ESTIMATION OF SHEAR WAVE VELOCITY PROFILES USING MICROTREMOR ARRAY EXPLORATIONS IN ISMAILIA CITY, EGYPT

Mohamed Maklad*
MEE16704

Supervisor: Toshiaki Yokoi**
Takumi Hayashida**

ABSTRACT

The Spatial Autocorrelation (SPAC) method was applied to microtremor array data at seven sites in Ismailia city, Egypt for the determination of phase velocity dispersion curves and estimation of 1-D S-wave velocity (Vs) profiles. The estimated Vs profiles indicate that the maximum Vs is about 500-700 m/s at deeper parts (90-350 m) and the minimum Vs is about 140-200 m/s for the shallow subsurface layer. The calculated *AVS30* values based on the estimated Vs profiles indicate that all the sites are categorized into site class C or D of NEHRP classification. The theoretical site amplification factors using Vs profiles show that the resonant frequencies for the sites located on the west side of Suez Canal range between 1 to 2 Hz, whereas they are lower than 1 Hz for the sites located on the east side. Microtremor horizontal-to-vertical spectral ratios (HVSR) were also calculated for all sensor records at each site. The derived HVSR show similar curves for all the sensors at each site, indicating nearly flat layered structure beneath each site. There are no clear peaks of the observed HVSR in the frequency range higher than 1 Hz, where high signal-to-noise ratios were detected. We also calculated the theoretical HVSR of the fundamental mode Rayleigh waves using the estimated Vs structures and plotted them with the theoretical amplification factors. The dominant frequencies from the both theories are similar to each other at five sites. We tried to modify the Vs models for them, but the results show that the originally inverted structure models are acceptable, since discrepancies between the observed and theoretical phase velocities are obvious except one site. Our results show that the combination of SPAC and HVSR methods is advantageous to support the results of each method and overcome observational limitations.

Keywords: Ismailia city, SPAC method, *AVS30*, Site amplification factor, HVSR method.

1. INTRODUCTION

Ismailia city is one of the most strategic cities in Egypt, located in the middle part of Suez Canal. Our study area in Ismailia city is focused under several integrated developments and ongoing projects such as New Ismailia City construction on the eastern-bank of Suez Canal, Suez Canal projects and tunnels construction. On the other hand, the city is located in moderate seismic activity zone and has been damaged by several earthquakes such as 1995 Aqaba Earthquake. Understanding the site effect is important for earthquake disaster mitigation in this area. The purpose of the study is to determine S-wave velocity (Vs) profiles using SPAC method with microtremor array data at seven sites in Ismailia city, situated on the west and east side of Suez Canal. The obtained Vs profiles can provide essential information about the dynamic properties of soil such as resonant frequency and site amplification factor. The estimated Vs profiles can also be used to calculate average shear wave

*National Research Institute of Astronomy and Geophysics (NRIAG), Egypt.
**International Institute of Seismology and Earthquake Engineering (IISEE), Tsukuba, Japan.

velocity for the top 30 m depth (*AVS30*), by which the ground classification can be carried out for each site.

2. METHODOLOGY

2.1. SPAC Method

The SPAC method estimates phase velocity dispersion characteristics of surface waves using a bi-dimensionally deployed array of seismographs, considering that the microtremors are dominated mainly by surface waves (Okada, 2003). The concept of SPAC method is based on the principles that the wave motion of microtremors is a stochastic process in time and space, the sources of microtremor waves are uniformly distributed, the Vs structure beneath the observation array has parallel horizontal layers, and Rayleigh waves are dominant in the vertical component. The conventional SPAC method requires a circular array that consists of four seismometers at least, three of them arranged on the circumference of the circle with radius (r) and one at the center to record all sources coming from different directions. Then, the azimuthal averaged coherence function (i.e., SPAC coefficient) can be obtained for records between sensors having the same inter-station distance, hence this function follows the theoretical Bessel function as shown in Eq. (1).

$$\rho_{AB}(r,\omega) = \frac{1}{2\pi}\int_{0}^{2\pi} \frac{\mathrm{Re}[s_{AB}(r,\omega)]}{\sqrt{|G_A(\omega)||G_B(\omega)|}}d\theta = \frac{1}{2\pi}Re\int_{0}^{2\pi} exp\left(i\frac{\omega r}{C_{app}(\omega)}\right)d\theta$$
$$= \frac{1}{2\pi}Re\int_{0}^{2\pi} exp\left(i\frac{\omega r\cos\theta}{C(\omega)}\right)d\theta = J_0\left(\frac{\omega r}{C(\omega)}\right) \tag{1}$$

where $\rho_{AB}(r,\omega)$ is the SPAC coefficient between station A and B in terms of inter-station distance r and angular frequency ω, $\mathrm{S_{A,B}}(\omega)$ is the cross spectrum for the records of station A and B, $\mathrm{G_A}(\omega)$ and $\mathrm{G_B}(\omega)$ are the power spectrum of records at station A, and B, respectively, (Re) is the real part of a complex, $C_{app}(\omega)$ is the apparent phase velocity, $J_0(kr)$ is the Bessel function of the first kind of zero order in terms of r, ω, and phase velocity $C(\omega)$.

Hence, the phase velocity of the dispersion curve can be calculated by fitting the observed SPAC coefficient for different interstation distances with the theoretical Bessel function, with respect to each frequency. Finally, the Vs profile is obtained using the resulted dispersion curve during the inversion process. Two inversion methods were applied; The Down Hill Simplex method (DHSM; Press et al., 2007) and the Very Fast Simulated Annealing (VFSA; Ingber, 1989) to obtain the optimum values of Vs and the thickness of each subsurface sedimentary layer that satisfies the observed dispersion curve (Yokoi, 2005). P-wave velocity (Vp) and density for each layer can be calculated by the empirical formulas introduced by Kitsunezaki et al. (1990) and Ludwig et al. (1970).

2.2. H/V Spectral Ratio Method

According to Arai and Tokimatsu (2004), the H/V spectral ratio of microtremors at a frequency (ω) $(\mathrm{H/V})_{\mathrm{m}}(\omega)$ is defined as the ratio of the horizontal power spectrum to vertical power spectrum at a single site using a three-component sensor as shown in Eq. (2).

$$(\mathrm{H/V})_{\mathrm{m}}(\omega) = \sqrt{\frac{P_{NS}(\omega)+P_{EW}(\omega)}{P_{UD}(\omega)}} \tag{2}$$

where $P_{UD}(\omega)$ is the Fourier power spectrum of the vertical motion and $P_{EW}(\omega)$ and $P_{NS}(\omega)$ are the Fourier power spectrum of the orthogonal horizontal motions. During this study, HVSR method was applied to the microtremor data to find the observed fundamental frequency.

3. DATA ACQUISITION

The microtremor array measurements were performed at seven sites in Ismailia City nearby the western and eastern sides of Suez Canal where several tunnels and New Ismailia city are being constructed (Figure 1). The array configuration was circular with 4-sensors and different sized-arrays were deployed at each site. Two different sized arrays were deployed at sites 1, 2, 3, 6, and 7, whereas three arrays were carried out at site 2 and only one array was performed at site 5 (Table 1). Each array consists of two interstation distances; one for the radius distance and the other for the side length distance. The smallest array size (side length) was about 34.6 m and the largest array was about 173.2 m. The sampling interval was 100 samples per second and the recording time was from 30 to 60 minutes at each site. The equipment used in this survey was the sensor integrated portable data acquisition system McSEIS-MT NEO, manufactured by OYO corporation.

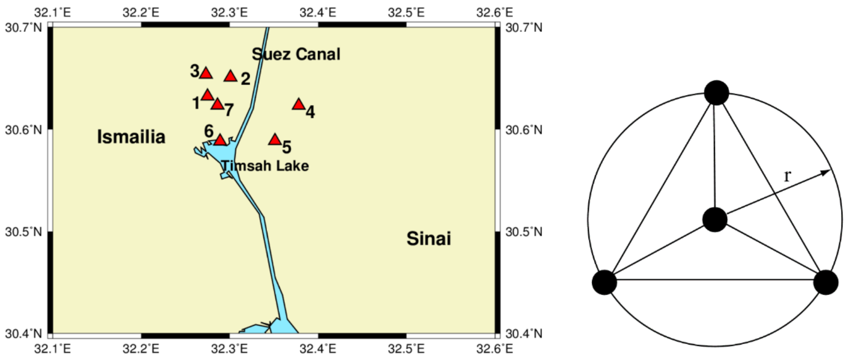

Figure 1. The location of microtremor array observation sites in Ismailia city (left). Circular array configuration with four sensors (right) (after Okada, 2003).

Table 1. The information of the microtremor arrays at the seven selected sites.

Site ID	Lat. (deg)	Long. (deg)	No of arrays	Min* array size (m)	Max* array size (m)	No of inter-station distances	Inter-station distances (m)
1	30.6324	32.2748	2	86.6	173.2	4	50, 86.6, 100, 173.2
2	30.6509	32.3008	3	34.6	173.2	6	20, 34.6, 50, 86.6
3	30.6537	32.2730	2	34.6	86.6	4	20, 34.6, 50, 86.6
4	30.6233	32.3780	2	34.6	86.6	4	20, 34.6, 50, 86.6
5	30.5887	32.3511	1	86.6	-	2	50, 86.6
6	30.5883	32.2890	2	34.6	86.6	4	20, 34.6, 50, 86.6
7	30.6235	32.2862	2	34.6	86.6	4	20, 34.6, 50, 86.6

4. ANALYSIS AND RESULTS

4.1. Data Analysis for SPAC Method

The SPAC method was applied to the microtremor array data recorded at seven sites in Ismailia city. Data analysis for SPAC method includes four steps; 1) multiplexing and screening, 2) calculation of SPAC coefficient, 3) determination of dispersion curve, 4) heuristic search of Vs structure.

The microtremor data was originally stored in the MTN format (.mtn), and then the data files were converted into single ASCII text format files for the vertical component only. Since the data were recorded simultaneously and individually, the single channel data files of an array were converted into multi-channel files of the time sequential format, using the multiplexing procedure. Next, the multiplexed data files were combined into a multi-channel, multi measurement file and two steps of screenings were applied to remove the noise.

The screened waveform obtained in the previous step was utilized to calculate the SPAC coefficient, which is the azimuthal average of coherence functions between microtremor records obtained by two sensors (Figure 2). The frequency range for analysis was set 0.1 to 10.0 Hz. The power spectral density for each station record and cross spectra between all possible pairs of stations were calculated and smoothed by Parzen window with a bandwidth of 0.25 Hz.

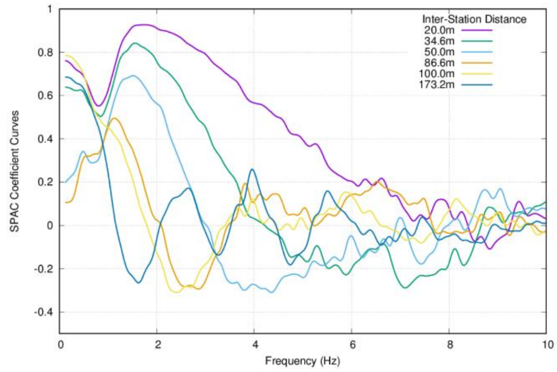

Figure 2. The obtained 6-SPAC coefficients of large, medium, and small arrays at site 2.

The next step is to determine Rayleigh-wave phase velocity dispersion curves from the obtained SPAC coefficients (Eq. 1). The SPAC coefficients were converted to phase velocities by applying the fifth order polynomial equation that approximates the inverse function of Bessel function $J_0(kr)$. At site 2, the dispersion curve was estimated by the combination of three different sized arrays in order to get a broad frequency range.

For the heuristic search of optimum Vs structure, the initial search range was set in terms of two parameters; thickness and Vs for each layer at site 2. This range was estimated based on general geological information and previous Vs profiles obtained by MASW technique near the study area (Mohamed et al., 2016). The inversion searched for the optimum Vs structure resulted in good fitting (the lowest misfit) between the observed dispersion curve and the calculated one (Figure 4). In each iteration, Vp and density values were calculated using the previously mentioned empirical formulas.

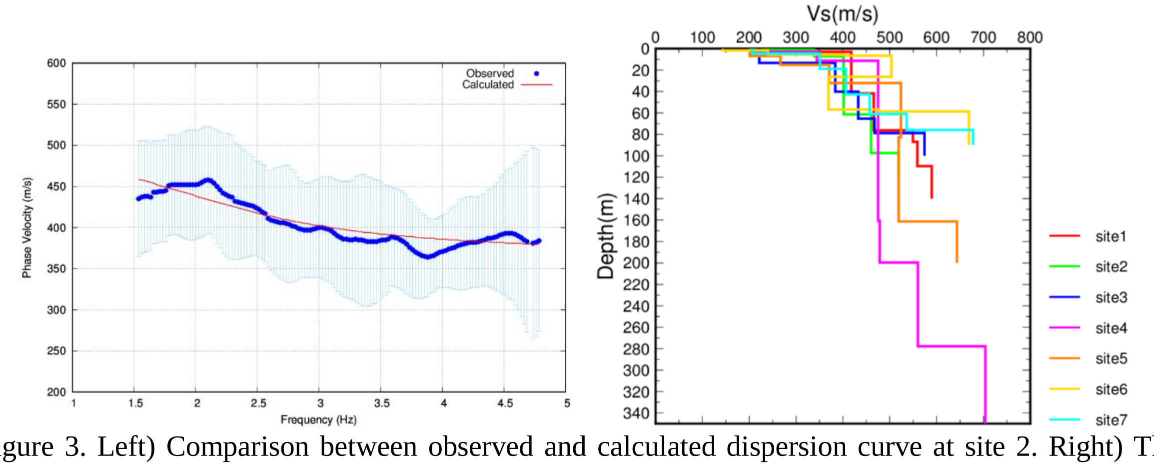

Figure 3. Left) Comparison between observed and calculated dispersion curve at site 2. Right) The resulted Vs structure models for the 7-sites in Ismailia city.

5. DISCUSSION

5.1. Ground Classification of NEHRP Approach Based on *AVS30*

AVS30 values were computed using the obtained Vs profiles for the seven sites and site classification was conducted according to the National Earthquake Hazards Reduction Program (NEHRP) approach

(Building Seismic Safety Council, 2001). The results show that sites 1, 2, 4 and 6 are classified into site class C, where the ground condition is described as very dense soil and soft rock. On the other hand, sites 3, 5 and 7 are categorized into site class D, where the ground condition is described as stiff soils.

5.2. Site Amplification Factor

The site amplification factor is defined as the ratio between the surface ground motion and the input motion from the bottom layer (Yamanaka, 2017). It was calculated for all the sites based on the estimated Vs profiles (Figure 4). Sites 1, 2, 3, 6 and 7 have the fundamental resonant frequencies in the range of 1 to 2 Hz. This range should be taken into account during the construction of low- or medium-rise buildings at these sites on the west side of Suez Canal. Sites 4 and 5 located on the east side of Suez Canal show the resonant frequencies lower than 1 Hz. Hence, these frequencies should be taken into account during the construction of high-rise buildings. To support the previous results, the observations of HVSR data using broadband sensors could be applied.

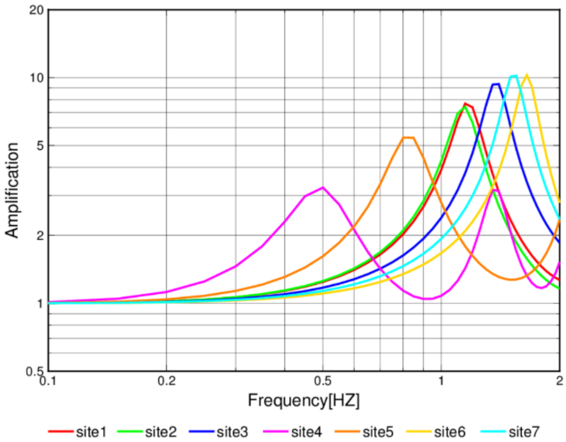

Figure 4. Theoretical site amplification factor for all the sites.

5.3. H/V Spectral Ratio Method

The data processing using HVSR method consists of four steps; 1) Dividing the data into time blocks, 2) Applying two steps of screenings, 3) Calculation of power spectrum for three-component records per each sensor, and 4) Calculation of HVSR for each sensor record at each site. HVSR curves for all the sensor records at each site were calculated to confirm the homogeneity of wave-field of microtremor and ground condition. The HVSR results show similar curves indicating the homogeneity assumption at each site and therefore the SPAC method analysis was supported to be on the right direction (Figure 5). They also show that a low signal to noise ratio was detected in the frequency range from 0.1 to 1.0 Hz, and no clear peak appeared in the frequency range from 1 to 10 Hz.

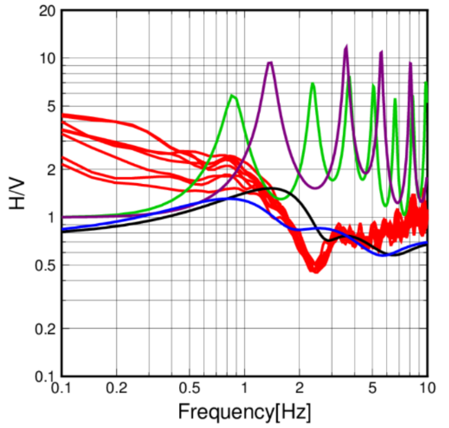

Figure 5. HVSR for the eight-sensors records (red curves) with the site amplification factor of inverted Vs-structure (purple curve) and that of the modified Vs-structure (green curve), and theoretical HVSR of inverted Vs-structure (black one) and that of modified Vs-structure (blue one) at site3.

5.4. Theoretical HVSR of Fundamental Mode Rayleigh Waves

Theoretical HVSR of fundamental mode Rayleigh waves was calculated at each site according to the theory of Arai and Tokimatsu (2004), using the estimated Vs models at the seven sites (see an example in Figure 5). For example, the dominant frequencies calculated by theoretical HVSR and theoretical amplification factor were similar at 1.4 Hz, whereas the peak dominant frequency observed on HVSR curves was 0.8 Hz at site 3. Then Vs model was modified to explain the peak dominant frequency around 0.8 Hz. Finally, the theoretical dispersion curve of Rayleigh wave was calculated using the modified Vs structure and plotted with the observed curve as well as the calculated curve for the originally inverted Vs structure, it was more deviated from the observed one and exceeded 20 % of the main standard deviation. Hence, it was more reliable to accept the originally inverted Vs structure with its calculated dominant frequency at 1.4 Hz, by considering the best fitting between the observed and calculated dispersion curves during SPAC analysis.

6. CONCLUSIONS

The Vs profiles at seven microtremor array observation sites in Ismailia city were estimated, using SPAC method. The engineering bedrock with Vs of 400-600 m/s is detected for all the sites at different depths (3–32 m). Based on the estimated structure models, all the sites were categorized into site class C or D. Interestingly, the combination of SPAC and HVSR methods at the same site is an advantageous tool based on the condition where HVSR was used to prove the homogeneity of wave-field and ground condition at the site and observed dispersion curves calculated by SPAC method were used during the search for the optimum dominant frequency with its corresponding Vs structure to overcome the low signal to noise ratio of HVSR curves.

7. RECOMMENDATION

The obtained Vs profiles and the related information can be used for different purposes such as engineering construction applications and site effect studies for simulation of strong ground motion as well as seismic microzonation applications in and surrounding the study area. Consequently, we recommend that microtremor exploration should be performed to enhance microzonation projects in Egypt. It also should be applied at several strategic cities in Egypt for infrastructure planning and Earthquake disaster mitigation. I wish to collect more useful information for Construction Engineers using the techniques I learned in Japan and support them to improve the Egyptian building code for better resilience against earthquakes.
On the other hand, for sites 5 and 6, it was realized that they will need further study by calculating the theoretical HVSR with the higher modes. This is considered as a further microtremor research topic.

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