

# THE USE OF MICROTREMORS FOR THE DEFINITION OF SOIL PROPERTIES AND BEDROCK DEPTH IN AN URBAN AREA

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## SUMMARY

In the present paper we use microtremor array measurements with both Spatial Autocorrelation Method (SPAC) and spectral ratio of the Horizontal to Vertical component of microtremor recordings (H/V technique) in order to define the vertical soil profiles and the construct 2D and 3D soil models down to bedrock, in a densely populated area. The methodology is validated in the experimental site of EUROSEISTEST where bedrock depth and detailed  $V_s$  profiles are very well known (http://euroseis.civil.auth.gr). The array measurements were performed at sixteen (16) sites in the city of Thessaloniki. SPAC method was used to determine phase velocity dispersion curves. An inversion scheme was subsequently applied to determine the  $V_s$  profiles at all examined sites. The same measurements were used to determine the fundamental frequency of soil deposits at every site using the H/V spectral ratio (HVSR). Fundamental frequency was used either to validate the rock depth determined by SPAC method or to estimate this depth at the sites in which bedrock was not explored, using 1D theoretical transfer function based on inverted V<sub>s</sub> profiles.

#### **INTRODUCTION**

Geometry, shear-wave velocity ( $V_s$ ) of the alluvial deposits and depth of the bedrock are the key parameters, which control the site amplification. The  $V_s$  velocity is usually determined in the field by using conventional seismic prospecting (e.g. reflection, refraction, borehole seismics) and in the laboratory through dynamic/cyclic tests (i.e. RC, CTX) on intact and remolded soil samples. The use of conventional surface seismic methods presents practical difficulties in cases where deep sedimentary structures are going to be investigated especially in urban areas. Moreover the cost of large scale geophysical prospecting is very high. Additionally, the cost for implementing deep borehole seismics is also very high while the reliability of these seismic methods, such as crosshole and downhole, at large depths is often questionable, because of practical limitations (e.g. energetic sources, equipment management, etc). All these are some reasons for which in site effect studies the depth of the seismic basement often is limited to a layer with  $V_s$  around the 700-800m/sec.

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In this paper it is proposed to overcome the aforementioned difficulties by using microtremor array measurements. Microtremors are used with both Spatial Autocorrelation Method (SPAC) and H/V technique; with SPAC method the  $V_s$  profile of soil formation at large depths and in some cases down to the rock basement was determined (Apostolidis et al., 2004). H/V technique is applied to calculate the fundamental resonant frequency of soil deposits and to verify  $V_s$  profiles through the comparison between the HVSR and the 1-D transfer function based on the Vs determined by SPAC. Moreover, fundamental frequency allowed an implicit estimation of the bedrock depth at the sites where this depth was not defined.

SPAC method has been primarily applied in EUROSEISTEST, where the determination of the geometry and dynamic properties of soil materials has been defined, in order to validate the method and to examine its efficiency (figure 1).



Figure 1. General layout of the vertical Vs at five sites (S1L, S3L, S4L, S5L and S6L) along the cross section.

The  $V_s$  profiles derived from microtremor array measurements (dashed lines) are compared with those proposed by Jongmans et al. (1998) (thin lines) and Raptakis et al. (2000) (bold lines) derived from other geophysical prospecting. An agreement at the  $V_s$  values of the top soil formations is observed although at deeper formation the profiles of Raptakis et al. and microtremor are in a better agreement than Jongmans et al. The only significant difference is revealed at S3L where the bedrock depth seems to be deeper according microtremor measurements. In any case it is concluded that array microtremor measurements applied with SPAC method allow the reliable determination of  $V_s$  profiles at high depths.

#### **MICROTREMORS MEASUREMENTS IN THESSALONIKI**

Microtremor measurements were performed at many sites, representative from geological point of view, in the city of Thessaloniki (figure 2). The city of Thessaloniki with a population of one million inhabitants has a long history of seismic catastrophes; it suffered severe damage during the last destructive earthquake in 1978 ( $M_w$ =6.5). The last two decades, a considerable research work has been done to investigate together with the role of site effects on the damage distribution of the 1978 earthquake, the soil stratigraphy and the dynamic soil properties in order to assess future potential damage scenarios.



Figure 2. Geological map of Thessaloniki and microtremor measurements in the city

The central aim of this study is to evaluate the ability of microtremor, applying both SPAC method and H/V technique, to determine the bedrock depth and the  $V_s$  profile of the soil formations at sites that the geological conditions vary within in an urban densely populated area. We present the analysis of microtremor at 2 sites and we discuss the limitations and the advantages of the use of microtremors.

Finally, we design the 3D map of the bedrock top surface within the city together with 2D cross sections in terms of Vs layering, adequate for site response interpretation and simulation.

## **V**<sub>S</sub> **PROFILES WITH SPAC METHOD**

The fundamental assumption in SPAC method is that microtremor consists mainly of surface waves, and that we are able to extract the surface wave in a form of dispersion curve; that is, the phase velocity as a function of frequency. The phase velocity is inverted to the shear-wave-velocity distribution with depth under the array deployed to obtain the noise measurements.

Aki (1957) gave a theoretical basis of the SPAC coefficient defined for ambient noise and developed a method to estimate the phase velocity dispersion of surface waves contained in microtremors using a specially designed circular array. Henstridge (1979) also introduced a lucid expression of the relationship between the spatial autocorrelation coefficient and the phase velocity of fundamental mode Rayleigh waves. Okada et al. (1990) and Okada (1997) extended it to an exploration method that is currently called the SPAC method. For a complete presentation of the method see also Okada (1999).

The measurements in Thessaloniki city were performed using circular arrays, which consists of three recording stations on the circumference and one common station, in case when different data sets were obtained at the same place, at the centre of the array. The instruments used consist of three-component broadband seismometers CMG-40T with standard frequency band from 0.033 $\zeta z$  to 50Hz and Reftek recorders, in order to get period bandwidths adequate to explore V<sub>s</sub> velocity at layers as deep as possible. For a more detailed description of the recording status (day and time of measurements at every site, geometry of the arrays, etc) see in a recent publication of Apostolidis et al., (2004).

## Definition of the V<sub>s</sub> profile at a rock site (SST)

A circular array with 7m radius at a site in which the bedrock seems to be outcrop was used in order to define  $V_s$  velocity SPAC method and the possible degree of the rock weathering. The original signal trains were divided into multiple equal time windows. The analysis procedure to estimate the SPAC coefficients and consequently the  $V_s$  profile is illustrated in figure 3.

In a first stage of processing we examine the stationary nature of the microtremor recordings. If the microtremors could be considered as stationary, then stationary random function and space-correlation function between two stations can be computed as a function of the phase velocity of the surface waves. The frequency range in which microtremor can be considered stationary was determined by the calculation of its power spectrum and the frequency coherence function (sometimes called the coherency squared function) estimated for different stations. In this example, the rock site SST, the similar power spectra calculated for one time - window for all stations (figure 3a) and the coherency functions (figure 3b) imply that the recorded ambient noise is stable in the frequency range from 2 to 18 Hz.

In a second stage, which is the main part of the analysis, the autocorrelation functions were calculated for each pair of stations of equal inter-stations distances. Figure 3c presents the spatial autocorrelation function (or the spatial autocorrelation coefficient) at the finally selected frequencies between 11 and 16Hz. The dispersion curve at lower frequencies was not determined because the distance of the array (7m) was small for describing larger wavelengths that correspond to lower frequencies. The experimental dispersion curve of phase velocity of Rayleigh waves resulted from the analysis of microtremor is presented in figure 3d.



Figure 3. Analysis procedure for the estimation of the SPAC functions and dispersion curve of Rayleigh waves, at site SST (outcrop conditions)

The third stage consists of the inversion of the experimental dispersion curve using an iterative inversion scheme introduced by Herrmann (1987) to reveal the  $V_s$  velocity structure below the circular array. For the determination of the vertical  $V_s$  profile a complete initial soil model with thickness,  $V_p$  and  $V_s$  velocities, and density for each layer is needed. The inversion procedure is presented in figure 4. In case that theoretical dispersion curve (solid line in figure 4a) fits well with the experimental one (circles in figure 4a), provided by microtremor measurements, it is considered that the inverted soil model is accurate and finally acceptable. The reliability of the inverted  $V_s$  profile is confirmed by the shape and the distribution with depth of the resolving kernels, in form of a delta function that corresponds to the depth of the layers of the initial soil model (figure 4b).



Figure 4. Fitting of the experimental and theoretical dispersive curve, the final inverted Vs profile and the resolving kernels at site SST (outcrop conditions)

The determined  $V_s$  profile at the rock site shows a cover stiff soil layer with 10m thickness and  $V_s$  velocity of 600m/sec derived from the complete weathering of the rock mass. The next 10m show a  $V_s$  velocity of 1100m/sec, which describes a weathered bedrock with rather poor quality overlying a real hard bedrock

 $(V_s: 1500-2000m/sec)$ . The reasonable  $V_s$  profile determined at site SST is a strong indication that SPAC method can be successfully used at any geological conditions. This is very important because the knowledge of  $V_s$  at the bedrock can be useful in the examination of the adequacy of a reference site used in site response study (Raptakis et al., 2003) and moreover because it is well known that the  $V_s$  contrast between sediments and bedrock controls the level of site amplification.

#### Definition of the V<sub>s</sub> profile at a soil site (IPO)

We perform microtremor measurements in many sites where the soil deposits are expected to have large thickness. Herein, one representative site is presented. Site IPO is located at the center of Thessaloniki where the bedrock depth is expected to be large. The use of SPAC method leads to the  $V_s$  velocity profile down to a depth of 110m, but bedrock depth was not defined since the  $V_s$  velocity of the last geological formation is only of 630 m/sec. In figure 5 the SPAC coefficient (4a) and the  $V_s$  profile (4b&c)



Figure 5. SPAC coefficients, fitting of the experimental and theoretical dispersive curve and the final inverted Vs profile at site IPO

are presented. The same procedure used for sites SST and IPO was followed at 16 sites in Thessaloniki city and  $V_s$  profiles were determined. The validation of the  $V_s$  values was done by the comparison of the SPAC  $V_s$  profiles with the Cross-Hole tests. The comparison shows that the  $V_s$  profiles from SPAC are in a good agreement with those from C-H. Some local discrepancies are due to the more detailed C-H measurements (Apostolidis et al., 2004). However, bedrock depth was not determined at the most sites. To accomplish this task, HVSR were computed and fundamental frequency at every site was calculated.

#### FUNDAMENTAL FREQUENCY WITH H/V TECHNIQUE

Although the penetration depths were successfully large, in some cases, the depth of the bedrock could not be estimated. For this, the H/V technique was applied on the same data sets in order to get a reasonable estimation of the 1D fundamental frequency of the sedimentary deposits. The fundamental frequency was used together with the inverted SPAC  $V_s$  profile to estimate the total thickness of the sediments down to the top surface of the bedrock, taking into account the theoretically defined transfer function.

To compute HVSR the Fourier spectra of each horizontal component and the vertical component were calculated. The Fourier spectra were smoothed with the weighted moving average method  $(\frac{1}{4}, \frac{1}{2}, \frac{1}{4})$  before calculating the horizontal to vertical spectral ratio (the sampling interval of the microtremor recordings was 0.008 sec and the recording duration was 30 minutes). First, the obtained waveforms were band-pass filtered from 0.1 to 25 Hz and corrected for the baseline and the instrument response. The time window length selected was depended on the wavelength associated with the desired penetration depth.

In figure 6 HVSR ratios for both horizontal components at site IPO are presented. The spectral ratios of all time windows are well constrained. The fundamental resonant frequency is 0.87Hz and the amplification amplitude is 3.6.



Figure 6. HVSR and their average for N-S and E-W components at site IPO

All HVSR ratios at 16 sites are presented in figure 7 and the larger penetration, H, depth determined with SPAC method and the fundamental resonant frequency,  $f_0$ , with peak amplitude, A, are shown in Table 1. The almost flat HVSR at the rock site at a big range of frequencies (figure 7) and the large variation of resonant frequencies at the other sites depict completely different soil conditions in the large area of the city. All these results indicate that the geometry of the soil structure, in which the city is located, is rather complex suggesting that complex site effects would be expected (Raptakis et al. 2003 a, b). However, to design 3D model of bedrock depth, the total thickness of sedimentary deposits was estimated at all sites following a back analysis procedure presented in the next paragraph.



Figure 7. Average HVSR at all sites

Table 1. Exploration depths of V <sub>s</sub> profiles determined with	n SPAC method, fundamental frequency
and amplification amplitude calculated with HVSR	

	KAL	KYV	KRH	MPO	KON	IPO	TOU	LEU	MET	AGO	LIM	TEL	LAZ	STA	EUO	SST
н	280	320	240	180	250	110	180	130	35	60	180	160	140	80	220	80
f <sub>o</sub>	0.85	0.35	0.5	0.4	0.9	0.87	1.8	0.87	3	4	0.9	0.62	3	2.2	0.63	20
Α	3	1.8	3.4	7	4.5	3.6	6	5.8	8.5	10	4.8	3.5	8	5	4	6

## ESTIMATION OF THE BEDROCK DEPTH

The V<sub>s</sub> profiles determined with SPAC method, reach the bedrock or its weathering zone at six (6) sites (KAL, KON, TOU, MET, AGO, and LAZ). At site MET, the bedrock depth was confirmed from a geotechnical borehole. At the sites KAL, KON and TOU, the examination of the reliability of this depth was not possible because there are not boreholes that reached at these depths. Finally, at sites AGO and LAZ the Vs velocity of the last geological formation has values that refer either at a weathered rock or at a stiff soil with V<sub>s</sub> between 950m/sec and 1190m/sec. For clarifying the V<sub>s</sub> profile at these 2 sites and to validate the bedrock depth at the other 4 sites, we compare at every site the HVSR with 1D theoretical transfer function. 1D modeling was based on reflectivity-coefficient method introduced by Kennett (1983) for horizontally polarized shear waves vertically propagated from bedrock to surface.

The basic idea is illustrated in figure 8 for site MET as an example. At site MET the bedrock depth has

been defined with SPAC method. This is also known from a nearby borehole. In figure 8 the dashed lines show the HVSR of both E-W and N-S components. The thin solid line is the 1D theoretical transfer function based on  $V_s$  model determined with SPAC method. The good agreement between empirical and theoretical fundamental resonant frequencies and peak amplifications denotes that the  $V_s$  profile has been accurately determined.



Figure 8. Empirical transfer functions of both components (HVSR) and theoretical transfer functions of the SPAC  $V_s$  at site MET

We followed the same procedure for the other 9 sites (KYV, KRH, MPO, IPO, LEU, LIM, TEL, STA and EUO) for which the bedrock depth had not been defined with SPAC method. We present as an example site IPO. We make 3 assumptions: a) The thickness of the last formation with  $V_s$  velocity of 610 m/sec terminates at the depth of 110m. At this depth a formation with  $V_s$  of 900 m/sec is expected. Below this depth it is the bedrock. This assumption corresponds at the geotechnical interpretation of the soil of Thessaloniki that has been performed and presented in Apostolidis et al. (2004). b) The  $V_s$  value of the rock basement presents large contrast with the upper sediments. More specifically, the bedrock does not appear a weathering zone because the depth of the soil deposits is too high to justify its presence.

In figure 9 the dashed lines show the HVSR for both components while the thin solid line is the theoretical transfer function based on SPAC  $V_s$  profile for site IPO. The difference of the fundamental resonant frequency between the theoretical and the empirical transfer functions denotes that the sedimentary deposits have larger thickness due to the accurate values of  $V_s$  velocities as several comparisons with C-H test have shown (Apostolidis et al., 2004 a & b). The thickness of the last formation ( $V_s$ : 900m/sec) is estimated to be 160m and consequently the total thickness of the soil deposits

reaches 270m. The aforementioned defined and estimated final  $V_s$  model is compared to the 1D theoretical transfer functions with bold solid line in Figure 9, which fits well at the fundamental frequency with the empirical HVSR. A rather satisfactory matching at the amplification level is observed. We followed the same procedure for the other sites, in which the bedrock depth was not determined explicitly. All estimated depths of the bedrock in every site are presented in Table 2.



Figure 9. Empirical transfer functions of both components (HVSR) and preliminary and final theoretical transfer functions at site IPO

Site	Exploration depth (m)	Estimated depth (m)	Fund. Freq.	$V_s$ of the last formation		
	(SPAC)	HVSR-1D	(Hz)	SPAC, (m/sec)		
KYV	320	790	0.35	1175		
KRH	240	420	0.5	820		
MPO	180	420	0.4	735		
IPO	110	270	0.97	610		
LEU	130	250	0.87	930		
LIM	180	180	0.9	780		
TEL	160	260	0.62	590		
STA	80	90	2.2	765		
EUO	220	350	0.63	940		

Table 2. Estimation of bedrock depth with a back analysis procedure

#### 2D CROSS-SECTIONS AND 3D MAPPING OF THE BEDROCK

Two 2D cross sections are presented herein. It is noted that from the recently performed Microzonation study the soils categories of the city of Thessaloniki were classified into five categories (A1, A, B, C and



D) (Anastasiadis et al., 2001; Apostolidis et al., 2004).

#### Figure 10. Two characteristic 2D cross-sections describing the basic formations of Thessaloniki

Formation A1 is a sub-category of the basic formation A, composed of the softest soils, about 10m thick with  $V_s$  values of 130 m/sec. Geotechnically, it is characterized as sandy silt (SM) and soft clay (CL). Formation A has  $V_s$  velocity values ranging from 150m/sec to 300 m/sec with thickness from 5 m to 35 m. It is characterized as clay with low to medium plasticity (CH-CL). In the eastern part of Thessaloniki, the thickness of formation A varies from 5m to 10m and the  $V_s$  from 250 m/sec to 300 m/sec. It is composed of clay with gravels (CL-CG). Formation B presents  $V_s$  values from 300 m/sec to 500 m/sec and the thickness is varying from 20 m to 130 m. Formation C has  $V_s$  values from 500 m/sec to 750 m/sec and thickness 50 m to 200 m. Geotechnically, formations B and C are characterized as stiff clays with sands (CL, CL-SC). Formation D is the deepest soil formation, overlying the bedrock, having  $V_s$  values varying from 750 m/sec to 1100 m/sec. Formation AA and BB appear only at the site TOU and describes two units of the geological formation of the Pleistocene mixed deposits (F,c-cm, see in Figure 1). AA is the upper formation with a mean  $V_s$  velocity of 230m/sec, while formation BB contains gravels and rock segments and the  $V_s$  velocity resulted to be on the order of 1000m/sec.

Finally, based on the combined data we design the top surface of the bedrock in terms of contours using a Geological Information System. More specifically,  $1D V_s$  profile ever 300 m were extracted from the fully designed 2D cross-section, in order to introduce all of them in the GIS system (Figure 11). Thus, we obtain the necessary number of spots to density the resulted 3D model of the bedrock depth. The 3D map



Figure 11. Characteristic spots that used in a GIS for designing the 3D model of the bedrock

presented in figure 12 shows that the bedrock top surface is deepening in two different directions; the NW and SW direction. This map could be successfully used for the estimation of the thickness of the sedimentary deposits at any site of interest in the frame of the microzonation study of Thessaloniki, which ensure a reliable and accurate site response analysis using 1D, 2D or 3D soil profiles.





## CONCLUSIONS

Microtremors array measurements that are analyzed with SPAC method can be used with high reliability both at rock and soil sites to determine the  $V_s$  profile. The method has been validated in an experimental site (EUROSEISTEST) and in the city of Thessaloniki as well. In case that the determination of the

bedrock depth can not be accomplished directly it seems that a back analysis procedure based on the combination of HVSR empirical technique, the 1D theoretical transfer function and the determination of  $V_s$  profile by the SPAC method. This is very important because we can trust the inverted  $V_s$  profiles without using other measurements. The knowledge of the bedrock depth at many sites with different thickness of soil deposits and the appropriate use of GIS allow designing 2D cross-sections and the 3D model of the bedrock depth to get most of the necessary parameters needed to perform a site response analysis. Finally, an indirect advantage of the analysis of array measurements is that the computation of H/V transfer function of microtremor can give a preliminary estimation of site response. All these tasks which were accomplished only with microtremor measurements encourage the use of ambient noise an essential and powerful tool for soil and site characterization, site response analyses, microzonation studies, design of infrastructures and urban planning.

**ACKNOWLEDGEMENTS:** The present research is partially funded by EC-DGXII, in the frame of EUROSEISRISK research project

#### REFERENCES

- 1. Aki K., 1957. Space and Time Spectra of Stationary Stochastic Waves, with Special Reference to Microtremors. Bull. Earthq. Res. Inst. Tokyo Univ. 25, pp. 415-457
- Anastasiadis, A., D. Raptakis, and K. Pitilakis, 2001. Thessaloniki's Detailed Microzoning: Subsurface Structure as Basis of Site Response Analysis, PAGEOPH Special Issue on Microzoning, Vol. 158, N.11, pp. 2497-2533.
- 3. Apostolidis P., D. Raptkis, Z. Roumelioti & K. Pitilakis, 2004. Determination of S-wave velocity structure using microtremors and SPAC method applied in Thessaloniki (Greece). Soil Dynamics and Earthquake Engineering 24, pp 49-67
- 4. Apostolidis P., D. Raptakis, M. Manakou and K. Pitilakis, The use of microtremors for soil and site categorization in an urban area. The case of Thessaloniki, Greece, submitted in the International Site Characterization Conference, (ISC-2), Porto, September 2004
- 5. Apostolidis, P., 2002. Determination of the soil structure using microtremors. Application to the estimation of the dynamic properties and the geometry of the soil formations at Thessaloniki city. PhD Thesis, Aristotle University of Thessaloniki, Greece.
- 6. Henstridge, J. D., 1979. A signal processing method for circular arrays, Geophysics, 44, pp. 179-184.
- 7. Herrmann, R., 1987. Computer programs in seismology, vol. III., Saint Louis University, USA.
- 9. Okada H., 1997. A new method of underground structure estimation Using Microtremors. Division of Earth Planetary Sciences, Graduate School of Science, Hokkaido University, Japan, Lecture notes.
- 10. Kennett, B.L.N., 1983. Seismic Wave Propagation in Stratified Media, Cambridge Univ. Press, Cambridge
- Jongmans, D., K. Pitilakis, D. Demanet, D. Raptakis, J. Riepl, C. Horrent, G. Tsokas, K. d P.Y. Bard, 1998. EURO-SEISTEST: Determination of the Geological Structure of the Volvi Basin and Validation of the Basin Response, Bull. Seism. Soc. Am., Vol 88, No. 2, 473-487
- 12. Okada, H., T. Matsushima, T. Moriya and T. Sasasatani, T., 1990. An exploration technique using longperiod microtremors for determination of deep geological structures under urbanized areas (in Japanese), BUTSURI-TANSA, 43, pp. 402-417.
- 13. Okada H., 1999. A New Passive Geophysical Exploration Method Using Microtremors. Division of Earth Planetary Sciences, Graduate School of Science, Hokkaido University, Japan, Lecture notes.
- 14. Raptakis, D., F. J. Chávez-García, K. Makra and K. Pitilakis, 2000. Site effects at EUROSEISTEST I. Determination of the valley structure and confrontation of observations with 1D analysis. Soil Dyn. Earthq. Engnr, 19(1), 1-22.
- 15. Raptakis D., K. Makra, A. Anastasiadis & K. Pitilakis, 2003, Complex site effect in Thessaloniki (Greece):I. Soil structure and confrontation of observations with 1D analysis, for publication
- Raptakis D., K. Makra, A. Anastasiadis & K. Pitilakis, 2003, Complex site effect in Thessaloniki (Greece):
  2D SH Modeling and engineering insights, for publication