Determination of Shear Wave Velocity Structure using Array Method; Case Study of a Site in Tonkabon City

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SUMMARY:
The aim of the paper is the definition of the shear wave velocity of sediments in the eastern part of Tonkabon city using microtremor array method. Microtremor data processing was performed using Geosphy software with conventional methods SPAC and F-K. H/V analysis using Nakamura method is done on three-component receiver records and has shown that the site is in the category of low-frequency sites. The results showed that both F-K and SPAC methods identified subsurface soil layering with reasonable accuracy. The results also have been shown that with increasing the depth of investigation, precision of both methods decrease. With comparison of the results obtained from F-K method with those obtained from SPAC method it can be inferred that shear wave velocity derived from SPAC method is closer to downhole test results. The results shown in both methods, especially in SPAC, differences of the results in different record's time are not significant.

Keywords: microtremor array method, shear wave velocity, downhole test, SPAC method, F-K method

1. INTRODUCTION

The characterization of site effects frequently relies on the determination of the soil profile at a site, followed by the forward computation of the local transfer function. The reliability of the result depends to a large extent on the reliability of the determined soil profile. The more reliable techniques are usually too expensive (exploration using boreholes) or unsuitable (e.g., explosion seismology is out of the question in an urban environment) to be of general application. For these reasons, alternative methods have been devised. Currently, the most popular technique involves the computation of horizontal to vertical ratios of Fourier spectra of microtremor amplitude or H/V method (Lermo and Chavez-Garcia, 1994). Although there is a general agreement that this technique allows the resonant frequency at a given site to be identified with confidence, the debate continues regarding the reliability of the maximum amplitude obtained from those ratios.

The most recent non-destructive method is based on microtremor waves. Microtremors are formed by a variable and irregular combination of different seismic waves, where surface waves are considered to be the dominant and most coherent component [Toksoz & Lacoss, 1968]. Therefore, when microtremors are recorded through an array of vertical seismometers simultaneously recording, the characteristics of the Rayleigh wave propagation in the medium can be extracted and subsequently the soil structure and the local S-wave velocity profile can be estimated. For obtaining the Rayleigh wave dispersion curve, different array techniques can be employed. Among them, we have used the frequency–wavenumber (f-k) and spatial autocorrelation (SPAC) method in this study.

F-K method is based on the fact that a stationary random process can be characterized by means of a spectral density function, which provides the information concerning the power as a function of frequency. In a similar manner, seismic noise can be characterized by a frequency–wavenumber spectral density function, which provides the information concerning the power as a function of frequency and the vector velocities of the propagating waves. The goal is to derive the different wave velocities and directions of approach as a function of frequency from the frequency–wavenumber spectral density function of the microtremor. For that, the stationary assumption in both time and two spatial coordinates has to be accomplished (Capon, 1969).

Spatial autocorrelation (SPAC) method is the method that is mainly used for the analysis of ambient noise measurements in the area under study. It was introduced by Aki [Aki, 1957] for the determination of the phase velocity of surface waves in microtremors array recordings. The dispersion data are derived from the cross correlation functions. The basic concept of this method relates to the simultaneously long time recording of ambient noise in instruments disposed at the site of interest, implying, however, a heterogeneous soil profile only in vertical direction. The ambient vibrations consist of plain waves propagating in different directions with a single-phase velocity at each frequency. Therefore, the cross correlation function between different pairs of stations, at the same inter-station distance, can be computed upon two hypotheses. The first is that ambient noise is stationary in both time and space and the second is that the wave field consists of surface waves propagating along the free surface with power distributed equally along all directions.

In this paper microtremor recording performed using 13 receivers array with triangular shape layout. Afterward recorded data analysed thorough f-k and SPAC method and finally the result compared with geotechnical and geophysical tests results, which conducted in studied site.

2. GEOTECHNICAL AND GEOPHYSICAL EXPLORATIONS

The studied site is restricted to the northern part of the Tonkabon city which is one of coastal cities of north of Iran. In Fig. 2.1. the aerial photo of studied region, along with the location of explorative boreholes, is shown. These boreholes include geotechnical and geophysical boreholes which are shown in Fig. 2.1. separately.

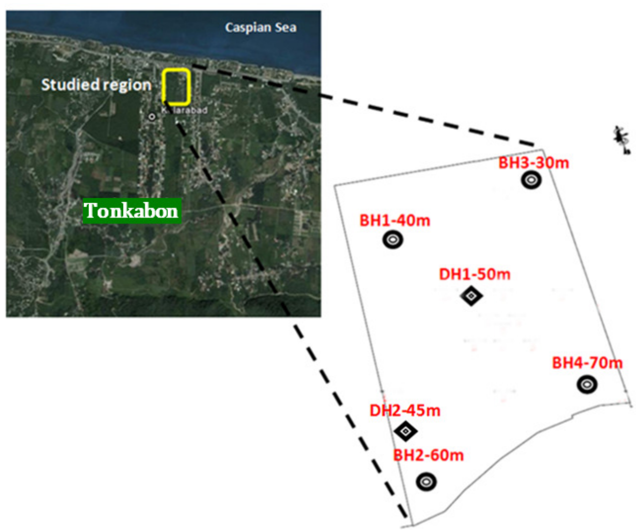


Figure 2.1. Aerial photo of studied area along with the location of geotechnical /geophysical boreholes (BH=geotechnical borehole and DH=geophysical borehole)

The studied area is a part of central Alborz Mountain which is located in the north-west of Damavand mount. Except a small part of this region located beside the Caspian sea, including studied site, which has a low altitude, the other parts of this region are mountainous, having an altitude around 3000 meters higher than the sea level. The deposits of northern plain of Tonkabon city are divided into two kinds: First, fluvial deposits which are in rivers channel and run-offs. This kind of deposits is mainly well-graded and rounded and depend on topography, their size have a wide range from clay size to boulders. Other kind of Quaternary deposit in this area is alluvial fans deposits.

In order to gain comprehensive information about the geotechnical properties of the studied region, four machine boreholes were drilled at the site. The depth of these boreholes, one after the other, is 30, 40, 60, and 70. The location and depth of each of these boreholes is shown on the aerial photo (see Fig 2.1.). These boreholes provide direct access to the subsurface soil of the studied area, and also make direct sampling and in-situ tests possible. According to these results, the exact geological/geotechnical column was drawn (Fig. 2.2.).

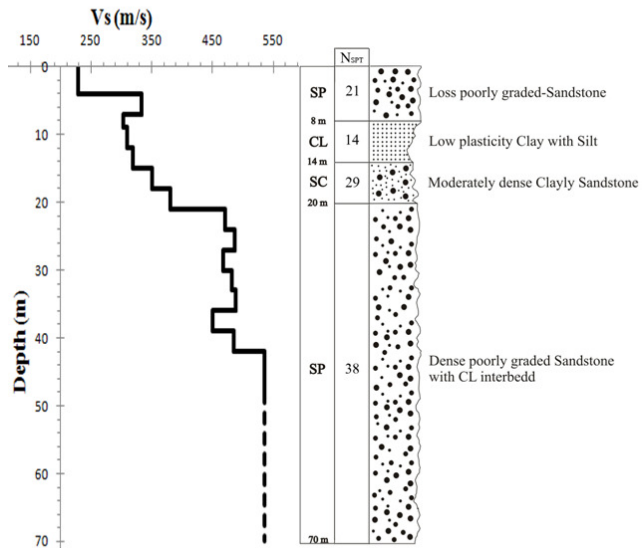


Figure 2.2. Geological column gained by direct drilling and sampling with 70m depth along with SPT test results and shear wave velocity profile obtained from downhole test

As it is illustrated, subsurface of study area, to the depth of 70 meters, is composed of four layers which layer 1 is mainly compose of loose poorly-graded sand, layer 2 is consist of low-plasticity clay or (CL), layer 3 includes moderately-dense clayey sand or (SC) and layer 4 consists of dense poorly-graded sand.

In order to gained precise shear wave velocity profile of the site two downhole tests conducted in separate boreholes. Generally, the intended borehole is drilled in an area, which is the representative of the whole area. For this end, as it is shown in Fig. 2.1., the boreholes positions were considered in the center of the studied region and the boreholes (DH-1/2) were 50 meters deep. In this test, in order to generating seismic energy for creating shear wave, a horizontal blow of a hammer on a metal plate was used, which was located in 2.5 meters from the borehole opening. It is important to mention that the ABEM RAS 24 seismograph and 3-component and 6-component in-hole receivers were used. The shear wave velocity profile obtained from the tests has been depicted if Fig. 2.2.

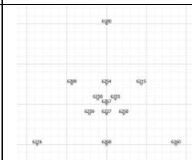
3. MICROTREMOR ACQUISITION AND PROSESSING

Data used in the present paper are collected either with conditional active seismic methods (Downhole test) or with passive microtremor measurements. The analysis and the correlation of these data aim to determine the geometry and the stiffness of the geological formations in the Tonkabon city, in order to study site response during strong ground motion shaking. The measurements took place in one place at the coastal (north) part of the city.

Regarding to recording microtremor waves at the studied site a triangular shape array with 13 receivers has been used. The seismographs applied in this paper are three-component digital

GURLAP CMG-6TD. It is noteworthy that the array was established in the site under study for 24 hours. The measurements were done continuously from 12 A.M. to 9 P.M. next day on April 13, 2009 for 21 hours. Then all the time-histories were analyzed and 10 time windows including 1, 3, 5, 7, 9, 15, 17, 19, 21, 23 (hours are in local time) were selected each for 1 hour as index. Layout and geometrical properties of used array in more detail is shown in Table 3.1.

Table 3.1. Shape and geometrical detail of used array

D_{Min} (m)	D_{Max} (m)	$\kappa_{Min}/2$	κ_{Max}	Sensor No.	Array Name	Array Shape
5	35.5	0.0554	0.7970	13	A	

According to the fact that the error source in measuring, mainly originates from instruments error, imbalance of receivers, artificial interfering vibration occurrences near receivers, and etc. it was tried to minimize these errors through calibration of the receivers and examination of the site before recording data. Moreover, the recorded data by each receiver were modified through calibration coefficient presented by the manufacturing company so to make certain of data obtainment with least possible error.

3.1. H/V Analysis

The H/V method represents a convenient and inexpensive means of investigation. It is based on a theory and hypothesis developed by Nakamura [Nakamura, 1989], who demonstrated that the ratio between horizontal and vertical ambient noise records is related to the fundamental frequency of the soil beneath the site and hence to the amplification factor. The theory and hypotheses are not unanimously accepted by the scientific community but comparisons with other techniques have proven the validity and efficiency of the method [Lermo & Chavez-Garcia, 1994].

The H/V spectral ratio (i.e. the ratio between the Fourier spectral amplitude of the horizontal to vertical component of microtremor) was first introduced by Nogoshi and Igarashi [Nogoshi & Igarashi, 1971] and further developed by Nakamura, [Nakamura, 1989]. Many experiments [e.g., Panou et al., 2005] supported by several theoretical 1D investigations have shown that ambient noise H/V spectral ratio is sharply packed around the fundamental S-wave frequency, if the upper layers have a sharp impedance contrast with the underlying stiffer layers [Mundepi & Kamal, 2006].

In the present paper, in order to evaluate the natural frequency of subsurface layers, after recording the microtremor waves in 13 stations and choosing 1 hour of records (time window of 01:00 A.M.), the single-station analysis H/V was carried out. These surveys in different points of the site in different times were performed. In Fig. 3.1. a sample of H/V ratio at the studied site for two stations 6180 and 6215 are shown.

The fundamental frequency in 13 stations was measured approximately 0.33 Hz according to the performed analyses in all the established stations in studied site. In this frequency, the magnification value is more than 6 and standard deviation value is low and acceptable. Considering the mentioned results, it can be stated that generally the site is categorized in the site classes of low natural frequencies.

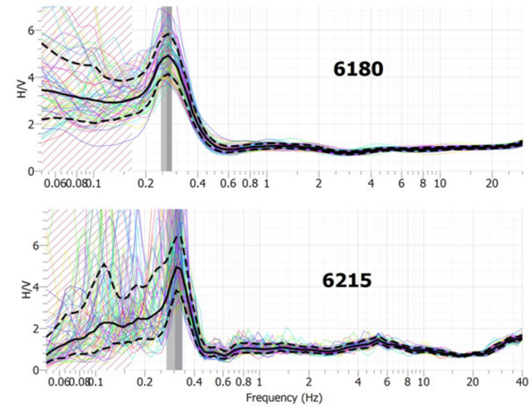


Figure 3.1. Results of single-station analysis (H/V) of microtremors in two stations in studied site

3.2. F-K Analysis

F-K method consists of computing a 2D frequency-wavenumber power spectrum from an array of sensors. Unlike SPAC, the F-K method shows best results when a dominant wave direction is present in the microtremor wavefield. By plotting the microtremors power spectrum for every frequency, we locate the direction and we calculate the phase velocity of the wave with most energy as follow:

$$C_0 = \frac{2\pi f_0}{\sqrt{k_{x0}^2 + k_{y0}^2}} \tag{3.1}$$

Where f_0 is fundamental frequency of site and (k_{x0}, k_{y0}) are the coordinates on the F-K spectrum (for more details refer to Capon 1969). The azimuth of the peak in the spectrum gives the provenance of the dominant wave. Interpretation of F-K data gives a phase velocity dispersion curve.

As mentioned before, the analyses of array data in this paper were carried out by SESARRAY software developed by Wathelet et al. in 2004. Here before drawing a comparison between obtained outputs from the array in ten time windows using F-K method and gained profile from downhole test, a part of analysing procedure of the array is presented in Fig. 3.2.

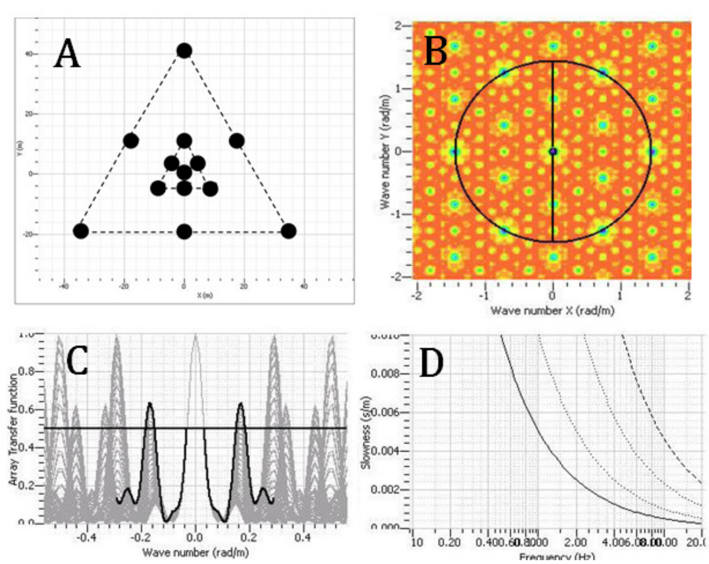


Figure 3.2. The general figure of the array configuration and the location of receivers (A), the theoretical response for array A with 13 receivers in (*Kx, Ky*) space (B), the transfer functions for different propagation directions (C) and K_{Max} and K_{Min} values in frequency-slowness domain (D)

In Fig. 3.3. the shear wave velocity profile obtained from downhole test and microtremor array method are shown, which all receivers are arranged in triangular shape. As it was mentioned before, the surveys in 10 time spans of 1 hour were conducted and data analysed using F-K method.

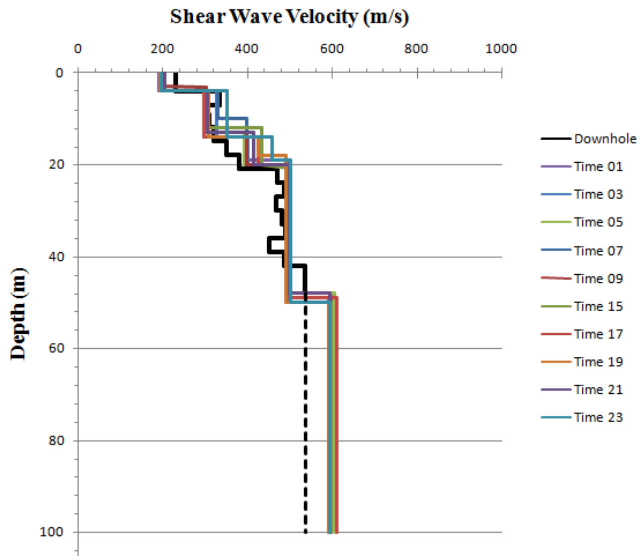


Figure 3.3. The shear wave velocity profile resulting from downhole test (thick black line) and F-K method in 10 different times

It can be inferred from the above figure that the difference of the results of different hours was not significant, which suggested these occasional noises in small time-spans are stationary. Moreover, disregarding the existing overburden of the site, which is 3 meters thick, four distinct layers were distinguishable in all analyses outputs that are in good agreement with the results of geotechnical studies and direct drillings. The results showed that in depth less than 20 meters, variations in the profiles are remarkable while in more depth the results of different hours are fitted on each other. Generally, in depth between 20-40 meters obtained shear wave velocities from microtremor are in good agreement with those obtained from direct downhole test.

3.3. SPAC Analysis

Spatial autocorrelation (SPAC) method evaluates coherencies between all pairs of sensors of an array. It was introduced by Aki (Aki, 1957) for the determination of the phase velocity of surface waves in microtremors array recordings. We calculate azimuthally averaged coherencies for multiple stations separations allowed by the centred triangular array. Averaged over all directions, the coherency has the form of a Bessel function of first kind and zero order as follow:

$$C(\omega) = J_0\left(\frac{2\pi fr}{V(f)}\right) \tag{3.2}$$

Where $C(\omega)$ is the spatially averaged coherency, J_0 the Bessel function of first kind and zero order, f the frequency and r the radius of the array. $V(f)$ is the shear-wave velocity dispersion function associated with a layered earth geology. We use SPAC to compute shear wave slowness profiles, from which we compute the shear wave velocity dispersion curve.

In this paper, for analyzing data through SPAC method, first, the different positions of pair stations for each array were defined in the software. Different rings for calculating spatial autocorrelation coefficient were adopted considering the different positions of pair stations' distance; next using

Geosphy which is a part of used software, the curve of spatial autocorrelation coefficient was calculated for all arrays in frequency band of 0.14-20 Hz., which for used array the results of this calculation for two different rings of 7 and 8 are presented in Fig. 3.4.

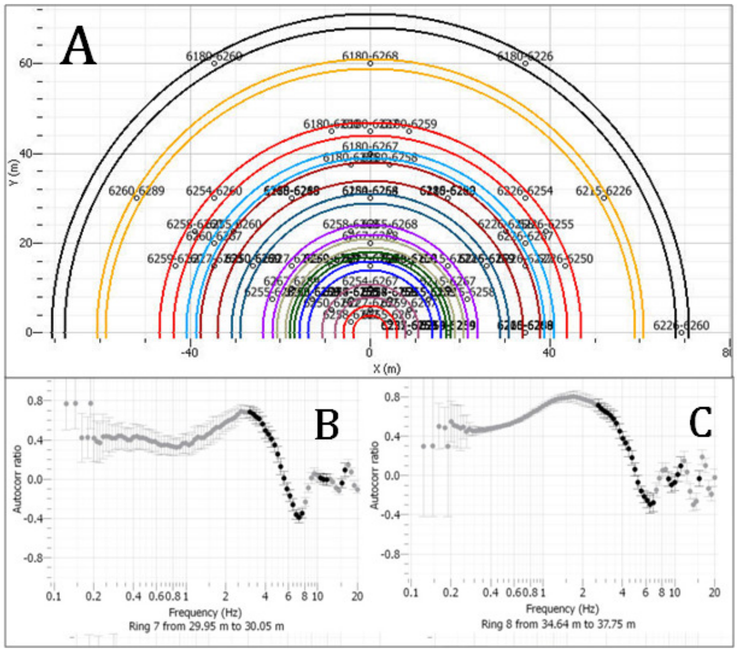


Figure 3.4. The selected rings for used array and different combinations of stations' distance and angle (A); the SPAC coefficient curve for the array in the frequency band of 0.14-20 for ring 7 (B) and ring 8 (C)

The stage following the calculation of spatial autocorrelation curves is conducting back analysis for estimating the shear wave velocity profiles. For performing back analysis and for studying the sensitivity of spatial autocorrelation coefficient in parameterizing properties of soil structure, the characteristics of subsurface layers were parameterized for each array based on the different assumptions.

For this end, several different models with different combinations of layers numbers and velocities were specified and the variation of profile of the shear and longitudinal wave velocity in terms of back analysis misfit were calculated.

In the end, the shear wave velocity profile obtained from the least-misfit model was presented as the final output. The shear wave velocity profile obtained from different hours using SPAC method and downhole test are depicted in Fig. 3.5. for comparing the final data obtained from the processes.

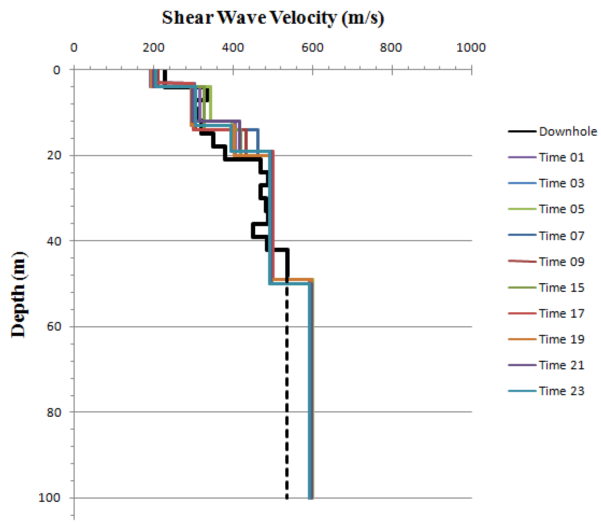


Figure 3.5. The shear wave velocity profile resulting from downhole test (thick black line) and SPAC method in 10 different times

First, same as the F-K method, the results of SPAC method showed that the difference of the results of different hours was not significant, which suggested these occasional noises in small time-spans are stationary. The difference of the profiles of shear wave velocity resulting from the array in this method is less than that of F-K method, this is the second noticeable point in this figure, and in fact the variation range of data is smaller. Next, it is worth noticing that, same as the F-K method, irrespective of overburden, four separate layers were distinguished in all analyses, which is in complete accordance with the direct drilling results. The results showed that in depth less than 20 meters, variations in the profiles are significant while in more depth the results of different hours are fitted on each other. Similar to F-K, in depth between 20-40 meters obtained shear wave velocities from microtremor are in good agreement with those obtained from direct downhole test.

4. CONCLUSION

In the present paper, F-K and SPAC methods were used to analyze array microtremor data in a site at the north part of the urban area of Tonkabon. Comprehensive information about geotechnical properties of subsoil were collected using several geotechnical and geophysical tests. Analysing microtremor data using single station H/V method showed that fundamental frequency of studied site is low. The Rayleigh wave phase velocity dispersion curves were determined using vertical component of microtremor waves and their inversion lead to the determination of deep Vs profiles, where other conventional seismic prospecting methods are constrained due to the cost of borehole drills, availability of open spaces in urban areas and requirement of powerful seismic sources. Comparison between results of F-K and SPAC methods with direct downhole tests showed the reliability of the both methods in determining shear wave velocity structure of subsurface soil. Moreover, deviation of the profiles obtained from different hours by SPAC method was less than F-K method and shear wave velocity derived from SPAC method was more accurate.

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