Evaluate Reliability of f-k and SPAC methods

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ABSTRACT :

In recent years, microtremors observation was widely in use for estimation of the sub-surface S-wave velocity (Vs) structure.

To evaluate reliability of ambient vibration array methods in Microtremor data analysis and to compare ones results for a same known field, a set of Microtremor array records was performed in selected site in Tehran (Iran capital). Furthermore, the results of in-situ tests like SPT, PS-Logging and DownHole (to 200m depth) and Refraction-Reflection of wave tests exist in the site and Vs profile is available. Therefore, it is possible to compare the results of Microtremor data processing (by two Array methods: f-k and SPAC method) and existing Vs profile (by In-situ tests).

This paper focuses on reliability evaluation and precision of array methods with small aperture arrays. By defining 3 errors types (Boundary detect error, Velocity detect error and Total error) relationships between array geometry (station number and distance …), data recording times, input vibration types (human or natural) and quantity or quality of results agreement in depth ranges that show more reliability are studied.

As a striking result, the SPAC method is probably more convenient compared to the f–k method, because it gives results as well as the f–k method by using less recording stations and with shorter dimensions arrays. However, the topic would deserve thorough further investigations.

KEYWORDS: Site Characterization, Geotechnical Earthquake Engineering, Site Effects, Ambient Vibration Array Methods (f-k , SPAC , …)

1. INTRODUCTION

In Geotechnical Earthquake Engineering, accurate evaluation of the S-wave velocity profile of the sub-layers (down to seismic bedrock) has particular importance on Site effect studies. Up to now, many studies have been performed on Geotechnical earthquake hazard about local ground effects in many countries, which the results have been presented as Microzonation maps.

There are many approaches to measure Vs profile of soil deposits. Nowadays, in additional to direct method of wave velocity measurements including laboratory and in-situ tests, indirect methods are often used. The direct methods require boring and geophysical or laboratory testing that impose significant cost and time. Whereas in indirect method, the Vs evaluation focus on economical, rapid and simple methods like H/V spectral ratio and Microtremor array recording.

In H/V spectral ratio method, natural frequency (quantity) and amplification factor (quality) of sedimentary deposits are evaluated from ambient vibration records with suitable precision. Notwithstanding advantages of H/V spectral ratio toward other methods, this method encounter with limitations like weakness in evaluating the Vs velocity variation with depth. Therefore, ambient vibration array methods are considered to evaluate the Vs profile of soil deposits, which is based on the surface wave's dispersion properties in subsurface layers. In fact, the dispersion properties of the surface waves are induced due to the different propagation velocity of the frequency component of the signal. In the Microtremor array methods, several measurement stations are used simultaneously to record vertical component of the ambient vibration. Then, the frequency-wavenumber (f-k) and the spatial autocorrelation (SPAC) methods are used to quantify the Rayleigh wave phase velocity spectrum (dispersion curve) and spatial autocorrelation curve, respectively. Since surface waves show individual dispersion property due to the layering of soil deposits, Vs profile of subsurface ground layers can be obtained from developed theoretical equations and using inversion analysis.

2. ACQUISITION and PROCESSING MICROTREMOR DATA

In continuing the array studies in Iran, to evaluate S-wave profile in subsurface layers in Tehran (2007) an investigation project was considered in typical site in south of the city (Shagayegh-park) which various field and lab studies were performed around this area. In this test, fifteen CMG-6TD seismometers (Güralp) were used simultaneously as 3 concentric circles arrays with 25, 35, 50m radiuses. Minimum stations distance was 25m and maximum one was 86m. Totally in this field operations, 3D seismograph systems recorded ambient vibrations along 15 hours with a sampling frequency of 100 samples per second. Briefly, circular array with radius 25m is marked as array A, circular array with radius 35m as array B, and array with radius 50m as array C (to analyze with SPAC method). Also a central sensor and six other sensors which located on the heads of two triangles is considered as array E (to analyze with f-k method) (FIGURE 1).

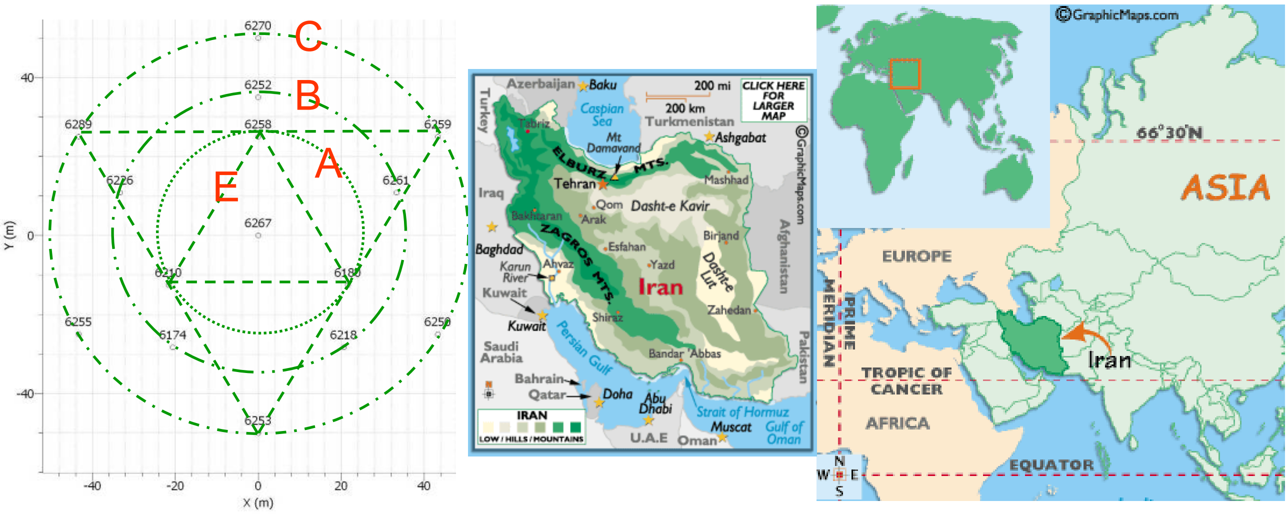

FIGURE 1. Arrangement of stations in Tehran site, Shaghayegh Park.

SESARRAY software which designed by Wathelet et al. is used to perform array processing of the test data in present study. To evaluate the subsurface structure following steps are necessary:

- Recording ambient vibration signals using array stabilized on the ground surface;
- Evaluating and determining of surface waves dispersion properties from response of subsurface structure;
- Evaluating subsurface structure by using inversion of dispersion properties principles.

In continue, processing results of two most adherent methods in acquisition and processing (to determine dispersion properties) of ambient vibration data, namely:

1. frequency-wavenumber method (f-k)
2. Spatial autocorrelation method (SPAC)

that are applied in Tehran's test (Shagayegh-park) will be presented:

At the first, Dispersion curve of Rayleigh wave was calculated for array E is showed in FIGURE 2. As it shown, dispersion curve divulges high standard deviation over 10Hz and lower 0.8Hz frequency ranges. Therefore the dispersion curve was selected in the range (0.8-10Hz) and this part of the curve was used to inversion. As it could be expected, the part response better in inversion processing.

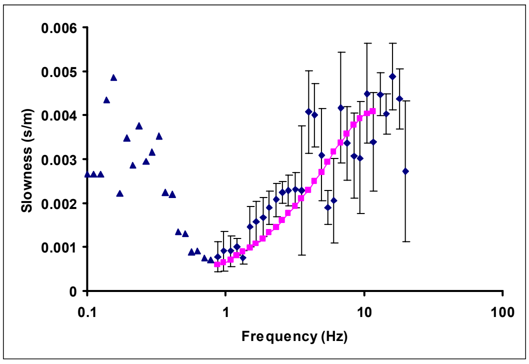

FIGURE 2. Derived dispersion curve for array E in 0.8-10Hz frequency range (Tehran site, Shaghayegh park).

In additional, "Theoretical array response" is the other criteria that are mentioned to determine reliable part of dispersion curve derived from Microtremor data in recent studies and tried to be mentioned and used in Tehran's site. Theoretical response of array E is shown in FIGURE 3(a,b,c). The summery of the criteria calculated results for all various arrays are presented in TABLE 1.

TABLE 1. k_{max} and k_{min} values for proposed arrays in the Tehran site, Shaghayegh park.

	Array Mark	Number of sensors	K_{max}	K_{min}
1	A	4	0.237384	0.1061992
2	B	6	0.180038	0.071133
3	C	7	0.120587	0.0490366
4	E	7	0.151037	0.0634138

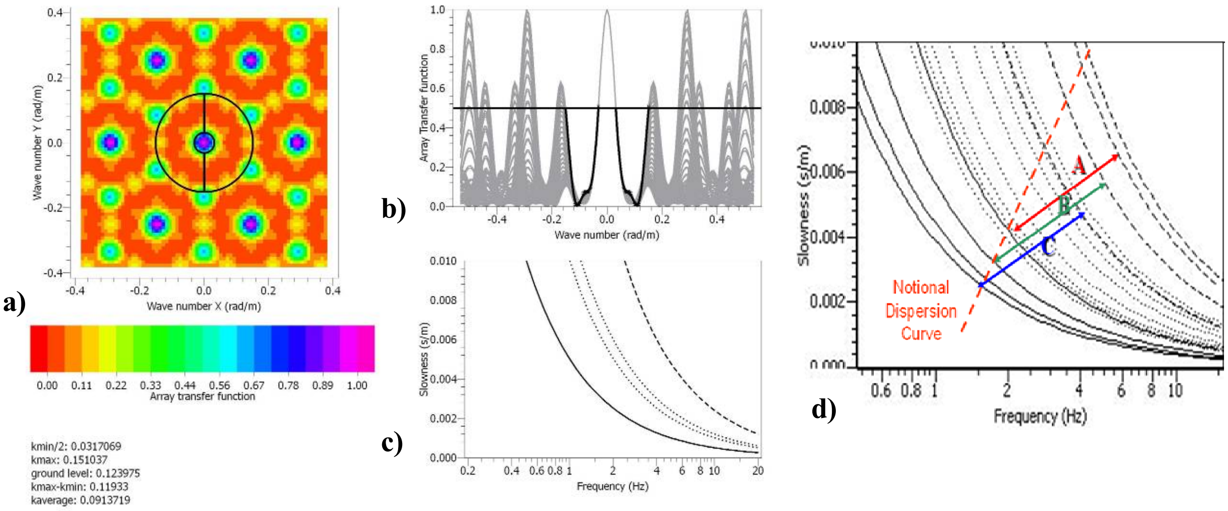

FIGURE 3. a) Theoretical array response in (k_x, k_y) plane for 7 sensors (array E) in Tehran site. b) The sections through (a) response for various propagation directions that shown by grey curves. c) k_{max} and k_{min} values in slowness-frequency domain. d) Comparatives between arrays A, B and C Th.responses.

Also, reliable spans comparatives were performed between arrays A, B and C are illustrated in FIGURE 3-d, follow to TABLE 1.

To use SPAC method In the test, the circular arrays using data was studied and analyzed and dispersion properties of Rayleigh waves were evaluated. For example, SPAC curve for array C in 0.95-18 Hz range which extracted from rings of FIGURE 4 is shown in FIGURE 5.

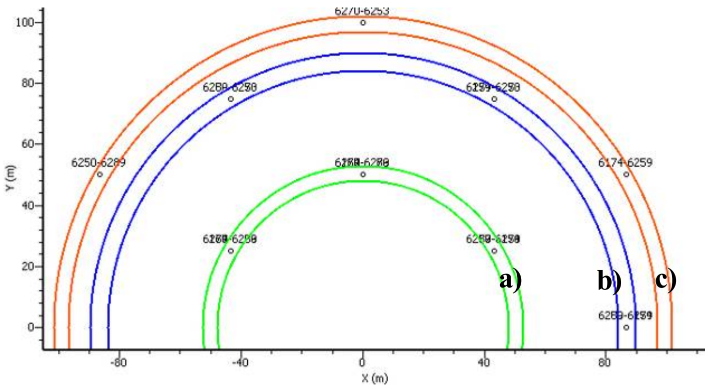

FIGURE 4. Selected rings and possible combinations of pair stations azimuth-distance in array C: a) green: 48-53m, b) blue: 84-90m, c) red: 97-102m (Tehran site, Shaghayegh park).

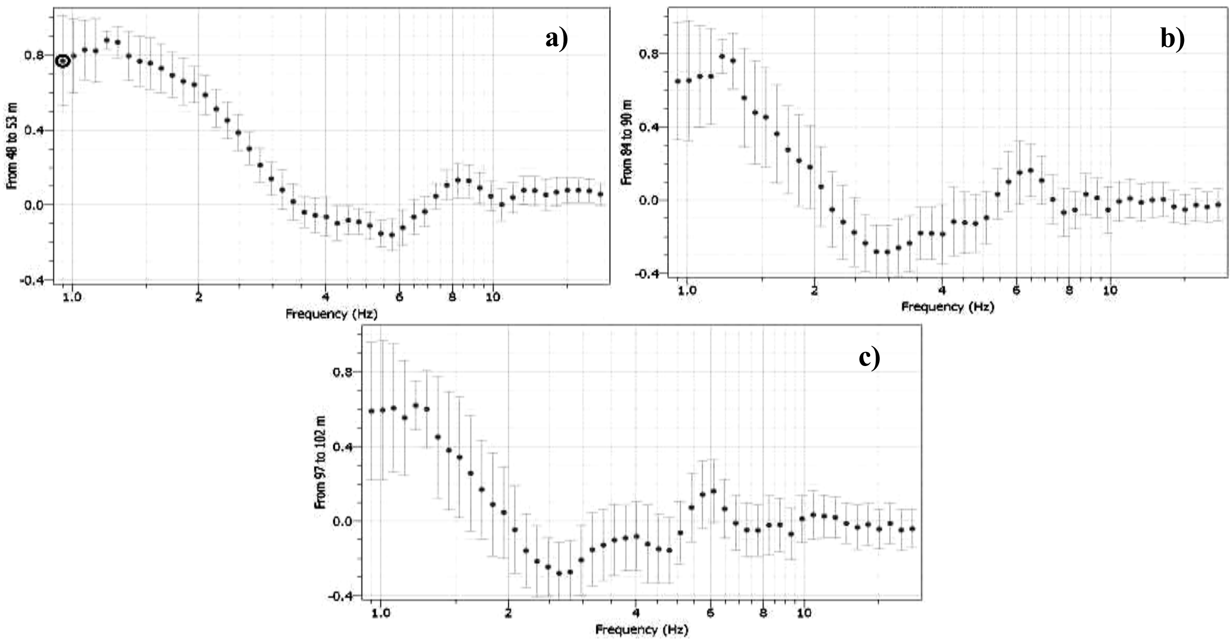

FIGURE 5. SPAC curves for array C in 0.95-18Hz frequency range and rings of FIGURE 4, (Tehran site). a) ring 48-53m, b) ring 84-90m, c) ring 97-102m.

3. RESULTS of NEIGHBORHOOD ALGORITHM

Inversion process can be mentioned as the final step of ambient vibration array methods algorithm. Considering of the neighborhood algorithm advantages (Sambridge, 1999) and because this algorithm is supported by SESARRAY, that is used to complete studies in Tehran (Shaghayegh park) for subsurface structure evaluation (Vs profile). Subsurface layers properties are parameterized based on different assumptions. One of proposed model is presented in Table 2(a). To compare two methods (SPAC and f-k) results, this parameterization was remained constant during inversion process for both methods.

TABLE 2. a) Parameterization of ground structure based on different limits of Vs to perform inversion operation b) Site Vs profile base on previous in-hole investigations (Tehran site, Shaghayegh park).

a)

Number of layers	Depth of layers (m)	Vs (m/s)
6	1-12	150-400
	12-30	200-500
	30-60	300-600
	60-100	400-700
	100-160	450-700
	>160	700-1000

b)

Depth of layers (m)	Vs (m/s)
0-5	120
5-13	260
13-28	360
28-60	400
60-160	600
>160	700

On basis of dispersion and SPAC curves that shown in FIGUREs 2 and 5, which derived using by f-k and SPAC methods, respectively and considering proposed model (TABLE 2-a), inversion process was followed and a sample of derived inversion results of Vs profile is shown in FIGURE 6-b (for array C in 21-22 (GMT+00)). As variation manner of minimum misfit through generated models during inversion operation is shown in FIGURE 6-a, the misfit was decreasing through algorithm processing in selecting various new models. Also variation manner of some unknown parameters from proposed model is shown in FIGURE 6-c against misfit value. In this figure, variation range of unknown parameters such as depth and velocity is plotted against misfit value. Also dispersion curves consistent with extracted models for misfit values lower than 0.78 is shown in FIGURE 6-d.

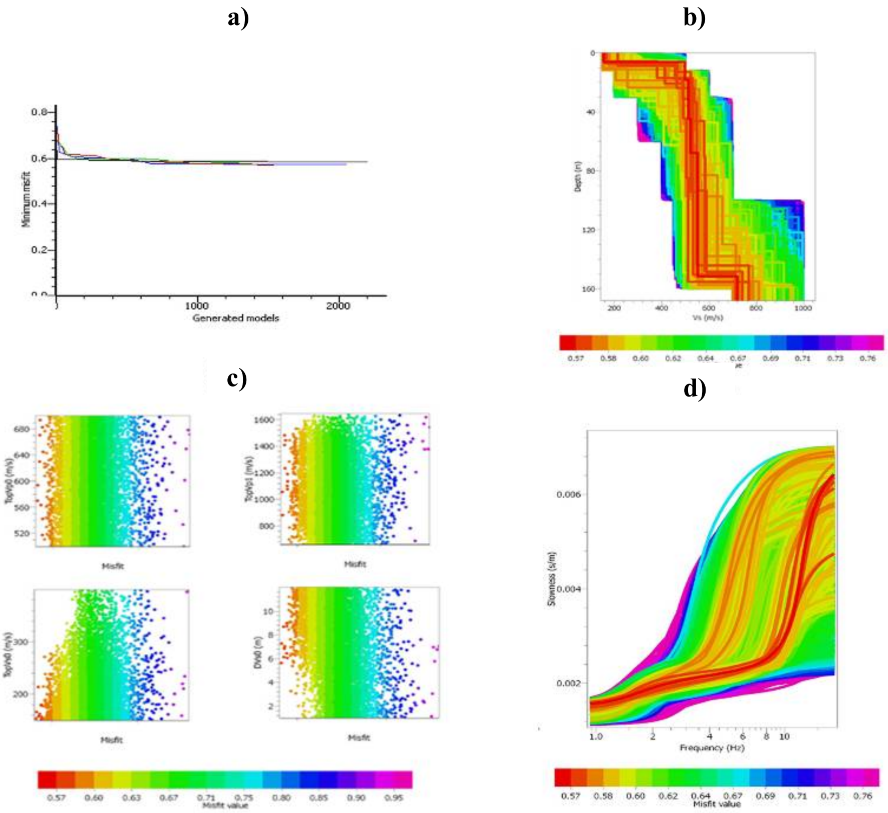

FIGURE 6. Array C, the results of inversion processing: a) Variation of minimum misfit for generated models during inversion operation (Tehran site, Shaghayegh park), b) Derived Vs for models with misfit values lower than 0.76, c) Variation manner of some unknown parameters from proposed model against misfit value, d) Derived dispersion curves for misfit lower than 0.76 corresponding to extracted models.

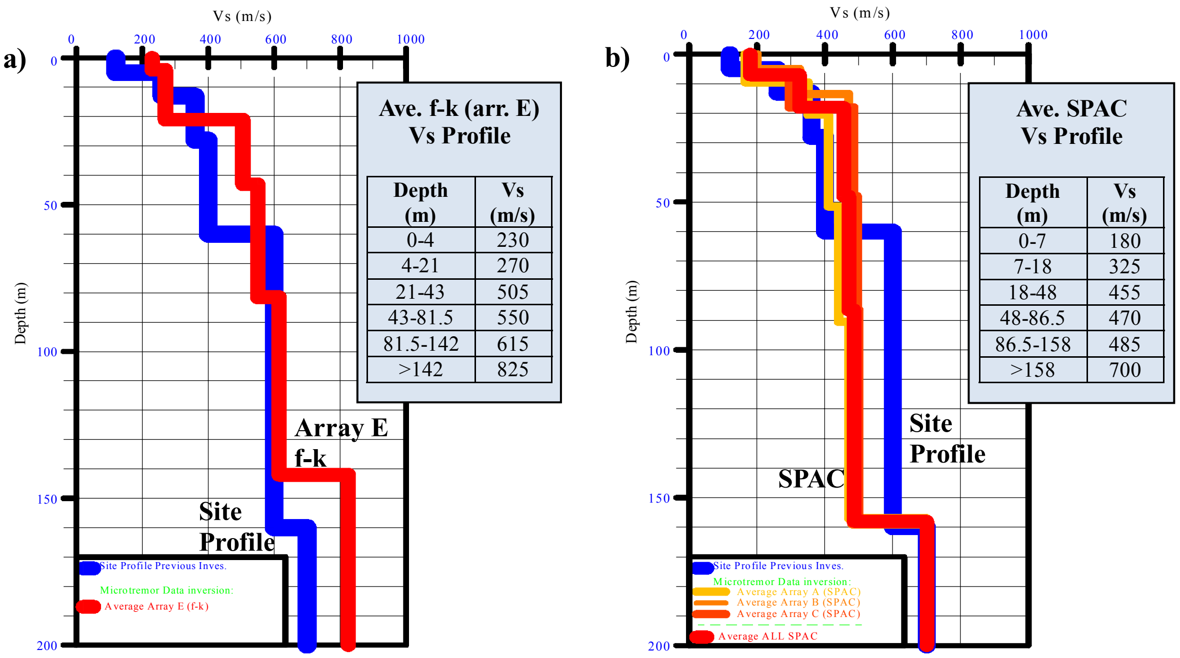

FIGURE 7. Final results of Vs profile comparisons with site profile, using array methods: a) f-k b) SPAC

On basis of obtained results from ESPAC processing method, it seemed that Vs profile derived from array C is more consistent with previous site investigation results (FIGURE 7-b). Also obtained results of f-k method in array E show that notwithstanding a part of observed dispersion curve lie in low frequency range (0.1-0.8 Hz) was not used in inversion analysis because of high dispersion data (FIGURE 2), but Vs profile has suitable consistent only in lower than 140m depth with previous site studies results (FIGURE 7-a). Therefore in comparing various arrays processing results together, it seems that using by ESPAC method in same conditions, deeper layer properties can be identified, clearly (FIGURE 7-b).

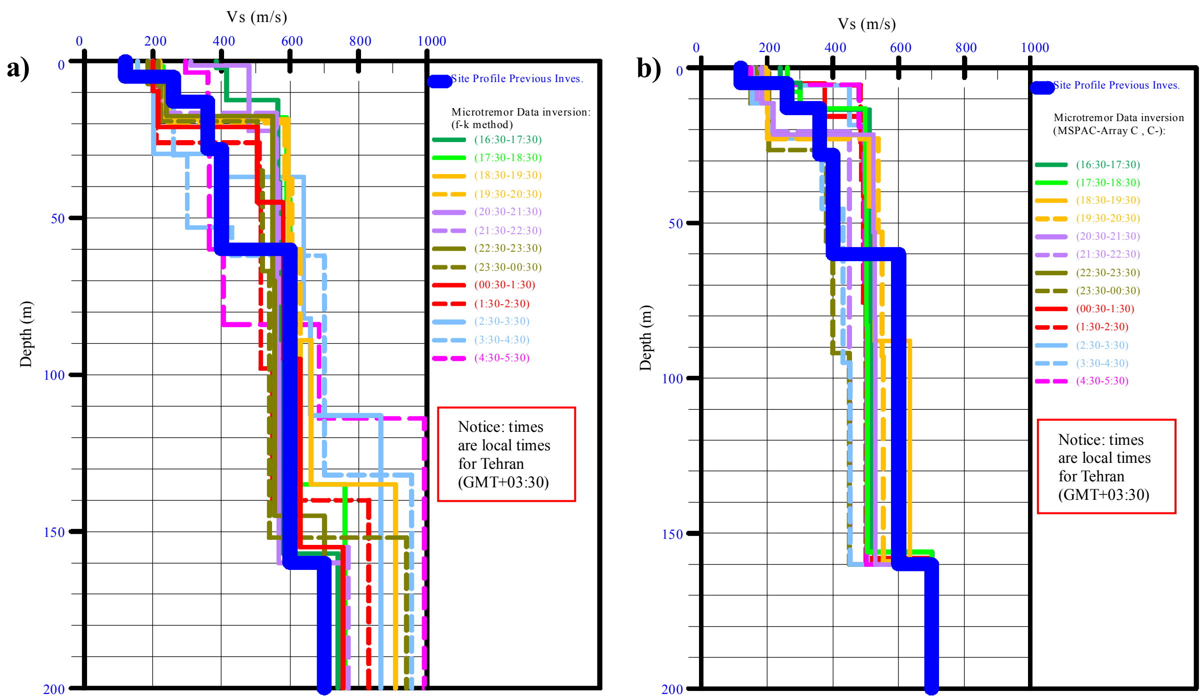

FIGURE 8. Comparing the shear wave velocity profile Between obtained ambient arrays results (in different recording times) And previous investigations in Shaghayegh park of Tehran (bold line is the site profile): a) for ambient array E (f-k method); b) for ambient array C (SPAC method)

4. EVALUATING the PRECISION VALUES

The results of E-array (using f-k method) in several times that are available compared to the reference Vs profile (In-Hole investigations) are presented in FIGURE 8-a; Also for array C (MSPAC) in FIGURE 8-B.

By defining 3 errors/precisions on those results (FIGURE 8) contains:

- (Boundary detect Error ≡ Eb):

$$E_b = \sum \left| \frac{\Delta H_i}{H_i} \right| \quad \& \quad \Delta H_i = (H_i - H'_i) \qquad \textbf{(4.1)}$$

Where, follow to FIGURE 9:

H_i: The thickness of each layer (Site profile, pervious investigations);

H'_i: The thickness of each layer (Microtremor data inversion);

- (Velocity detect Error ≡ Ev):

$$E_v = \frac{\sum \left(\frac{Vs_i - Vs'_i}{Vs_i} \right) . H_i}{\sum H_i} \qquad \textbf{(4.2)}$$

Where, follow to FIGURE 10:

Vs_i: The Shear wave velocity of each layer (Site profile, pervious inv.);

Vs'_i: The Vs of each layer (Microtremor data inversion).

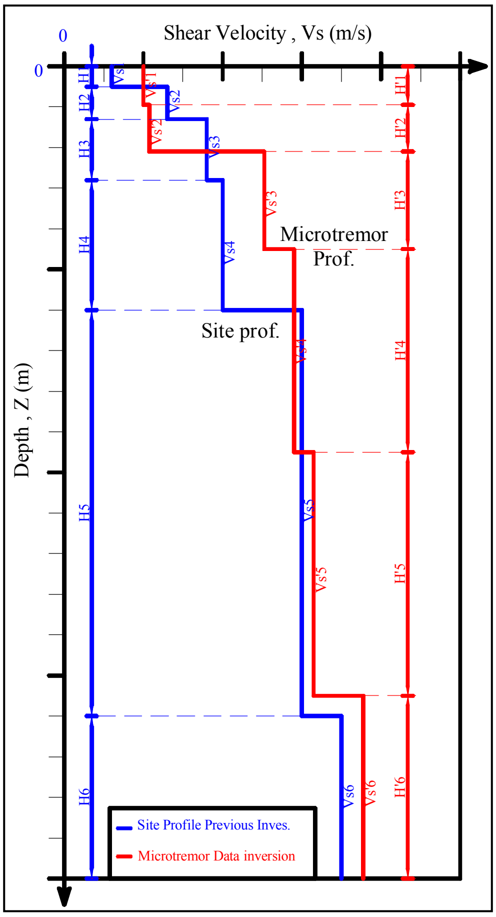

FIGURE 9. Defining of parameters (Depth, Vs …) to calculating E_b , E_v. ↑

- (Total Error ≡ Et):

$$E_t = \frac{\sum A}{\sum S} \qquad \textbf{(4.3)}$$

Where, follow to FIGURE 10:

A : Area between the site Vs profile and microtremor data inversion one (V's);

S: Area behind the site Vs profile.

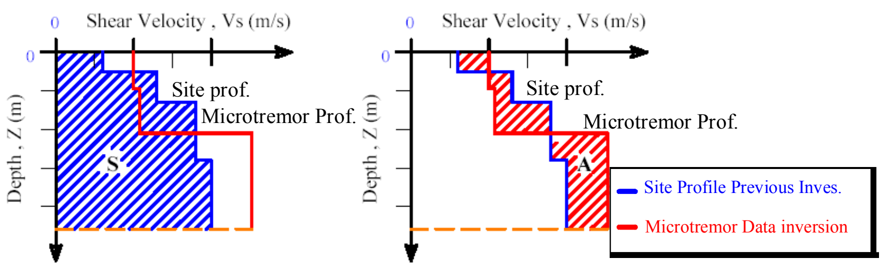

FIGURE 10. Defining of parameters (Depth, Area(S, A) …) for Total Error.

some adequate accordance are presented in FIGURE 11 for 60-160m depth (ambient array E, C-Shaghayegh Park).

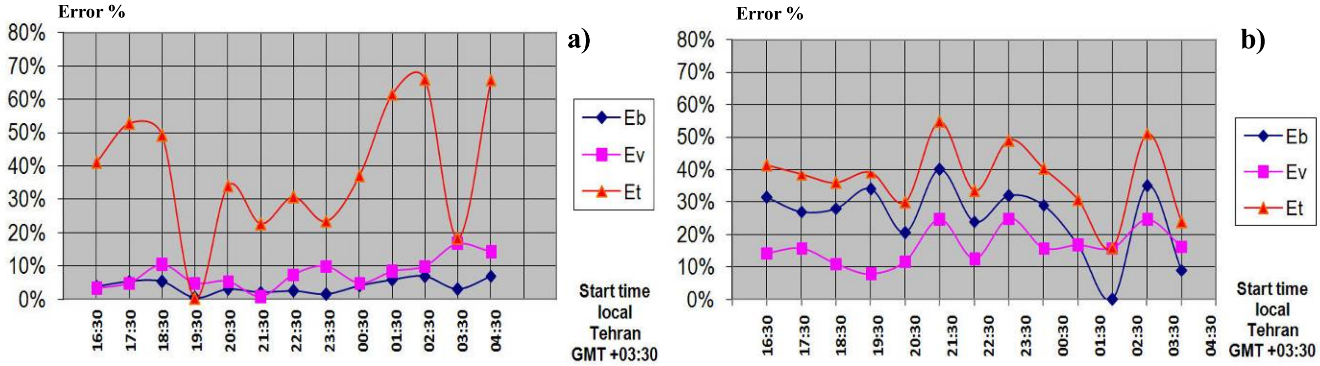

FIGURE 11. The variation of 3 Errors/ Precisions in different recording times for 60-160m depth: a) array E, b) array C.

5. DISCUSSION and CONCLUSION

1. Comparing the shear wave velocity profile obtained from ambient array test and PS-Logging test generally reveals that the SPAC method is more performable and easier than f-k method. In SPAC method, better results are obtained from microtremor data processing by applying fewer seismometers and also locating them in smaller radius arrays. Also it is possible to use 3-D seismometers in SPAC method in order to separate Rayleigh waves from Love ones. Besides, it is possible to achieve locations of microtremor sources using frequency-wavenumber (f-k) processing method.

2. By comparing the processing results of different array methods with the previous studies, it can be seen that the ESPAC method present results similar to f-k method in high frequency ranges. While in low frequency ranges, the ESPAC method acceded more suitable results than f-k one.

3. Optimum array geometries are of challenge topics. Since array output for all arrangements must be the same, it is observed in most performed experimental studies that quasi-circular shape can be actually the best selection for sensors arrangement. However, there is no necessary to locate all sensors on a circle when there are snags against performing test in the site; but always suitable central symmetric are suggested in sensors arrangement.

4. In ESPAC processing method that requires at least 4 seismograph systems, better and more accurate results were derived by using more seismographs (up to 7 systems). It was evidence that using more than 7 sensors have not significant effect on results improvement. Instead, it is recommended to use arrays with different radiuses simultaneously to increase precision in Vs evaluation. Unlike to ESPAC method, using more recording stations in f-k method provides more precision results in evaluating the shear wave velocity of subsurface structures. Based on the results of present study and considering the limitations in sensor locations and analysis time, optimum number of seismographs for evaluating the subsurface layers is recommended 10 sensors. In the Tehran ambient array test results, it is observed that by using 7 sensors as array E, just the 0.8-10Hz frequency range of dispersion curve was extracted carefully. Consequently, the appropriate V_s profile of the subsurface was extracted only till 140m depth using f-k method. It is obvious that the identification of deeper subsurface layers is related to the maximum sensor distances and the Rayleigh waves dispersion properties in low frequencies (less than 1Hz).

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