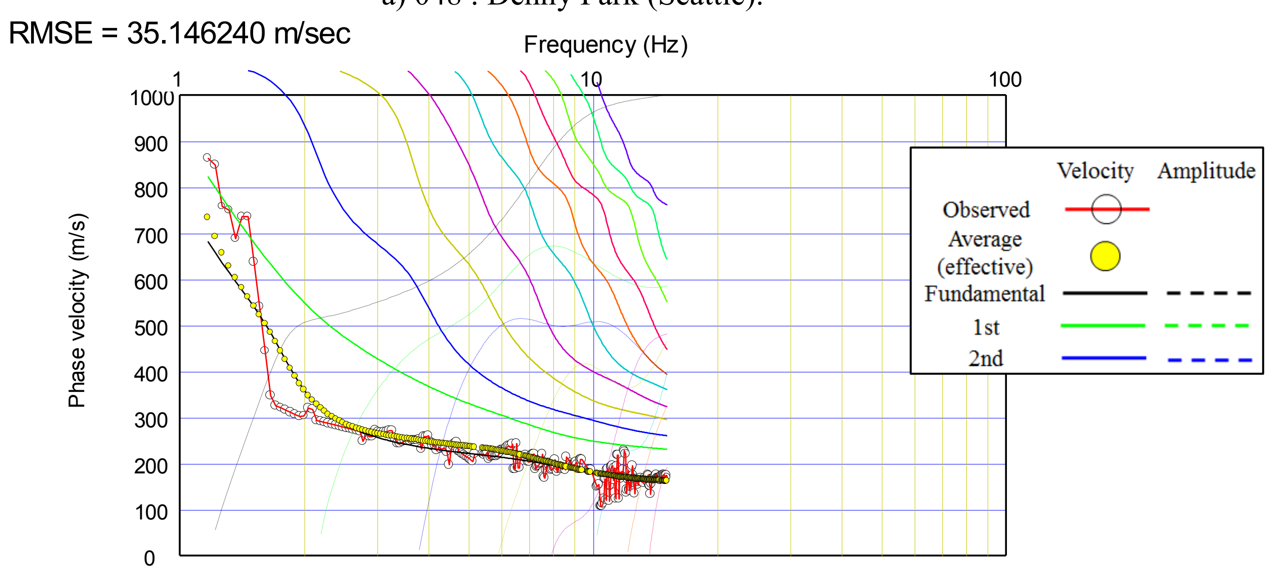


Figure 5: Comparison of S-wave velocity profiles in shallow (top) and deep (bottom) region.



a) 048 : Denny Park (Seattle).



b) 051 : Centennial Park (Olympia).

Figure 6: Comparison of observed and theoretical dispersion curves.

response. We can see that the theoretical dispersion curves (effective mode) almost agree with observed data.

Conclusions

Two-station micro-tremor array measurements (2ST-MAM) were performed at several sites in Seattle and Olympia, Washington in order to estimate deep S-wave velocity structures of the area and evaluate the applicability of the method to such investigations. Our investigation results imply that the

2ST-MAM can detect accurate phase velocities down to a frequency of 0.2Hz and a maximum penetration depth as deep as 2 to 3km. At the downtown Seattle, the bedrock with an S-wave velocity higher than 1500m/s was determined at a depth of greater than 2500m. At the Alki (049), S-wave velocity deeper than a depth of 500m is clearly higher than that of the Denny Park (048). At the Centennial Park (051), a low velocity layer with S-wave velocity less than 400m/s was determined to a depth of 90m. At the Regional Athletic Park (052), S-wave velocity at the depth range from 40 to 600m was approximately 550m/s and clearly slower than other sites in Seattle area. These preliminary results have shown that using the 2ST-MAM method is applicable to deep and shallow depth-to-bedrock investigations, and provides fast, cost-effective and accurate S-wave velocity estimates.

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