ESTIMATION OF SUBSURFACE SHEAR WAVE VELOCITY STRUCTURE IN KATHMANDU VALLEY USING MICROTREMOR ARRAY MEASUREMENTS

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ABSTRACT

Two microtremor array analysis methods, Spatial Autocorrelation (SPAC) and Centerless Circular Array (CCA) were used to estimate the subsurface shear wave velocity (Vs) structure. The data for the analyses were acquired by deploying three types of arrays in the premises of the Department of Mines and Geology, Kathmandu Nepal. The vertical component of microtremor records that are supposed to be dominated by Rayleigh waves are used for analysis. Using the determined SPAC and CCA coefficients, the dispersion curves of Rayleigh-wave phase velocity were determined. The dispersion curves from the 3P- and L-arrays for the SPAC method are independently determined and combined together for the estimation of Vs structure. The estimated Vs structure from the determined dispersion curves by using both methods show the increment of Vs with depth. The result of the exploration down to 25 m depth from the both methods can be summarized as a two-layered structure; the sub-surface layer, Vs = 145 ~ 195 m/s which can be up to 13 m thick, and second layer, Vs = 227 ~ 237 m/s. By the convenience of deployment, CCA method seems more effective in the urbanized area since it gives similar exploration depth even in much shorter array radius.

Keywords: Microtremor, SPAC, CCA, Dispersion curve, Vs structure.

1. INTRODUCTION

Kathmandu valley is one of the large intermontane basins within the entire lesser Himalaya of Nepal. The evolution of the Kathmandu basin started in Neogene-Quaternary time as a consequence of the higher rate of uplift in the Mahabharat range in the south in comparison with the north as a response to evolving Himalaya thrust tectonics. A simplified geological map of the Kathmandu valley and surrounding area shows three distinct lithological units; basement rock of Pre-Cambrian to Devonian age is surrounded in the periphery and Plieo-Pleistocene semi-consolidated thick sediments are in the central part. Between these two formations and along the recent river flood plains, unconsolidated quaternary sediments are deposited.

This study is aimed to conduct the microtremor array exploration for the estimation of shallow Vs structure around the strong motion observation station of DMG and to check the performance of the CCA method by the comparison of the results given by the two different methods of microtremor analysis (SPAC and CCA). The microtremor array method is gaining popularity due to its reliable results in exploring Vs structure which provides information about dominant frequency of the subsurface soil.

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2. DATA

Three types of arrays (Three point (3p)-array, L-Shaped (L)-array and Hexagonal mini (Mini)-array) micrometer measurements were conducted in the central part of the Kathmandu basin to evaluate the shallow subsurface structure as shown in Figure 1. Spatial Autocorrelation (SPAC) Method and Centerless Circular Array (CCA) Method are used to determine the shear wave velocity structure (Vs structure). Three sets of three-component accelerometers (McSsis-MT NEO) for 3P-array, 24 geophones for L-array and seven seismometers (L22D) for Mini-array along with data logger (McSeis-SW) were used for the data acquisition.

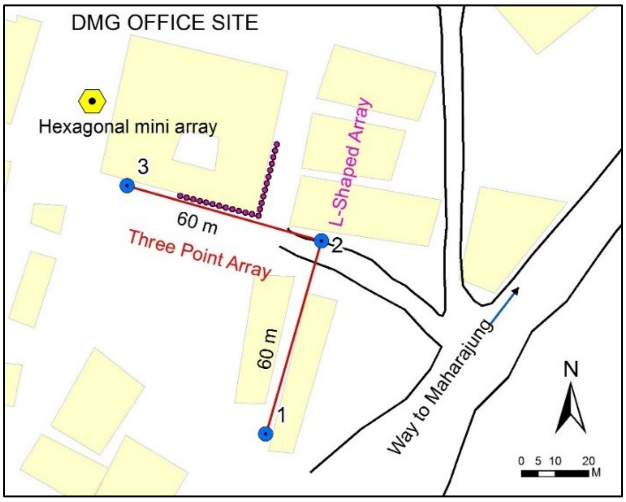

Figure1. Array deployment for data acquisition for the microtremor measurement. The blue circle indicates sensors for the 3P-array, pink circle shows the geophone's location of the L-array and yellow hexagon shows that of the Mini-array.

3. METHODOLOGY

Among different microtremor array measurements, the most commonly used method applied nowadays is the Spatial Autocorrelation (SPAC) Method and relatively new one is the Centerless Circular Array (CCA) Method (Cho et al., 2004; Cho et al., 2013).

3.1. Spatial Autocorrelation (SPAC) Method

The SPAC method is based on the theory proposed by Aki (1957, 1965). Microtremors are the stochastic waves that are stationary both time and space and they consist of dispersive surface waves, i.e. Rayleigh waves (Okada, 2003). Under these assumptions, Aki (1957) proposed a formula to calculate the coherence function (SPAC coefficient) which is theoretically expected to be equal to the zero-order, Bessel function of the first kind, $J_0(kr)$.

$$\rho(r_{AB},\omega) = \frac{1}{2\pi}\int_0^{2\pi}\frac{E[\emptyset(\omega,r,\theta)]}{E[\emptyset(\omega,0,0)]}d\theta = \frac{1}{2\pi}\int_0^{2\pi}\frac{Re[C_{A,B}(\omega)]}{E[(C_{A,A}\ (\omega)]}d\theta = J_0(kr), \tag{1}$$

where, ω is angular frequency, r is distance between the two sensors A and B, θ is azimuth of a sensor from another, E [ ] denotes average over time block, Re is real part of a complex number, $C_{A,B}$ (ω) is cross spectra of station A and B, and $C_{A,A}$ (ω) is power spectra of station A.

The practical way to calculate the SPAC coefficient (azimuthal average of coherence function) from the microtremor is shown as follows.

$$\rho(r,\omega) = \frac{1}{M}\sum_1^M \frac{Re[C_{A,B}(\omega)]}{\sqrt{E[C_{A,A}\ (\omega)].\ E[C_{B,B}\ (\omega)]}}, \tag{2}$$

3.2. Centerless Circular Array (CCA) Method

The CCA method that is proposed by Cho et al. (2004, 2006) is based on the theory of circular array given by Henstridge (1979). As well as the SPAC method, the CCA method uses the microtremor records in the vertical component and estimates the Rayleigh-wave phase velocity however it was developed based on a completely different principle. The coefficient of CCA is calculated as;

$$\frac{G_0(\omega,r)}{G_1(\omega,r)} = \frac{PSD\langle\int_{-\pi}^{\pi} Z(t,r,\theta)d\theta\rangle}{PSD\langle\int_{-\pi}^{\pi} Z(t,r,\theta)exp(-i\theta)d\theta\rangle} = \frac{J_0^2[rk_1\ (\omega)]}{J_1^2[rk_1\ (\omega)]} = M[rk_1\ (\omega)], \quad (3)$$

where, ω is angular frequency, r is sensor spacing, k_1 is wave number, J_0 & J_1 are the Bessel functions zero and first order of first kind and G_0 & G_1 are the power spectral densities expressed as G_0 and G_1. PSD < > is power spectral densities and Z (t, r, θ) is vertical component of the microtremor observed at distance (r, θ) and time t.

3.2. Inversion of dispersion curves for Vs structure

The subsurface structure, including the density (ρ), P- and S-wave velocity (Vp and Vs), is estimated by the inversion using the derived dispersion curves from the SPAC and CCA methods. In the inversion, the Vs structure is obtained by heuristic search which is combination of Downhill Simplex Method (DHSM, e.g., Nelder & Mead, 1965) and Very Fast Simulated Annealing Method (VFSA, Ingbar, 1989). Vp is calculated from Vs by using the empirical formula of Kitsunezaki et al. (1990) shown in Eq. (4).

$$V_p = 1.11 * V_s\ + 1.29\ \left(\frac{m}{s}\right), \quad (4)$$

The density (ρ) is calculated by using the empirical formula of Ludwig et al., (1970), as shown in Eq. (5).

$$\rho = 1.2475 + 0.399 * V_p - 0.026 *\ V_p{}^2, \quad (5)$$

4. RESULTS AND DISCUSSION

The data analysis is conducted separately for all arrays using two different methods.

4.1. Data analysis by SPAC Method

The data acquired by 3P and L-arrays are analyzed by using the SPAC method. The complete analysis procedure of this method consists of four steps; multiplexing and resampling, calculation of SPAC coefficient, determination of dispersion curves and estimation of velocity structure.

In the 3P-array and L-array microtremor data was originally in the mtn and seg2 binary format. The multiplexed data was resampled to reduce the size as well as to screen out the non-desired noise. For resampling a band pass filter was applied in the frequency range between 0.1 and 20 Hz. After the resampling, the SPAC coefficient is calculated by using the formula of Eq. (1). The frequency ranges of the analysis are set between 0.1 and 10.0 Hz for the 3P-array and 1.0 and 20.0 Hz for the L-array, respectively. There are two station pairs in 3P-array and 276 station pairs with 81 interstation distances in L-array. The calculated SPAC coefficient is shown is shown in Figure 2.

From the SPAC coefficients, the dispersion curve of the Ryleigh waves is determined. First the obtained SPAC coefficient curve is converted to phase velocity *c (r, ω)* through the following fifth order polynomial equation that approximate the inverse function Eq. (6).

$$y = 6.0803x^5 + 9.2477x^4\ - 3.9322x^3\ + 0.1815x^2 - 1.7079x + 2.4121, \quad (6)$$

where, $y = kr = r\omega/c(r,\omega)$, and $x = \rho(r,\omega)$.

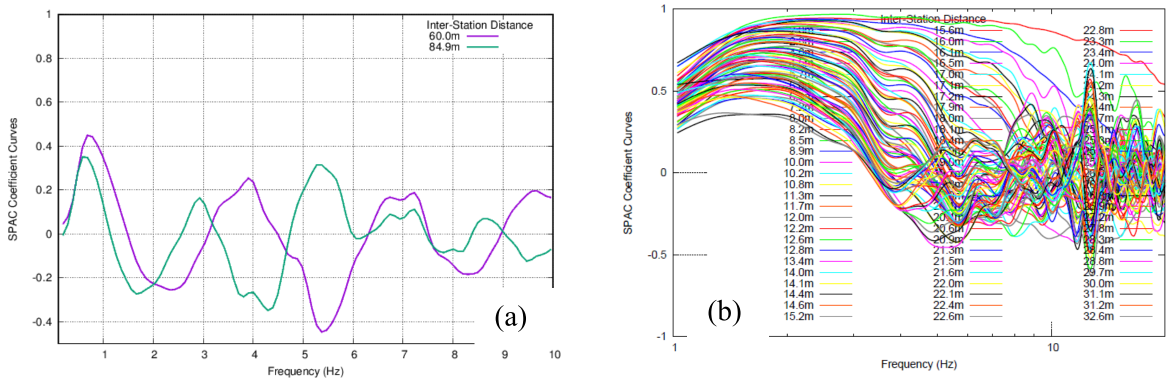

Figure 2. SPAC coefficient curves calculated for 3P-array (a) and L-array (b). Colors indicate the different interstation distances.

For each individual SPAC coefficient curve, the frequency range is selected so that the corresponding wavelength is between two times of the corresponding interstation distance and the frequency of the first peak of SPAC coefficient curve. The former is for considering the Nyquist wavelength (Cornou et al., 2006). Then the dispersion curve was determined at each frequency by the phase velocity that can give the minimum of the misfit function. We combined the dispersion curve of 3P-array with L-array to capture the information in a wider frequency range for the inversion. The combined dispersion curve is shown in Figure 3a.

For the final Vs structure, initial model is selected that consists of search range of thickness and shear wave velocity (Vs) for each layer as shown in Table 1. By using the search range, final Vs structure is estimated as shown in Figure 3b. The final Vs structure consists of three layers; the top layer from the ground surface down to 12 m depth, Vs = 145~195 m/s, the second between 12 m and 34 m depth with Vs = 237 m/s.

Table 1. Searching range of parameters of the initial model for the Vs structure.

Thickness h_{min} (km)	Thickness h_{max} (km)	Vs_{min} (km/s)	Vs_{max} (km/s)
0.001	0.020	0.08	0.20
0.001	0.025	0.1	0.25
0.001	0.030	0.1	0.30

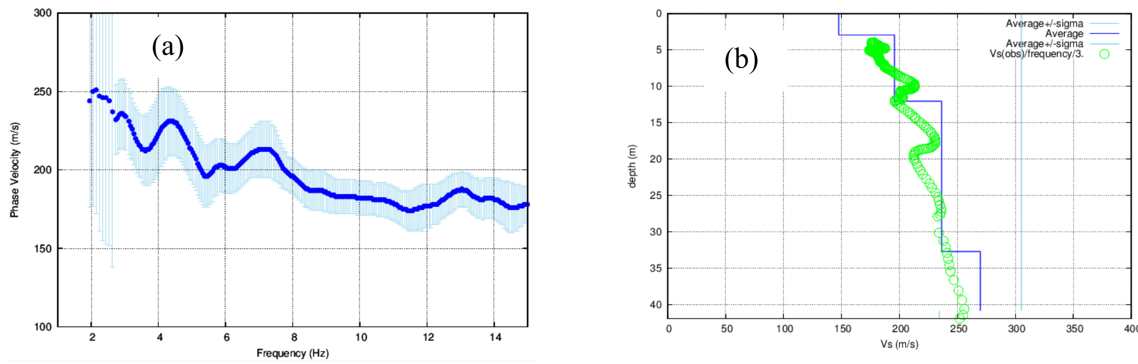

Figure 3. Dispersion curve obtained by the combined 3P-array and L- array (a) and Inverted Vs structure obtained from the dispersion curve (b).

4.2. Data Analysis by CCA Method

The analysis procedure of CCA is also similar like SPAC method. For the multiplexing, the field data of the seg2 binary format is converted into ASCII text format by using the FORTRAN code in the time sequential format. The original data had the sampling interval 0.001 s. The resampled interval is 0.02 s. Then the CCA coefficients were calculated for each radius array by using the formula Eq. (2) as described above. The calculated CCA coefficients and observed dispersion curves using Mini-array with radius 1 m, 2 m and 4 m are shown in Figure 4a and 4b.

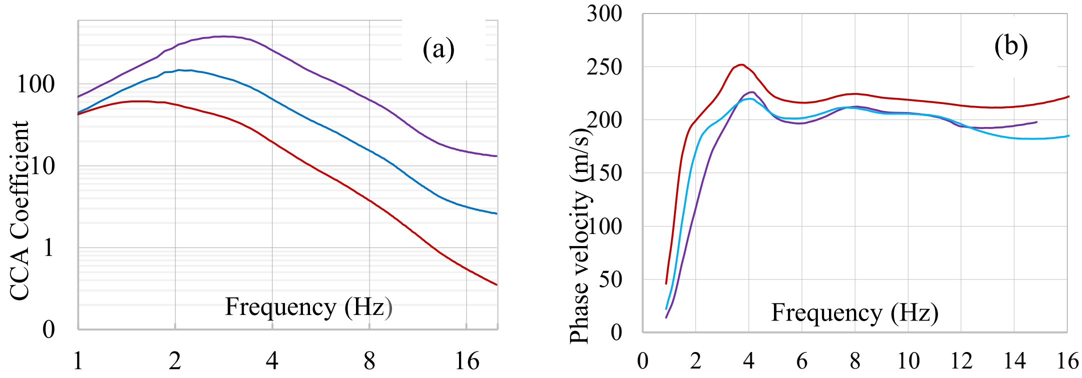

Figure 4. The CCA coefficients (a) and the dispersion curves (b) of the mini-array of radius 1 m (purple), 2 m (blue) and 4 m (red).

The heuristic search of Vs structure was conducted by the inversion of the dispersion curves based on the combination of DHSM and VFSA methods. The estimated Vs structure by inversion of the dispersion curves obtained by the array of radius 1 m, 2 m, and 4 m are shown in Figure 5.

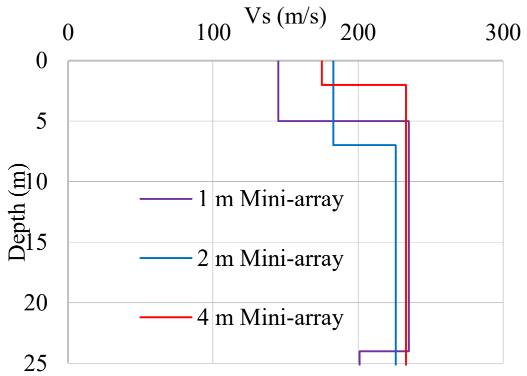

Figure 5. Vs structure estimated from CCA method using the dispersion curves of mini-array of 1 m, 2 m and 4 m radii.

4.3. Comparison of the results

The dispersion curves obtained from the SPAC method as well as CCA method with 1 m and 2 m radius mini-arrays show the good aggrements of Vs ~ 200 m/s whereas the curve of Mini-array of 4 m radius shows little higher phase velocity than others (Figure 6a). The Vs structures obtained from both methods up to 25 m depth is also comparable as shown in Figure 6b. That shows two-layered structure; the subsurface layer Vs value from 145 to 195 m/s down to 12 m, and the second layer that has higher Vs, from 227 to 237 m/s.

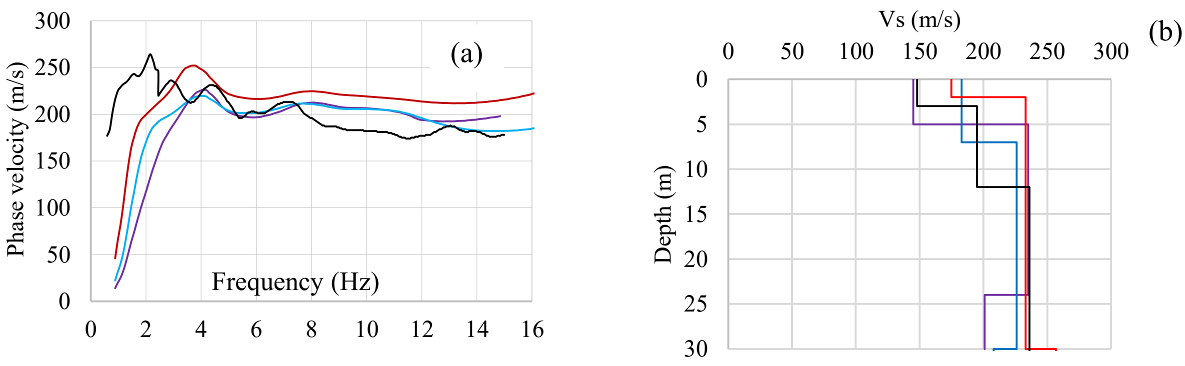

Figure 6. The dispersion curves (a) and Vs structure (b) obtained from the two different methods. The black is from SPAC method whereas purple, blue and red are of mini-array of 1 m, 2 m and 4 m for CCA method.

5. CONCLUSIONS

The SPAC and CCA methods for microtremor array exploration are used for the analysis of the data acquired from central part of the Kathmandu Valley.

Three types of array composed of vertical component of ground velocity are used for analysis. 3P-array and L-array is analyzed by SPAC method whereas mini-array of radius 1 m, 2 m and 4 m for CCA method.

The dispersion curves of Rayleigh wave that are determined using 3P- and L-arrays for the SPAC method, are combined together and the Vs structure is estimated using the dispersion curve assuming that the structure consists of three layers. The estimated structure, shows the top layer with Vs = 195 m/s down to 12 m depth and the second layer between 12 m to 34 m with Vs = 237 m/s.

Vs structure from the CCA method shows two velocity layers, top layer with Vs = 145 ~ 184 m/s down to 7 m depth and the bottom layer with Vs = 227 m/s ~ 236 m/s down to 24 m depth.

The result of the exploration down to 25 m depth is summarized as a two-layered structure. The surface layer has Vs from 145 to 195 m/s down to 12 m, followed by high velocity layer with Vs value from 227 to 237 m/s.

The results show that CCA method seems available and more effective than the SPAC method as it explored the same depth even in the smaller radius array in term of the applicability in sites densely built up such as Kathmandu city, where there is less space for the array of SPAC method.

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