Deep subsurface shear wave velocity investigation in south of Tehran, using large aperture ambient noise array measurement

E.Haghshenas, M.Fazlavi
International Institute of Earthquake Engineering and seismology, Tehran, Iran

SUMMARY
The seismic hazard in southern part of Tehran is very high due to its vicinity to the active faults, in one hand and the high amplifying characteristics of local geological condition on the other hand. Beside these 2 factors the high density of housing and huge number of inhabitants in this part of the city resulted in very high seismic vulnerability and risk. The previous experimental studies, using weak motions and single station ambient noise recordings, revealed a very high amplification especially for low frequencies (0.3- 1 Hz) despite to the existence of stiff to hard alluvial deposits near to the ground surface. The interpretation of this amplifying characteristic cannot be achieved without recognition of deep profile of the subsurface condition and the depth of the geological bedrock. This problem conducted us to perform a series of ambient noise array measurement with the aim of identification of deep shear wave velocity profile. The small aperture arrays, have been done in 2007 did not give us the satisfying results, so some large aperture arrays are tested. This paper discussed the results obtained by the large aperture measurements.

Keywords: Shear wave velocity, Large aperture ambient noise arrays, Tehran

1. INTRODUCTION

Recognizing of geometrical and physical property of sedimentary layers is essential for earthquake hazard studies, especially in urban area. Tehran, capital of Iran, is a city with high population surrounded by active faults. Up to now, all the previous site effects estimation for this city is based on the engineering bedrock ($V_s \geq 600$ m/s) consideration that can be reached in shallow depths (<50 m) almost in all part of the city. Two of most important researches in this regard are a series of earthquake geotechnical microzonation projects of Tehran that were started in 1994 by International Institute of Earthquake Engineering and Seismology (Ex. Jafari et al, 2001 & 2004) and seismic microzonation of Tehran, by JICA (Japan International Cooperation Agency) & CEST (Centre for Earthquake & Environmental Studies of Tehran, Tehran Municipality) completed in 2001. This depth of bed rock and stiff characteristics of the overlying layers resulted in moderate amplification only for frequencies greater that 2 Hz obtained by both of these major projects. These results are totally different with the results of the experimental researches that were performed later, using a temporarily seismological network and ambient noise measurements. This study revealed very high amplification factor (>7) for a wide range of frequencies (0.3-8) (Haghshenas 2005) using the standard spectral ratio technique, introduced by Borchert (1979). These differences conduct us to define a major project in order to identify the deep Vs profile for alluvial deposits of Tehran using ambient noise array measurements. The measurements were designed in two perpendicular north-south and east-west section (Fig. 1) using 7 multi aperture arrays (small to large) in north-south direction and 3 arrays in east-west direction, passing through the area with highest amplification. .This paper shows the results for Vellayat Park (ancient airport and garrison of Ghale-Morghi) that is located in southern part of Tehran, at the area with highest amplification and resonance frequency of 0.45 Hz.

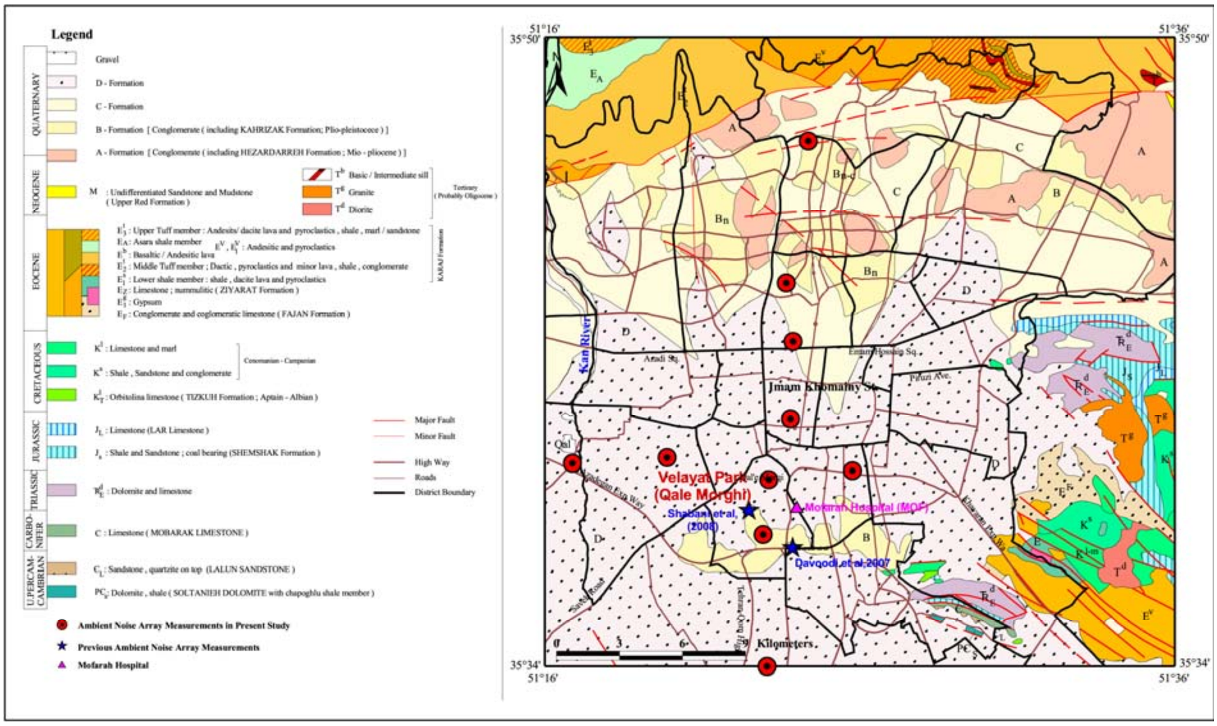


Figure 1 : geological map of Tehran. red circles show location of arrays in north-south and east-west section that Vellayat Park is in their intersection. Also two previous array measurements study and MOF station is shown with blue star and pink triangle.

2. MICROTREMOR MEASUREMENT

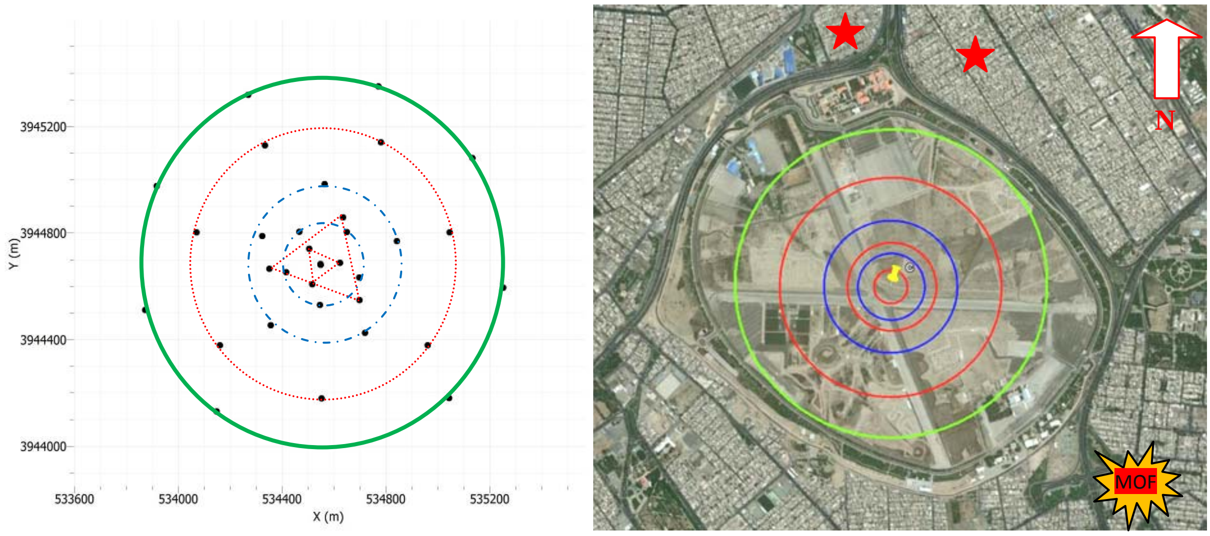
Two previous ambient noise array studies have been done before the present research. First one presented in Davoodi et al (2007) by measuring 3 concentric circular arrays with radius 25, 35 and 50 meter at southern Tehran (Shaghayegh Park), using 15 seismological stations installed for 15 hours. This study failed to detect the geological bedrock due to small arrays aperture, and of course the goal of the project was to study up to depth of 100 meters.

Another test was performed in 2006 by International Institute of Earthquake Engineering and Seismology (Shabani et al, 2008). Joint inversion of dispersion curve and ellipticity curves revealed that inverted profiles are very sensitive to the weight on different input data (dispersion curves, ellipticity curves and resonance frequency) introduced during the inversion for computing the global misfit function. Also they computed the SH transfer functions for the ensemble of inverted Vs profiles and by scanning different bedrock depths. Although they could not identify the depth of bedrock directly by array data and inversion processes but they suggested 700 to 1200 m is a suitable estimation for seismic bedrock depth to satisfy very low resonance frequency around 0.4 Hz for that location. This depth is accordance with our guesses based on geological knowledge.

In the present study we performed 5 circular arrays in Vellayat Park in 2011 (Figure 2 and Table 1) using 11 CMG6TD Guralp seismometers. All of these arrays in exception of Array C consist of 2 concentric circles installed simultaneously. The radius of the array varies from 150 to 700 m. The absolute times of recordings were provided by GPS antenna connected to each station and the duration of simultaneous measurements were 2-3 hours for each array.

Table 1 : Configuration of different arrays measured in Vellayat Park.

Name	label	Radius (m)		Station number without center		Date	Remark
A		150	300	5	5	11-June	2 stations did not work
A'		150	300	5	5	25-June	
B		200	500	3	7	12-June	
B'		75	500	3	7	26-June	
C		700		9		13-June	



a b

Figure 2: a) stations design in five arrys, (array A, A' : blue dashed line, array B,B' : red dotted line and Array C : green line) b) satelate image over Gale Morghi site (blue circle and red stars shows geotechnical site investigations and location of Downhole test consecutively)

2.1 Geotechnical information

Unfortunately there is not any deep geotechnical borehole near the studied location. However based on the information obtained from 12 borehole (maximum depth of 50 meter), drilled during 2 civil construction projects at the distance near to Vellayt Park, the geotechnical characteristics of the studied location can be summarized as table 2. As can be seen for the first 30 meters the soil profile consist of relative stiff to stiff clay and sandy clay soils, for which the shear wave velocity vary between 200 m/s to 650 m/s from top to depth.

Table 2 : Geotechnical and Geophysical data

Depth(m)	**classification**	**SPT**	**density**	**Vs**	**Vp**	**Poisson ratio**	**Shear Module**	**Yang Module**
	USCS	**N**	**Kg/m^3**	**m/s**	**m/s**	**--**	**Mpa**	**Mpa**
0-5	CL	20-40	1900	225	550	0.4	70	300
5-10				325	950	0.44	160	550
10-15			2000	410	1350	0.46	250	700
15-20		15-30		475	1450	0.45	350	1000
20-25				575	1525	0.41	660	1900
25-30	SC	30-50		630	1450	0.4	670	1950
30-35				645	1500	0.39	800	2200

3. H/V RATIO

The H/V ratios for 22 measurements have been calculated using the Geopsy software packages prepared by the SESAME consortium. To calculating the H/V ratio, after required waveform operation such as offset removal and band pass filtering, stationary windows was selected to avoid transient signals using a STA/LTA threshold (0.3 to 2.0). The length of the windows was determined at 40 to 60 sec with 5% cosine tapering on them. Spectral amplitudes using FFT and Konno and Ohmachi smoothing (40%) are calculated for the three components with a quadratic average for horizontal components (E & N).

H/V spectral ratio method has been proposed originally by Nogoshi and Igarashi (1970, 1971), but this technique was in fact introduced by Nakamura to the knowledge of the western world by a paper published in 1989. In Figure 3, Major peak on H/V curve is observed in low frequency band about 0.4 Hz. This value is consistent with pervious study by Haghshenas (2005) based on earthquake recording on Mofarrah Hospital (MOF) (see Figure 1and Figure 2b). There is a mismatch between amplification ratio obtained by H/V technique on ambient noise in the present study (< 3) and amplification ratio obtained by site/reference spectral ratio for MOF station using earthquake data (>7), presented in Haghshenas (2005). This mismatch may be caused by lack of sufficient energy in noise wave field in respect to earthquake records and were discussed by Haghshenas (2005) and Haghshenas et al (2008).

Another peak on H/V curve can be observed around 1.3 and 5 Hz on all stations. The first one is an industrial peak and the second one seems to related to a minor impedance contrast in shallow depths (see Haghshenas, 2005).

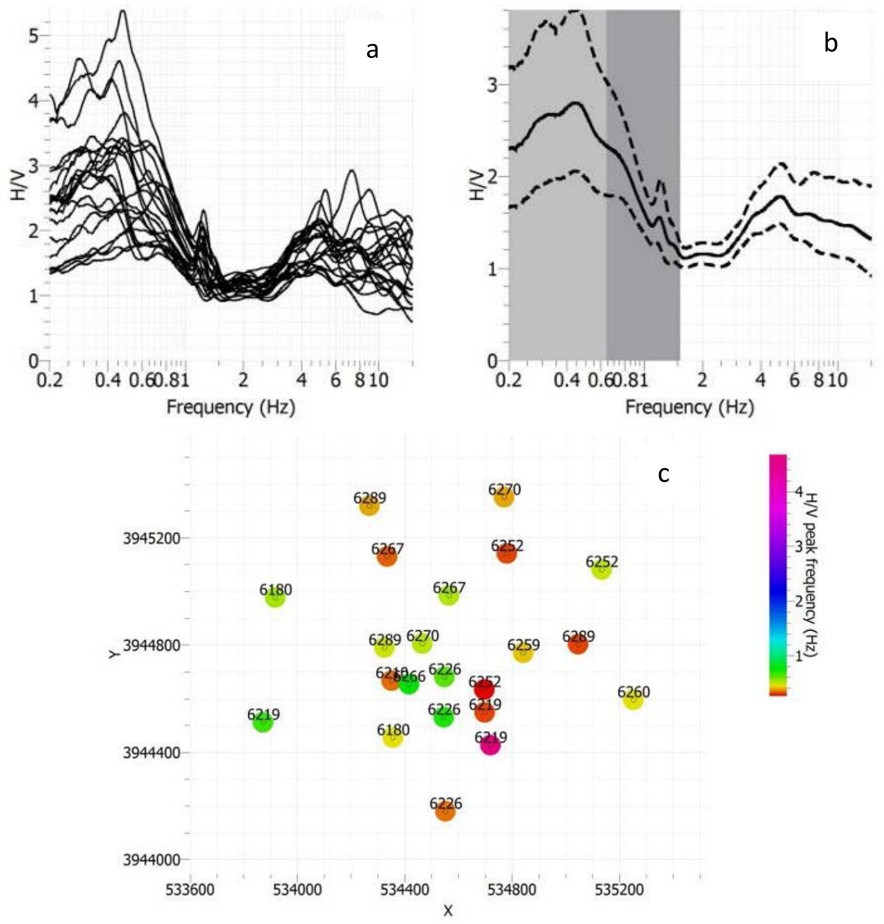


Figure 3: a) H/V curve for 22 stations. b) Mean value of H/V c) H/V peak frequency for each station

4. ARRAY DATA PROCESSING

Dispersion property of surface wave is a base of array microtremor measurement method (F-K, SPAC). Since depth of penetrating of surface wave is frequency depended, shear wave velocity (Vs) profile can be driven from inverting of dispersion curve. But due to contribution of different mode of surface wave, estimated shear wave velocity is not unique. In general array processing methods (F-K and SPAC) are performed only applying vertical component of seismological recordings using dispersion property of Rayleigh waves, but the horizontal component can also be applied using Love wave field.

Frequency-wave number analysis (F-K, Lacoss et al. 1969, Capon 1969, Kvaerna and Ringdahl 1986) assumes horizontal plane waves traveling across the array of sensors. Considering a wave with frequency f, a direction of propagation and a velocity (or equivalently k_x and k_y, wavenumbers along X and Y horizontal axis, respectively) the relative arrival times are calculated at all sensor locations and the phases are shifted according to the time delays. The array output divided by the spectral power is called the semblance (Lacoss et al. 1969, Asten and Henstridge, 1984). The location of the maximum of semblance in the plane (k_x, k_y) provides an estimate of the velocity and of the azimuth of the traveling waves across the array.
Spatial Autocorrelation Coefficient Method basically was defined by Aki (1957) using ambient vibration processing. As well as Henstridge (1979) developed relationship between Spatial Autocorrelation Coefficient and Fundamental mode phase velocity of Rayleigh waves. The SPAC method is designed to estimate the dispersion curves for surface waves by analyzing the correlation between noise recordings made at nearby sites. Since the method is based on a statistical investigation in time and space, we assume that the signal is a stochastic noise, stationary in both domains. The SPAC method modified using correlation concept between vertical components of recorded noise at each both stations keeping same azimuth especially at the irregular and large aperture array in urban area (Bettig et. al, 2001). Detail formulation of F-K and SPAC method presented by Okada (2004, 2006) with limited stations at least 3 or odd number on circumference.

Tokimatsu (1997) presented the following relationship between the inter-station distances and the desired wavelengths that can be used in array measurement design.

$$2D_{min} < \lambda_{min} < \lambda_{max} < 3D_{max} \tag{1}$$

D_{min} and D_{max} is minimum and maximum distance between 2 station also λ_{min} is minimum wavelength to avoid the aliasing error and λ_{min} is maximum valid wavelength (2 to 4 D_{max}) due to site filtering. Considering that k=2π/λ, Table 3 shows valid ranges wavenumber intervals for the measured arrays that should be considered in selection of valid parts on dispersion curves.

Table 3: valid wavenumber intervals for measured arrays in Vellayat Park

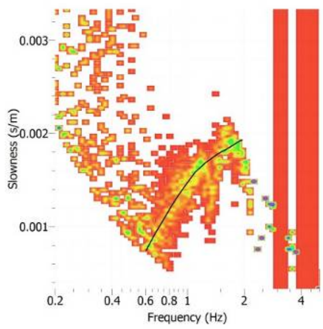
Array apertures	K min	D max	k max	d min
75-500	0.001571	1000	0.0419	75
150-300	0.002708	580	0.0209	150
150-300	0.002708	580	0.0224	140
200-500	0.001587	990	0.0157	200
700	0.001122	1400	0.0073	430

Due to wavelength validity interval and its relationship with array aperture and limited equipment, two procedures can be used (Okada, 2006). style1; array measurement with various apertures at different periods of time for the same place, style 2; concentric circular arrays configuration that measure simultaneously but with different apertures.
Style 2 is more suitable for combined analysis method such as FK, however it requires more equipment. The same results as style 2 can be obtained in style 1, using combination of dispersion

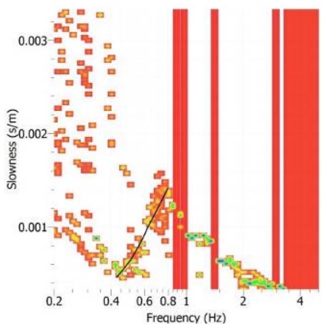
curves in their valid intervals.

In present study, due to deep sedimentary substructure, different array with medium to large apertures would be needed. According to equipment limitation, five arrays recording plan was designed (style1) that four of them contain two circles (style2).

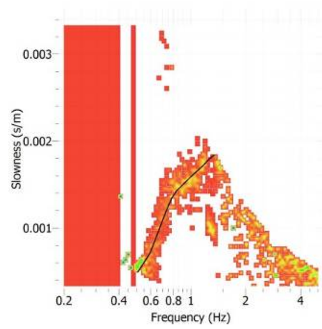
Dispersion curves of five arrays were derived using Geopsy package using both approach SPAC and F-K. Band pass fitter (0.2 - 20 Hz) applied to all data. Figure 4 shows the results of F-K analysis that their semblance is greater than 70%. Each curve filtered in the reliable range according to Table 3. After applying this filter, the high power narrow band, observable on slowness- frequency space, can be picked up. It is noted that we should jointed all dispersion curve together and resampled them in a common interval to obtain a dispersion curve with larger band frequency ranges. Then, this driven combined dispersion curve (Figure 4d) can be applied in inversion process.



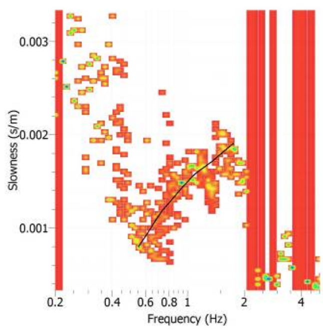
a :Array A(150, 300 m)



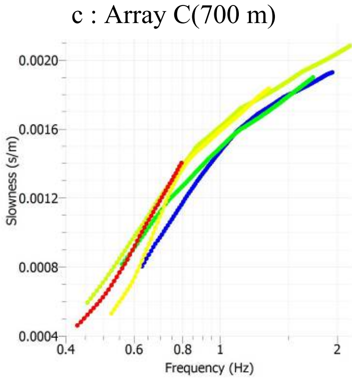
c : Array C(700 m)



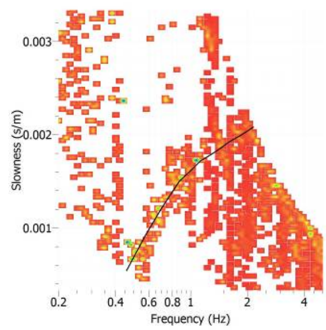
e: Array B(200, 500m)



b :Array A'(150, 300 m)



d : all arrays (A,A',B,B',C)



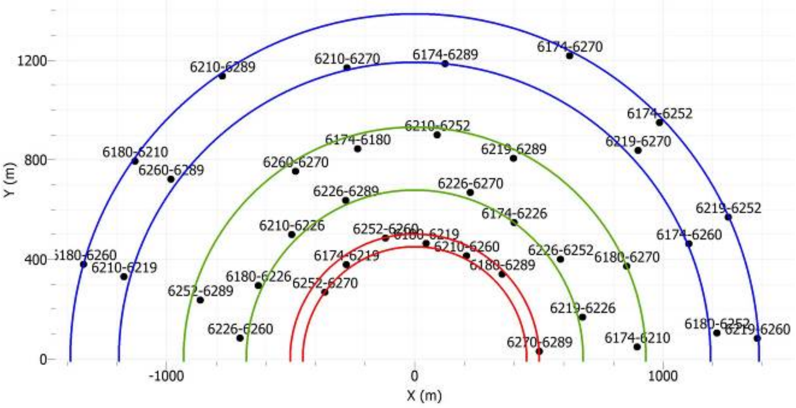
f : Array B'(75, 500 m)

Figure 4 : F-K analysis dispersion curves for all arrays. This figure shows slowness against frequency for windows having semblance and beam power greater than 70%. All the dispersion curves were plotted together in panel d (blue: array A; green: array A'; yellow: Array B, olive: Array B' and red: array C)

In SPAC method, after selecting the appropriate rings on possible combinations of pair stations azimuth- distance (see Figure 5 for array C), autocorrelation curves for each ring can be calculated. We obtained dispersion curve by analysis of all auto-correlation curves simultaneously. The reliable dispersion curve can be selected with picking the appropriate band of dispersion curve as the Figure 6.

Although SPAC coefficients of large aperture rings have weak coherency comparing to other rings with small aperture, but according to Figure 6, analysis of all autocorrelation curves together can provide appropriate dispersion curve.

In the next step, Inversion analysis was performed using the Conditional Neighborhood Algorithm (Wathelet, 2008) to get best models of substructure layers with minimum misfit. After applying inversion process, P and S wave velocity profiles and theoretical dispersion curves can be plotted (see Figure 7).



Array C(700 m)

Figure 5 : Selected rings and possible combinations of pair stations azimuth-distance in an array C of radius 700 meter, Gale Morgi , Tehran

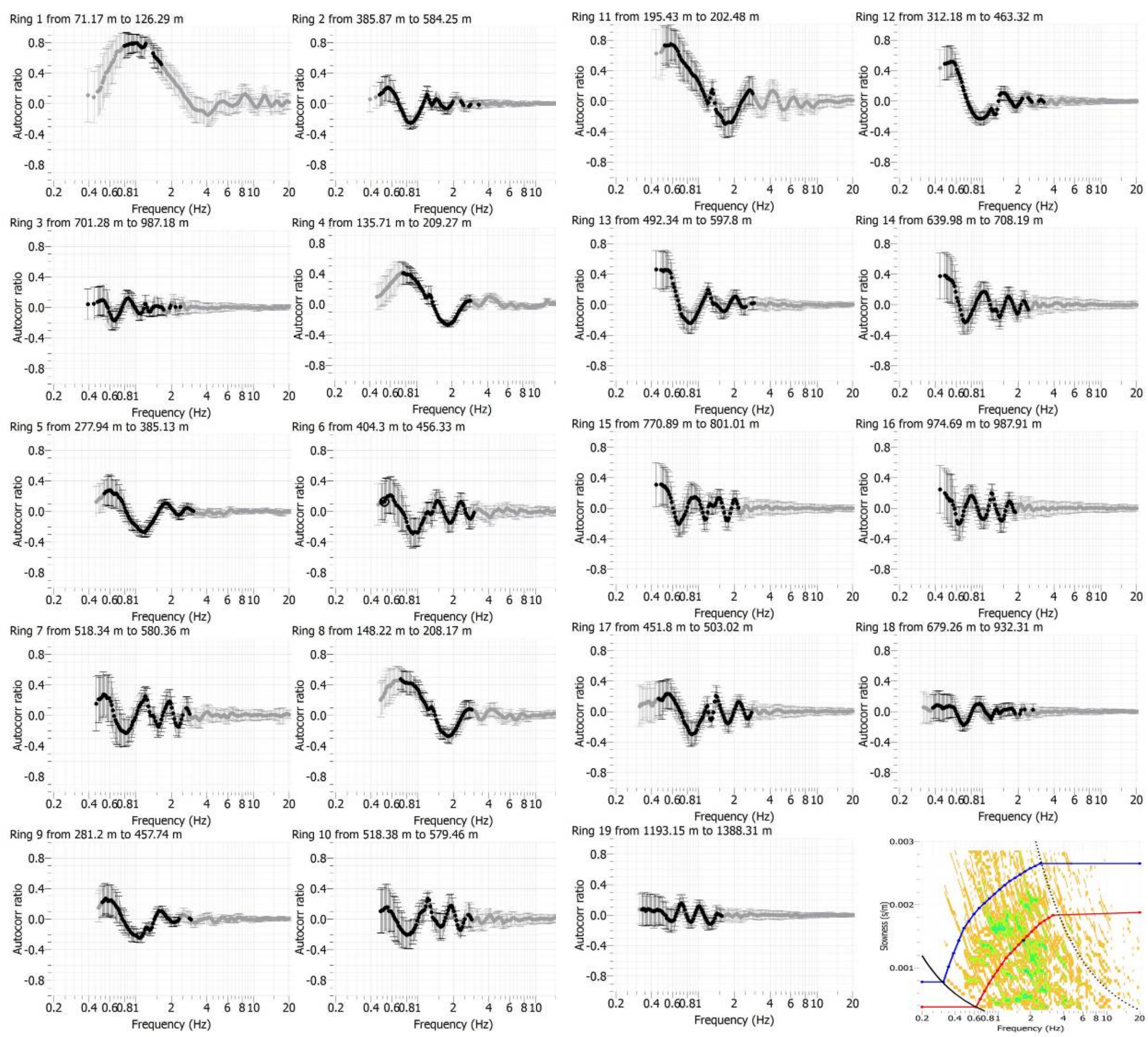


Figure 6 : Auto correlation ratio curve for all arrays

Table 4 : the primary parameters of sub sedimentary layers used in the inversion analysis

Depth	Vs	Vp
m	m/s	m/s
10	200-300	500 - 1000
20		
30	300-600	1200 - 1600
50		
100	T:600 - 800 B:800 - 1200	T:1500 - 2000 B:2000 - 5000
1000		
1500		
>1500	1000 -3500	3000 -5000

Inversion processing was initiating using estimated parameters shown in Table 4. P and S-wave velocity range to 50 meter depth has been achieved from previous geotechnical and geophysical information. Also the unknown sub layers parameters were estimated using linear approach that any iteration was considered 10 layers with top and bottom specified limit until bedrock layer. Poisson ratio interval and density was variable between 0.2 to 0.5 and 2000 to 2300 Kg/m^3 respectively. Ground profile and theoretical dispersion curve obtained from F-K and SPAC analysis separately is shown in Figure 7a,b. Of course joint inversion of 5 F-K dispersion curves and 19 SPAC Autocorrelation curve was carry out together that Figure 7c is visible.

It is noted that sharp contrast is visible Using F-K and SPAC analysis. F-K analysis results show that the contrast at 700 meter depth has shear wave velocity larger than 2000 m/s while SPAC analysis results show that bedrock contrast located at a depth between 600 to 900 m with mean shear wave velocity equal 2000m/s (between 1500m/s to 2500 m/s).also joint inversion of F-K and SPAC show the contrast at 600 m, Gradual hard sedimentary to 900 m and layer with constant velocity.

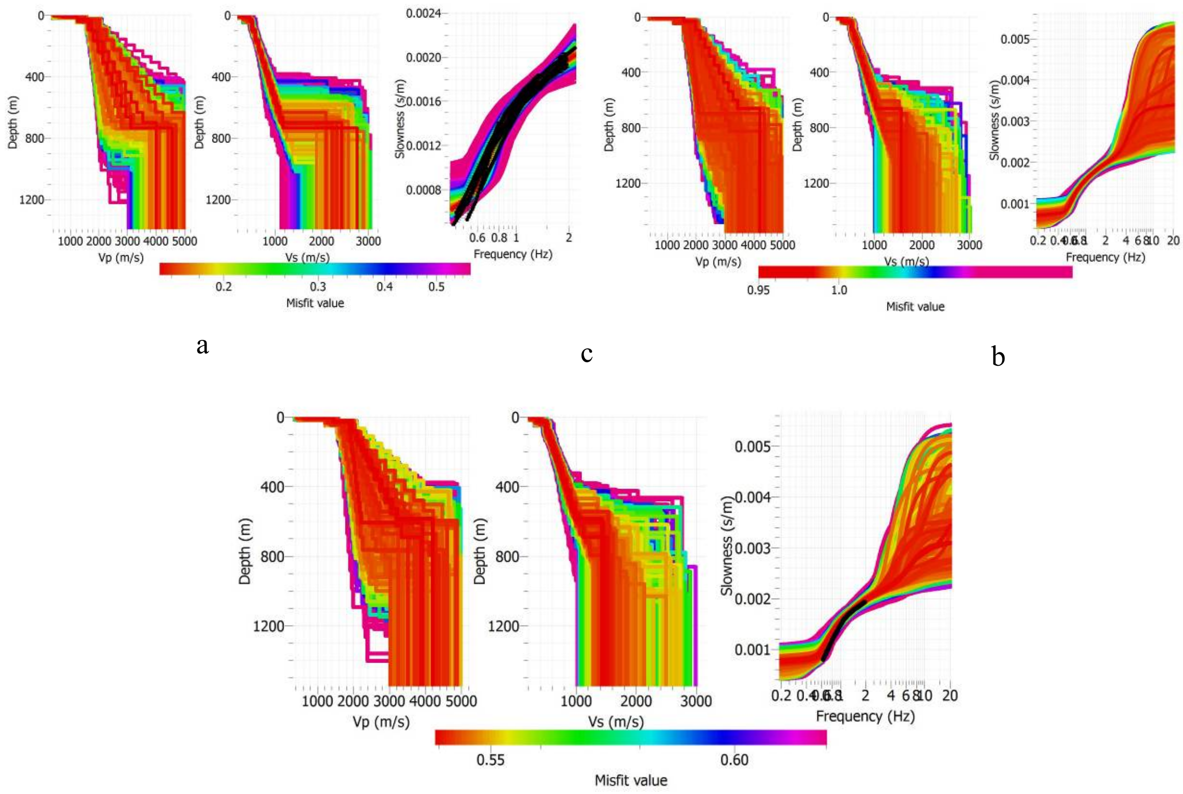


Figure 7 : Dispersion curve and ground profile to 1500 m. a)F-K b)SPAC c) joint inversion of F-K and SPAC

5. DISCUSION AND CONCLUSION

Five medium to large aperture array measurements (radius: 150 to 700 meters) were performed at 11 to 26 June 2011 in Vellayat Park, southern part of Tehran with the objective of identification of deep shear wave velocity profile and seismic bedrock contrast. Identification of this deep Vs profile is essential for the region of Tehran considering very low resonance frequency, observed in previous studies as well as in the present study on calculated H/V spectral ratios.

In contrary to previous array studies in Tehran using array with small aperture that failed to detect any deep impedance contrast, the present study revealed relatively a clear contrast in depth 600 to 900 meters. This depth is in agreement with geological evidences and the results obtained previously by SH transfer function calculation (shabani et al, 2008) considering many model with different bedrock depth. This range of bedrock depths can also explain relatively the existence of very low resonance freauency (0.4 Hz), observed for this part of the city. Due to the large aperture of measured arrays and invalid obtained dispersion curves for the frequencies higher than 2 Hz the present study cannot predict the soil profile for the depth near to surface and the contrast related to minor secondary peak observed in H/V ratio at 4-5 Hz. More measurement of small aperture arrays and considering the higher mode contribution will be needed to detect the shallow contrast simultaneously.

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