

# VALIDATION OF SPAC AND HVSR METHODS, AN EXPERIMENTAL STUDY

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## ABSTRACT

Pakistan is an earthquake prone country. A wide area including major cities is covered by thick sediments and the amplification of seismic waves is likely to occur. Studies to estimate velocity structure and amplification ratios in sedimentary layers in various parts of country are necessary. The microtremor can be considered as a dominant tool for estimating the earthquake site response. Therefore, the two methods, i.e., SPAC and HVSR, selected to carry out the present study are mainly based on microtremor. This study was carried out to check the validity of these microtremor methods. The focus was on the estimation of subsurface shear wave velocity structure and the calculation of the resonant frequency and/or the amplification of seismic waves in sedimentary layers. Velocity structures estimated by SPAC method were reliable and fairly accurate. The HVSR curve corresponded to the resonant frequency of the thick sediments but no clear relationship was found between this ratio and the amplification of waves.

**Keywords:** Amplification of seismic waves, velocity structure, microtremor, SPAC, HVSR.

## 1. INTRODUCTION

It is earnestly needed first to carry out a detailed study to estimate the sedimentary thickness at various areas in the country and secondly to determine the level of shaking while considering the amplification of seismic wave in those areas and eventually to upgrade the building codes and by laws accordingly. The methods used in this study are the SPatial AutoCorrelation (SPAC) and the Horizontal to Vertical Spectral Ratio (HVSR). Both of these methods have characteristics of being cost effective, noninvasive and reliant on passive source(s). Also they do not have any bad impact on the environment. These features make these methods more practical for their implementation in urbanized areas.

## 2. METHOD

For the evaluation of expected level of earthquake damage at a given site, Horizontal to Vertical Spectral Ratio (HVSR) method is used. It was empirically found by Nakamura (1989) and based on short period microtremor but have been extended to the longer period range up to 10 s. The HVSR reflects the S-wave resonance on soft surface layer. However, this hypothesis has been contradicted by several other researchers who argue that there is a relationship between the ellipticity of the Rayleigh waves of fundamental mode and the HVSR curves, e.g., Bonnefoy-Claudet (2004) and Yamanaka et al. (1994).

Aki (1957) proposed a theory based on the relationship between the temporal and spatial spectra of seismic waves to obtain phase-velocity dispersion curve. Based on this theory, he developed

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an array technique called SPatial AutoCorrelation (SPAC) microtremor method to determine the underlying subsurface velocity structure of the S-waves and phase velocity of Rayleigh waves using short period microtremor with frequency more than 1.0 Hz. The SPAC coefficient is a function of the frequency and phase velocity based on the distances between various stations in the array is a quantity to be calculated firstly during data analysis.

### 3. DATA ACQUISITION AND ANALYSIS

In this study two microtremor datasets were processed by SPAC and HVSR methods. One of them is termed as Dataset N101. This dataset consists of the synthetic microtremor waveform computed for 1D model. The simulation was done using the finite difference method (Cornou et al. 2006). The range of frequency for this dataset is from 0.1 Hz to 20 Hz. The array of receivers used to simulate Dataset N101 comprised of fifteen stations in all and consisted of one equilateral triangle with side 150 m, within which there was a regular hexagon of side 24 m and a smaller regular hexagon of side 6 m,

The other dataset was obtained from two field surveys at the same site. First field survey was performed from March 5 to 7, 2009 and the other was from June 15 to 17, 2010, and the site for these field surveys was located near the Toyota Community Baseball Ground, Jyoso City, Ibaraki Prefecture, Japan. The suspension P- and S-wave (PS) velocity logs (SPSVL) method was earlier applied before these two surveys at this site and the data so obtained then from SPSVL method was used as a reference model in the present study. There are two main roads passing nearby the site for field survey, which are regarded as the main source of microtremor for this field survey. The VSE12-CC (0.01 Hz to 100 Hz) feed back type long period velocity seismometers were used in both field surveys. The seismometers had sensitivity 5.0 V/cm/s and the manufacturers are Tokyo Soku-shin Ltd. The 24 bit single channel digital recorders McSeis-MT were used on the field. Their frequency coverage is from DC to 500 Hz (manufactured by OYO Co.). During the field surveys in March, 2009 and June, 2010 equilateral triangular arrays with a side length of 150 m and 600 m each were deployed, respectively. Each array had seven stations.

#### 3.1 Data Analysis for SPAC

The sampling rate at the data acquisition in the field was 100 Hz. A digital anti-alias low pass filtering technique was applied on this dataset. This filtered data was re-sampled at a new sampling interval of 0.04 s. The length of time block used was 512 data and the consecutive time blocks were overlapped 50% upon each other. Then screening was done which had two steps. *1st step*: Elimination of the time blocks that contained impulsive noise due to traffic. The time blocks of which maximum absolute value exceeded "a" times of its root mean square amplitude within the same time block were excluded from the analysis. *2nd step*: Elimination of the time blocks of which root mean square amplitude was deviated "b" times of the standard deviation from the average of root mean square amplitude over all time blocks survived from the 1st step. The values of "a" and "b" were set as 4.0 and 2.0 respectively for both datasets, i.e., Dataset N101 and data from field survey. It was necessary to give the value of the band width of the Parzen window. In the present analysis, its value was set equal to 0.04 for both datasets. From this procedure SPAC coefficient was yielded.

The next step was to estimate the dispersion curve from SPAC coefficients. For this purpose, the inversion of SPAC coefficient  $\rho(\omega, r)$  was done within a frequency range corresponding from  $kr = 0.0$  to the first trough of  $J_0(kr)$ , the Bessel's function of first kind and zero order. In the process of finding the dispersion curves from the SPAC coefficient, heuristic searches were also conducted using the downhill simplex method (DHSM, e.g., Press et al. 2002) combined with the very fast simulated annealing method (VFSA) proposed by Ingber (1989). The combined method is called the DHSM-VFSA.

The inversion of underground velocity structure from the dispersion curve of Rayleigh waves is done using the optimum, namely, the fastest schedule. According to Yokoi (2005) the parameters describing the cooling schedule of VFSA are  $t_0$ ,  $m$ , and  $n$ , having values equal to 1.0, 0.6 and 1.3,

respectively. The cooling schedule itself can be given as,  $t_k = t_0 \exp(-nk^m)$ , where  $t_k$  denotes the temperature at the  $k$ -th step iteration (Ingber 1989; Yamanaka 2004). The compressional wave velocity  $V_p$  was calculated from shear wave velocity  $V_s$  using the formula  $V_p = 1.11 V_s + 1.20$  (km/s) proposed by Kitsunezaki et al. (1990).

### 3.2 Data Analysis for HVSR

For data analysis, the data recorded in all was divided into several time windows. Then aforementioned screening was applied. After that Fast Fourier Transform (FFT) was applied to obtain power spectra of each time block for two horizontal and one vertical component. These power spectra were averaged over the time blocks survived from the screening. In order to get a better correlation between the amplification factor of shear waves and peak values in HVSR, Konno and Omachi (1998) smoothing function was applied to the curves of averaged power spectra. Finally horizontal to vertical spectral ratios were generated

## 4. RESULTS AND DISCUSSION

### 4.1 Dataset N101

The SPAC coefficients for each inter-station distance in an array were calculated and plotted against the frequency, as seen in Figure 1. The curves for each inter station distance  $r$  shown with different colors and patterns, look like the one for Bessel's function of first kind and zero order.

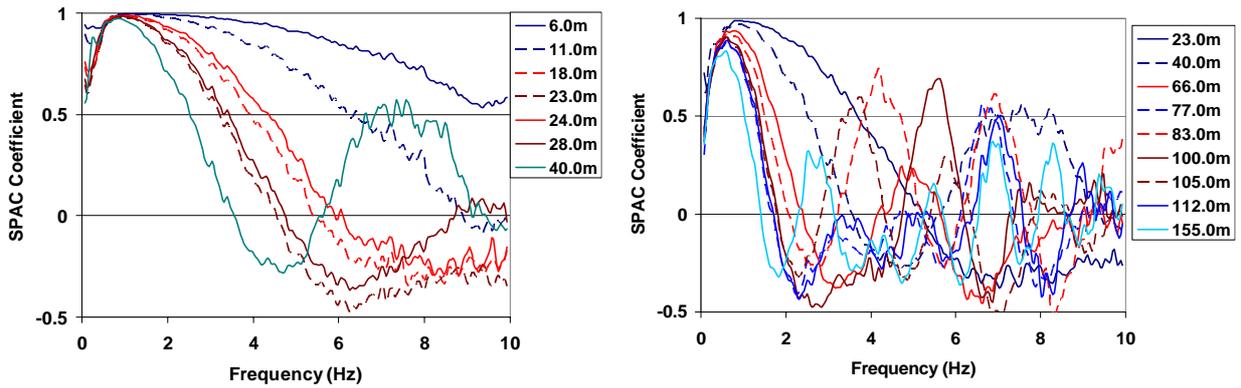


Figure 1. SPAC coefficients obtained from (Left: Small array, Right: Large array) Dataset N101.

After performing the inversion process in order to find the phase velocity  $c(f)$ , a dispersion curve was achieved as shown in Figure 2. It can be seen clearly that the best fitting of the observed dispersion curve with that of theoretical one is found at lower frequency e.g., below 2.5 Hz. The velocity model obtained after performing heuristic search is shown in Figure 3. The dashed lines show the velocity model obtained after applying the SPAC microtremor method while the solid lines show the one theoretically calculated and used as a reference model. At shallow depths the difference of  $V_s$  in both models is very small, but in deeper

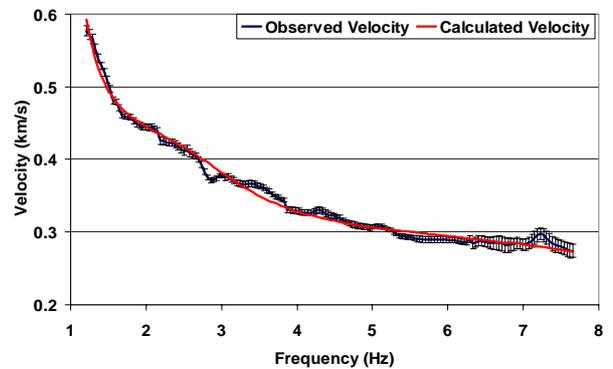


Figure 2. Dispersion curve from Dataset N101.

parts this difference becomes significant. In contrast to the compressional wave velocity  $V_p$ , the shear wave velocity  $V_s$ , has values very close to each other in both velocity models. The estimated  $V_s$  values had a good agreement on the average with those provided in the reference model. The number of layers given in the estimated  $V_s$  profile was less than that in reference model but the noticeable fact is that there was gradual increase in the velocity with depth in the reference model while clear contrasts were assumed at each interface of every layer in estimated model. That is why it is asserted that the  $V_s$  values yielded from Dataset N101 had a good agreement on the average with those in the reference model.

The HVSR curve obtained by processing Dataset N101 had a maximum at a value slightly lower than 4.0 on vertical axes. This value of HVSR did not fulfill the criteria set by Horike et al. (2001) for peak value of HVSR to be pronounced as the resonant frequency of sedimentary layer. Hence, the limitation of HVSR method was observed. By comparing the HVSR from each receiver with their average, it was found that the curves so obtained had stability at frequency band under consideration, which implied the reliability of calculated HVSR.

#### 4.2 Data from Field Survey

The curves for SPAC coefficient plotted against frequency are shown in Figure 5. In case of both large and small array, it can be seen that the curves are not as smooth as in an ideal case for plotted Bessel's function. However, their characteristics are similar to the Bessel's function i.e., the first peak value is lying close to 1.0 and then gradually decaying. The peaks of SPAC coefficient curves do not lie at 0.0 Hz because of the limitations of frequency coverage of equipments used.

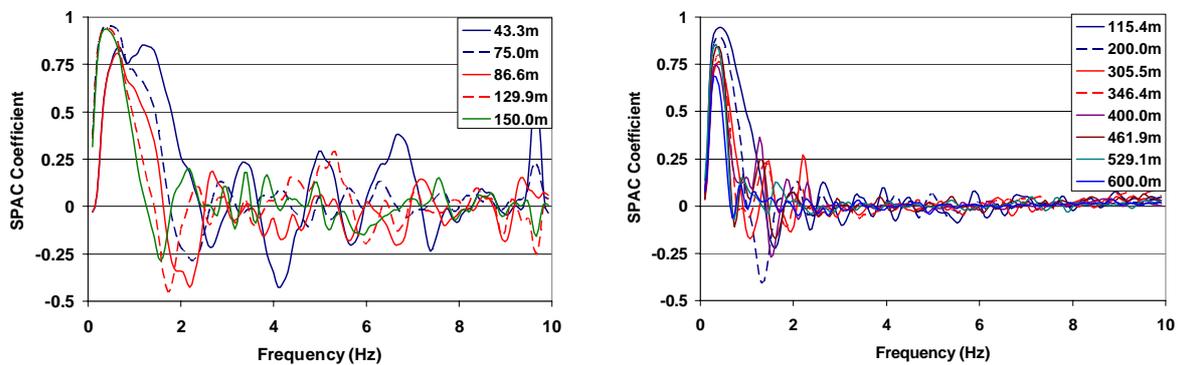


Figure 5. SPAC coefficients, obtained from (Left: Small array with radius = 150 m. Right: Large array with radius = 600 m) field survey data.

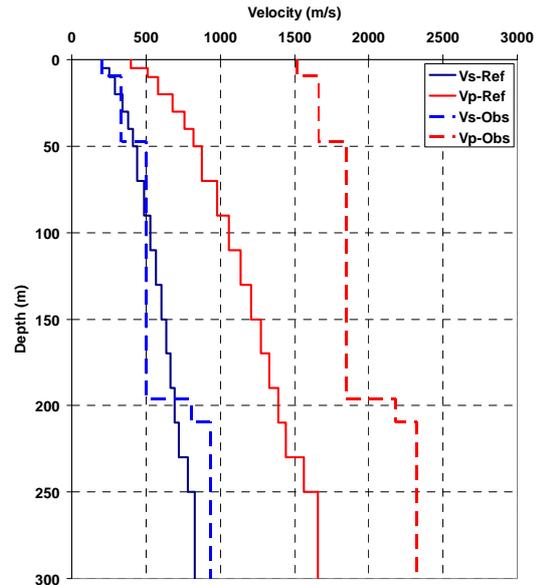


Figure 3. Velocity model comparison from Dataset N101.

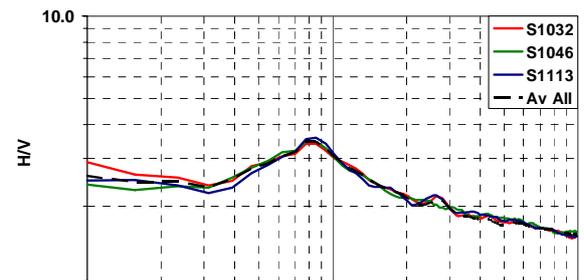


Figure 4. HVSR curves for Dataset N101.

The observed dispersion curve is in good fitting with the theoretical one at almost all the frequencies, as can be seen in Figure 6. The reason for this good fitting may be the size of the array. The larger arrays are designed usually to investigate the deeper parts of the sedimentary structures. The frequency range of the waves recorded with the help of large arrays is mostly very small e.g., in the case under consideration, the frequency ranges from 0.4 Hz to 2.6 Hz.

The estimated velocity model has very small contrasts with the reference model. As it can be seen from Figure 7 that right from the surface of the ground to depths as shallow as around 580 m, the velocities are in nice agreement with each other. However, parts deeper than that have a clear contrast. The reason for this big difference in velocities is the size of the array. The radius or lateral extent of the arrays used for field survey, were 150 m and 600 m. While applying a geophysical exploration technique, especially using an array method, it is believed that the deepest possible depth explored is of the order of the size of array. Therefore, it can be seen clearly that the values of velocities are very close to each other at a depth shallower than 600 m which is also the lateral extent of the large array.

The values of  $V_s$  at all depths were in concise agreement in case of microtremor data from field survey. The depth resolution of interfaces of some sedimentary layers with respect to the reference model had differences. In spite of this minute discrepancy, the overall goal of estimation of  $V_s$  was achieved successfully.

The microtremor data from single station in the field survey were used to calculate H/V spectral ratio and a curve for the same was plotted against frequency, as shown in Figure 8. In order to check the reliability of the HVSR, these ratios were also calculated using the record of aforementioned July 4<sup>th</sup> event. The horizontal to vertical Fourier ratio, hereafter referred as H(S)/V(S), for this event was calculated, for data of ground motion from surface and also the horizontal to horizontal Fourier ratio, hereafter referred as H(S)/H(B), for data of ground motion from bottom seismometer. These ratios have been plotted against frequency and shown in Figure 8. The earthquake records had not sufficient signal to noise ratio in the frequency range lower than around 0.6 Hz; therefore, the frequency under consideration in this case was set higher than 0.6

Hz. Also due to the paucity of data at lower frequency range, the HVSR from microtremor is also considered at higher frequencies e.g., higher than 4 or 5 Hz.

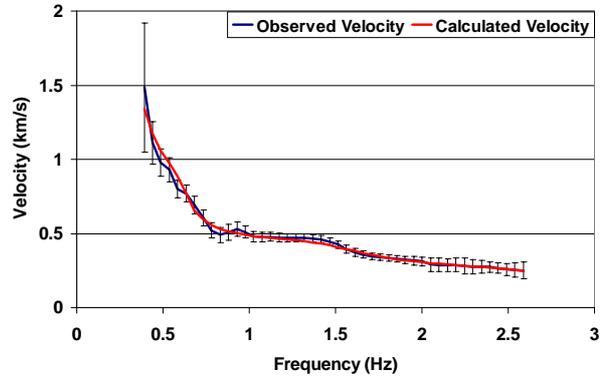


Figure 6. Dispersion curve from field survey data.

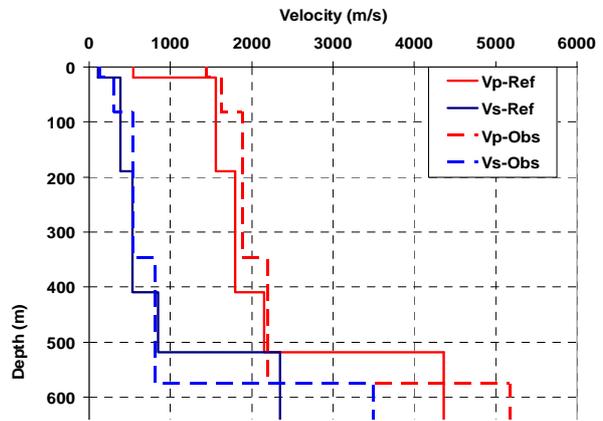


Figure 7. The comparison of velocity model for the field survey data is illustrated.

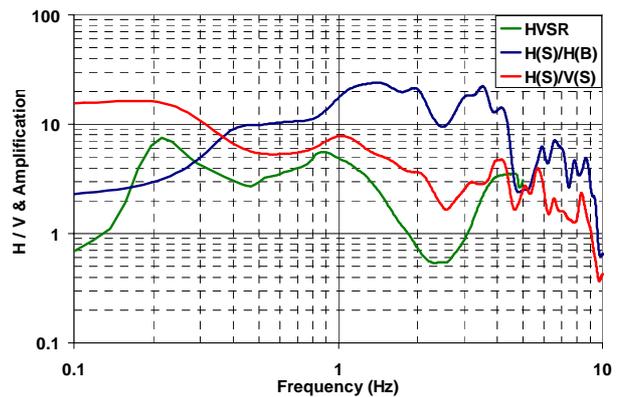


Figure 8. Curves showing HVSR (green) and H/V Fourier spectral ratio (red) from surface seismometer and the ratio between the vector sums of horizontal components at surface to bottom seismometers at IBRH10 (blue).

In case of HVSR computed from field survey microtremor data and that from the earthquake record from surface seismometer at IBRH10 station, a good agreement was observed between the dominant peaks of curves. Horike et al. (2001) showed that HVSR of microtremor is comparable with those of earthquake records or relatively smaller. Figure 8 shows the same tendency. No clear relationship was found between HVSR of microtremor and H(S)/H(B) of earthquake which is generally regarded as amplification.

## 5. CONCLUSIONS

This study was based on experiment for the validation of SPAC and HVSR microtremor methods. Two datasets were processed by SPAC method, one is the field survey while the other synthetically simulated. In addition, an earthquake record from surface and borehole seismometers was also taken into account to check the reliability of results from field survey data processed by HVSR method.

For Dataset N101, the number of layers was different for estimated and reference model. However, there was a significant match between the two velocity models. For the data from field survey, the estimated velocity structure of shear waves was in good comparison with its reference model. The curve of H/V spectral ratio obtained from microtremor had similar characteristic as compared with that of the earthquake data recorded by the seismometer at ground surface. The idea that there exists a relationship between HVSR of microtremor and that of earthquake records was supported by this study. The comparison between S-wave amplification from earthquake record and HVSR from microtremor did not show any resemblance. Therefore, the idea that there exists a relationship between H/V spectral ratio and amplification of waves in sedimentary layers was not supported by this study.

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