UNDERGROUND VELOCITY STRUCTURE EXPLORATION USING SURFACE WAVES IN IWAKI CITY HALL, JAPAN

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ABSTRACT

We performed microtremor array survey in the Iwaki City Hall in Fukushima prefecture, Japan in order to estimate underground structure beneath the site and to understand the effectiveness, limitations, and advantages of surface-wave array measurements as a tool for seismic microzonation and earthquake disaster mitigation. Two methods were applied to microtremor and surface wave data: the spatial auto-correlation (SPAC) method and the multi-channel analysis of surface waves (MASW) method with common mid-point cross correlation (CMPCC) analysis. The SPAC method performed well in relatively low frequency range (0-5Hz) that covers deep shear wave velocity (Vs) structure and the results show that the engineering bedrock (Vs > 400m/s) depths are deeper than 40 m. The MASW method has advantages in higher frequency range (5-20Hz) that covers lateral variations of shallow underground structure and the results show that the subsurface soft layer (Vs < 150m/s) varies between 15-40m. These results indicate that the soft sediment layers are several tens of meters in thickness and characteristics of the estimated Vs structure were comparable to those from the reference borehole data, indicating the soft sediment bottom declines more deeply from east to west. The study has shown that the combination of the SPAC and the MASW methods is an effective tool for seismic microzonation with more stable resolution.

Keywords: Microzonation, SPAC, MASW-CMPCC, Vs structure.

1. INTRODUCTION

Indonesia is one of the most seismically active countries in the world due to a complex tectonic environment. In order to minimize the damage caused by earthquakes, establishment of the seismic microzonation database can be a crucial factor. The surface-wave survey method including microtremor survey plays an important role in the seismic microzonation and has advantages in terms of its convenience, cost and environment-friendliness. We selected Iwaki City Hall in Fukushima prefecture, Japan as the study area because abundant strong-motion records have been observed in the premise after the 2011 Tohoku earthquake (Mw9.0) and the site is suited for investigating the relation between underground velocity structure and local site effects. The purpose of this study is to estimate shear-wave (Vs) structure beneath the site and to understand the effectiveness, limitations, and advantages of surface-wave array measurements as a tool for earthquake disaster mitigation.

2. METHODOLOGY

This study uses two kinds of method: the spatial auto-correlation (SPAC) method and multi-channel analysis of surface waves (MASW) method. Li (2009) has shown that the MASW method has advantages in higher frequency range while the SPAC method has good performance in relatively low

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frequency range. This indicates that the combination of these two can provide better constraint on Vs structure.

2.1. SPAC Method

The SPAC method is a method to estimate phase velocity of surface waves that come from various directions using bi-dimensionally deployed array of seismographs. The concept of the SPAC method is based on assumptions that microtremors are a spatiotemporally stationary stochastic process, and also the wavefield consists of dispersive waves propagating along the free surface (Aki 1957, 1965, Okada 2003, Yokoi and Margayan 2008). The SPAC method requires a circular array that consists of evenly spaced sensors (usually three sensors) on the circumference of a circle and one sensor at the center point. The SPAC coefficient is obtained by the azimuthal average of coherency between microtremor records observed by two sensors. According to Okada (2003), the SPAC coefficient at angular frequency ω between microtremors observed by two sensors in different locations $A(0,0)$ and $B(r,0)$ is written as:

$$\rho(r_{AB},\omega) = \frac{1}{2\pi}\int_0^{2\pi} exp\{irk\, cos(\theta - \emptyset)\}\, d\theta = \frac{1}{2\pi}\int_0^{2\pi} \frac{Re\left(E\left[C_{A,B}(\omega)\right]\right)}{E\left[C_{A,A}(\omega)\right]}\, d\theta = J_0(kr) \qquad (1)$$

where E[·] and *Re* in the third member of the equation denotes the ensemble average over time block and the real part of a complex, respectively. $C_{A,A}(\omega)$) is the power spectrum of sensor at A and $C_{A,B}(\omega)$ is the cross-spectrum between sensors at A and B. $J_0(kr)$ in the fourth member of the equation is the Bessel function of the first kind of zero order.

The Vs profile is finally estimated using the derived dispersion curve in the inversion analysis. In this study we combined two different kinds of inversion method (Yokoi, 2005): the downhill simplex method (DHSM, e.g., Press et al. 2007) and the very fast simulated annealing (VFSA) method (Ingber, 1989) to find optimal values of Vs and thickness of each sedimentary layer.

The P-wave velocity (Vp, m/s) of each layer is estimated using the empirical relationship between Vp and Vs for sedimentary layers saturated by underground water (Ludwig *et al*., 1970):

$$V_p = 1.11V_s + 1200(m/s) \qquad (2)$$

The density (ρ, g/cm^3) for each layer is estimated by the following relationship (Kitsunezaki et al., 1990):

$$\rho = 1.2475 + 0.399V_p - 0.026V_p^2 \qquad (3)$$

2.2. MASW Method

The MASW method was first introduced in geophysics (Park *et al*., 1999) as an evolution of the spectral analysis of surface waves (SASW) for one-dimensional (1D) shear wave velocity structure (Nazarian *et al*., 1983). The method is a kind of seismic exploration survey that directly converts time-distance domain waveform data into an image of phase velocity versus frequency. The method utilizes the dispersion property of surface waves for the purpose of Vs profiling in 1D (depth) or 2D (depth and surface location) format.

Data processing of the MASW method generally consists of three stages: 1) measurement of seismic surface waves generated from various types of seismic sources (such as sledge hammer), 2) analysis of the surface wave phase velocities (extracting the fundamental-mode dispersion curves, one curve from each record), and 3) inverting these curves to obtain 1D (depth) Vs profiles (one profile from one curve) (Park *et al*., 1999).

We also use the common mid-point cross correlation (CMPCC) analysis that can improves the accuracy and resolution of the MASW method, and also enables the SASW method to perform a pseudo multi-channel analysis in order to distinguish a fundamental mode from higher modes visually (Hayashi and Suzuki, 2004).

The CMPCC analysis utilizes multi-channel surface wave data from moving-source and corresponding moving-receiver array observations. According to Hayashi and Suzuki (2004), data processing of the CMPCC analysis consists of the following steps: 1) calculations of cross-correlations for every pair of traces for each shot gather, 2) grouping of the cross-correlation traces for different sensor spacing, 3) stacking of cross-correlation traces that have equal sensor spacing in the time domain, 4) arrangement of the stacked cross-correlations with respect to their spacing at each CMP, like shot gathers, 5) application of multi-channel analysis to the CMP cross-correlation gathers for calculating phase velocities of surface waves, and 6) construction of 2D Vs structure image through the non-linear least squares inversion.

3. DATA

The microtremor measurements were performed with OYO Company during the daytime from December 22 to 23, 2012. The arrays for the SPAC method were deployed in two different sizes (see Figure 1); large (L- and M-arrays) and small (SS-arrays) ones. Each array consists of two sizes of triangular array (r=75m and 150m for large arrays, r=40m and 50m for small arrays). For the area where small triangular array cannot be deployed due to the limited space, we introduced an L-shape array (SS6). Data acquisition for the MASW-CMPCC method is similar to acquisition for a 2D seismic reflection survey. The geometry is based on the end-on spread, and both source and receivers move up along survey line. Receivers are fixed at the end of survey line. Here we deployed a line array (see Figure 1) consisting of 24 receivers. The interval of sources and receivers are 1 meter each. Total numbers of data acquisition for line SW-1 through SW-3 are 68, 65, and 57, respectively.

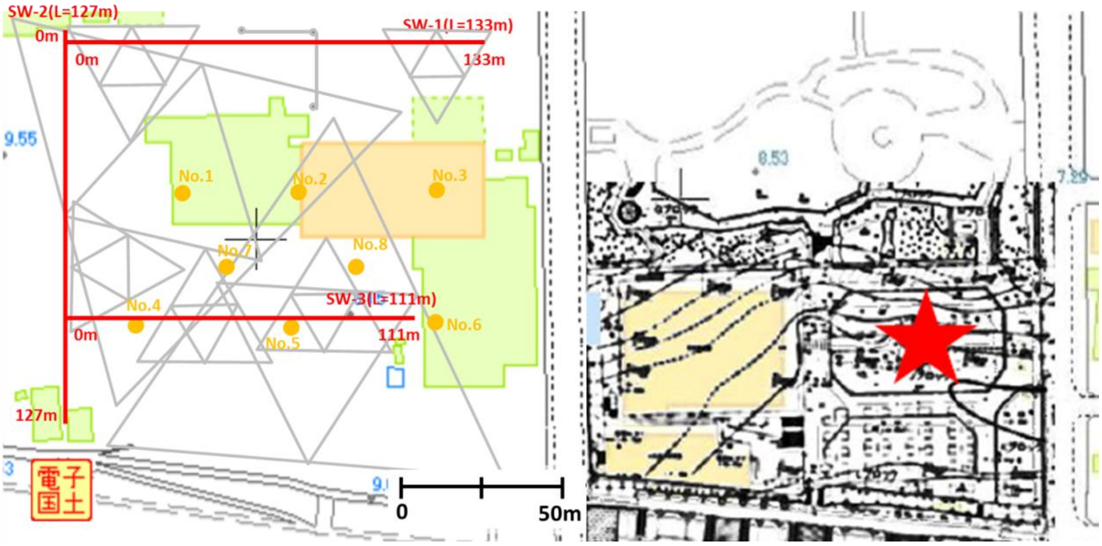

Figure 1. Array deployment for the SPAC (grey lines) and MASW (red lines) methods. Red star and yellow dots (No. 1-8) indicate the location of boreholes for PS-logging and standard penetration test (SPT), respectively (based on Guerra-Carballo, 2012).

4. ANALYSIS AND RESULTS

The SPAC and the MASW-CMPCC methods were applied to multi-channel microtremor and surface wave data observed at Iwaki City Hall. All data processing for the SPAC and MASW methods were carried out using FORTRAN programs developed by Dr. Toshiaki Yokoi.

4.1. Data Analysis for the SPAC Method

Data analysis for the SPAC method mainly consists of four steps; 1) multiplexing and resampling, 2) calculation of SPAC coefficient, 3) determination of Rayleigh-wave dispersion curve, and 4) heuristic search of Vs structure (after Yokoi, 2011).

The microtremor data was originally stored in the SEG2 format (.sg2) and then the data files was converted to single channel ASCII text format files. The single-channel data files of an array (UD component) were converted into a multi-channel data file of the time-sequential format, in the multiplexing procedure. Next the data was resampled to reduce it in size. This can cause an aliasing effect so it is necessary to apply a digital anti-aliasing filter that has high cut characteristics before thinning out.

The waveform data derived in the previous step were used to calculate the SPAC coefficient, which is an azimuthal average of the coherency between microtremor records observed by two sensors (Figure 2). The frequency range of analysis was set from 0.1Hz to 10Hz. Smoothing was carried out on the averaged cross- and auto-correlations by the Parzen window with 0.4Hz for the L- and M-arrays, and with 0.7Hz for SS-arrays.

The next step is to estimate dispersion curve of Rayleigh waves from the derived SPAC coefficients. The SPAC coefficients were converted to the value of kr in Eq. (1) by applying a fifth order polynomial equation that approximates the inverse function of $J_0(x)$. We combined small and large sized array data to estimate the dispersion curves in a broad frequency range.

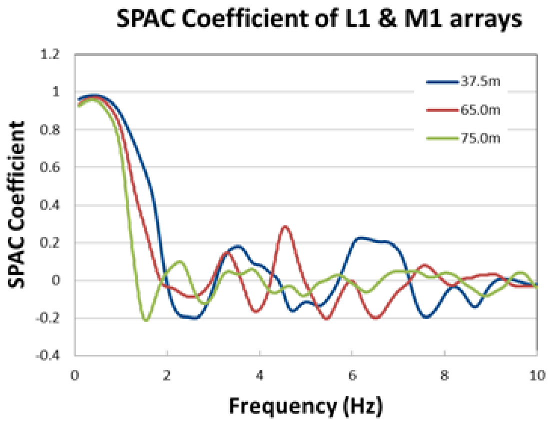

Figure 2. Derived SPAC coefficients L1 and M1 arrays.

For the heuristic search of Vs structure, we set the search range of each layer thickness and Vs values considering estimated physical properties of the existing borehole data. The optimum values of Vs and thickness of each layer were estimated to explain phase velocity for the given dispersion curve of the Rayleigh wave (result shown in Figure 3). The values of Vp and ρ are calculated from the estimated Vs after each iteration using Eqs. (2) and (3), respectively.

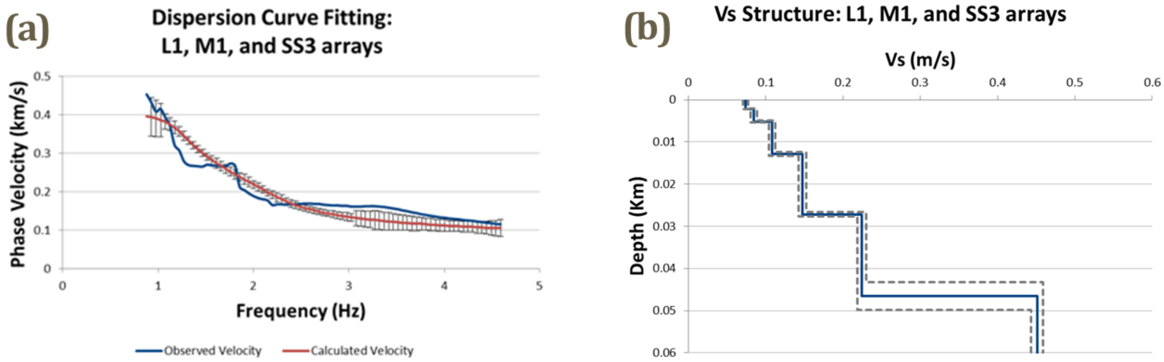

Figure 3. (a) Comparison between observed and theoretical dispersion curves. (b) Vs structure and its standard deviation estimated by the inversion method for a combination of L1, M1, and SS3 arrays.

4.2. Data Analysis for the MASW Method

Data analysis for the MASW method in this study mainly consist of four steps; 1) data acquisition, 2) CMP gathering, 3) velocity analysis and 1D inversion of dispersion curve for all CMP, and 4) plotting 2D velocity structures (after Yokoi, 2012).

Fast Fourier Transform (FFT) was applied to all waveforms of common shot gather and cross spectra were calculated for all pairs of channels to obtain cross-correlograms. The cross-correlograms were then sorted over various shot gathers to form CMP gathers. The CMP gathers (distance-time space) were again transformed into the frequency domain by FFT. The frequency domain data was integrated over spacing with respect to apparent phase velocity to derive the velocity-frequency (*c*-*f*) domain image. The maximum amplitude of stacked CMP gathers at each frequency was used to determine the phase velocity dispersion curve. The dispersion curve in the lower phase velocity was recognized as the fundamental mode and then extracted (Figure 4). For the heuristic search of Vs structure (see Figure 5), we used the same inversion method that we adopted in the SPAC method.

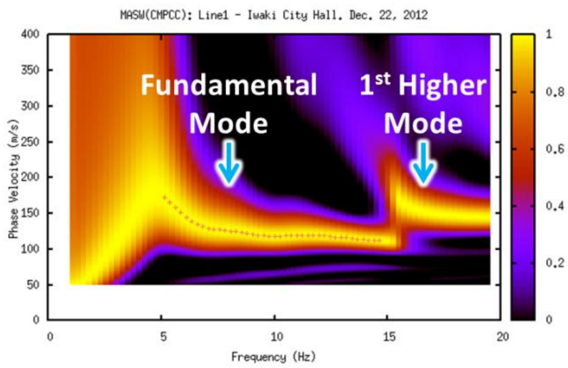

Figure 4. The *c*-*f* images from the CMPCC gathers. Red crosses indicate the estimated phase velocities

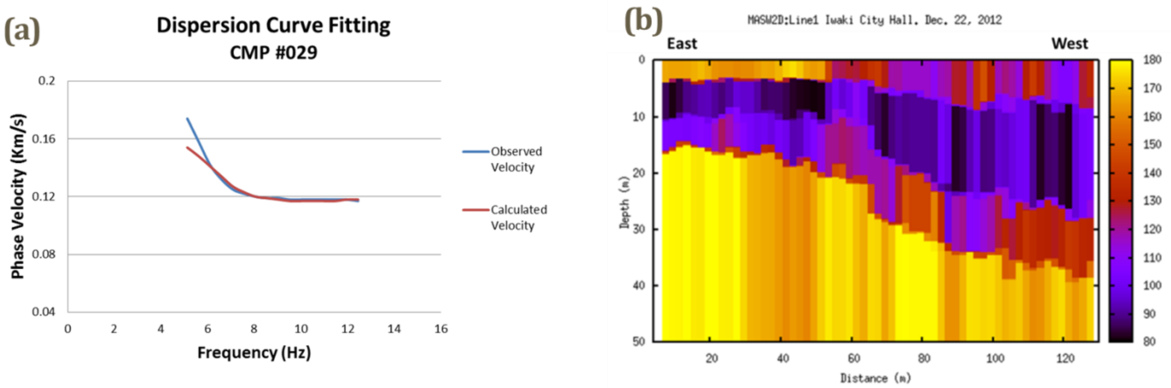

Figure 5. (a) Comparison between observed and theoretical dispersion curves of line SW-1 at a lateral distance of 14.5 m. (b) Estimated 2D Vs profile along line SW-1.

5. DISCUSSION

The Vs structures obtained through the SPAC and MASW methods were compared well to the reference borehole data. It is noteworthy that all the analysis procedures were critically checked with the help of available standard tools. However, as for the MASW results, there is a difference in Vs value trend between the PS-logging data and the estimated model. In the PS-logging data, Vs values in the second top layer is larger than those in top and third layers, while the estimated Vs value in the second layer is substantially smaller than those of top and third layers. It is speculated that the different trend is due to geological irregularities at the site. In addition, the fourth layer of the MASW results has low Vs values, indicating the MASW method provides information of the sediment at a shallower level than that from the SPAC method.

Figure 6 shows estimated contour lines for the engineering bedrock depth inferred from the SPAC results and borehole data. Figure 7 shows estimated contour lines for the bottom subsurface layer inferred from the MASW results and borehole data. The results indicate that the bottom of the soft sediment and bedrock are inclined toward the west.

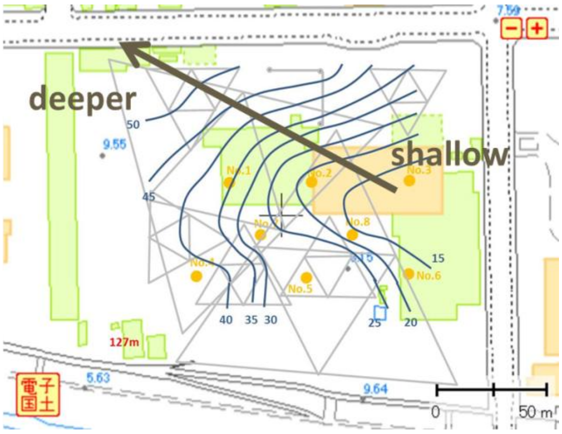

Figure 6. Estimated contour map for the engineering bedrock depth inferred from the SPAC results and existing borehole data.

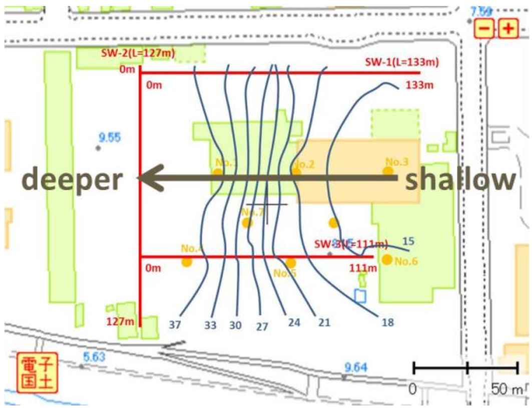

Figure 7. Estimated contour map for the bottom subsurface layer inferred from the MASW results and existing borehole data.

6. CONCLUSIONS

The estimated Vs structures from the SPAC and MASW methods indicate the existence of soft sediment layers that have thickness of several tens of meters. The structural characteristics are not largely deviated from those of the existing borehole data, indicating the combined use of two kinds of inversion methods provided reasonable solutions. Considering our results and existing survey data, the depth to the engineering bedrock becomes gradually deeper in a westerly. And it is my intention to apply the knowledge I have gained to help my institution on the microzonation program, specifically using microtremor array observation.

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