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SEISMIC CHARACTERIZATION OF SHALLOW BEDROCK SITES WITH MULTI-MODAL MONTECARLO INVERSION OF SURFACE WAVE DATA

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KEY WORDS

Site characterization, Shallow bedrock, Seismic site response, Surface waves, Monte Carlo inversion, Geophysical methods.

ABSTRACT

Sites with a limited overburden over a stiff basement are of particular relevance for seismic site response. The characterization of such stratigraphies by means of surface wave methods poses some difficulties in the interpretation. Indeed the presence of sharp seismic contrasts between the sediments and the shallow bedrock is likely to cause a relevance of higher modes in the surface wave apparent dispersion curve, which must be properly taken into account in order to provide reliable results. In this study a Monte Carlo algorithm based on a multimodal misfit function has been used for the inversion of the experimental dispersion curves. Case histories related to the characterization of stations of the Italian Accelerometric Network are reported. Spectral ratios and amplification functions associated to each site are moreover evaluated to provide an independent benchmark test. The results show the robustness of the inversion method in such non trivial conditions and the possibility of getting an estimate of uncertainty related to solution non-uniqueness.

INTRODUCTION

The relevance of stratigraphic conditions with shallow bedrock for seismic site response evaluation is well recognized in the literature. Contemporary seismic codes (IBC 2000, UBC97, EC8) consider the mean value of shear wave velocity over the shallowest 30 meters as the main parameter for soil classification. However many studies (see for instance [1], [2]) have proved that such approach can be misleading in sites with a shallow and abrupt stiffness change between the bedrock and the soft top layer. These sites are characterized by high values of $V_{S,30}$ which lead to an underestimation of the site amplification in conventional approaches introduced by the codes.

Surface wave tests are commonly used for seismic site characterization because they are both economically and time convenient when compared to borehole seismic methods. It has been shown by several authors that these methods are reliable, especially when dealing with $V_{S,30}$ estimation [3, 4]. Possible uncertainty in the determination of the soil profile due to non-uniqueness of the inverse problem solution are of minor influence in the evaluation of site amplification parameters [5].

In non-trivial stratigraphic conditions, like shallow bedrock situations or inversely dispersive profiles, the interpretation of surface wave tests has to be performed with particular attention [6, 7]. Surface wave propagation is indeed a multimodal phenomenon, i.e. the dispersion curve is composed by several modal curves while in surface wave analysis it is often assumed that only the fundamental mode is excited. This assumption, which is reasonable for normally dispersive profiles, can lead to severe errors when the experimental dispersion curve is an apparent dispersion one, generated by mode superposition [6]. The relevance of higher modes is a common feature both in presence of velocity inversions in the S-wave velocity profile and in presence of a strong impedance contrast in the near surface [7]. The potential errors associated to fundamental mode inversion of multi-modal data are discussed in [8].

In this note some case studies of the application of a Monte Carlo inversion algorithm based on a multimodal misfit function [8, 9] are reported and discussed. The surveys are part of a project aimed at improving and updating the Italian strong motion database (ITACA; http://itaca.mi.ingv.it/ItacaNet/).

METHOD

The Haskell-Thomson matrix determinant misfit function proposed by Maraschini et al. [8] allows all the modes to be automatically taken into account avoiding mode misidentification and with limited computational cost. The implementation in a Monte Carlo inversion scheme allows uncertainty caused by non-uniqueness to be quantified, while mitigating the risk of falling into local minima [9]. The results of the inversion is a set of profiles which are “equally good” with respect to available experimental information, accounting also for data uncertainty. In this paper the distribution of the experimental dispersion curve is assumed to be Gaussian, with a standard deviation of 5%, in line with previous experimental evidences [10]. The results of the Monte Carlo inversion are reported using a representation based on the relative misfit. The darkest colour always corresponds to the model having the lowest misfit with reference to the experimental dispersion curve. The same colour is used to represent each shear wave velocity model and its associated dispersion curve.

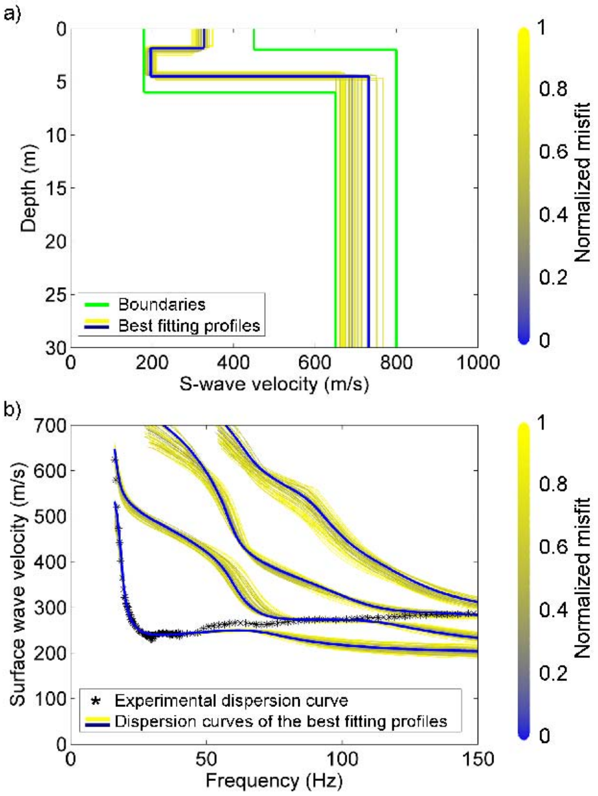

Figure 1 Sestri Levante Site: a)Best fitting profiles; b) Dispersion curves of soil profiles compared with the experimental dispersion curve.

EXPERIMENTAL EXAMPLES

Four case histories are presented in this study. For all sites, shallow bedrock conditions or velocity inversions are expected. The sites are locations of permanent stations of the Italian accelerometric network, an assessment of actual stratigraphic conditions is therefore a requirement for the correct use of real accelerograms for earthquake resistant design. All datasets have been acquired using a 5 kg sledge hammer source and an array of 48 vertical geophones with spacing of about 1 meter. Dispersion curves have been obtained using fk analysis implemented in the package SWAT, developed in Matlab® environment at Politecnico di Torino.

At Sestri Levante (Liguria Region) site, the superficial layer is constituted by an alluvial-colluvial heterometric deposit a few meters deep which lies over a weak torbiditic bedrock (interbedded silts and sands). Tests have been executed along an unpaved track used for the passage of trucks. A velocity increase with frequency is noted in the experimental dispersion curve (Figure 1b). In such situations the apparent dispersion curve follows higher modes in the high frequency range and the subsoil profile likely presents a velocity inversion [6, 7]. This dataset is particularly challenging for a surface wave inversion algorithm. The apparent dispersion curve, which is composed by a single branch, follows higher modes both in the low and in the high frequency ranges with smooth transitions i.e. it is not possible to identify the mode number for the data points. The best profiles selected by the Monte Carlo algorithm are plotted in **Errore. L'origine riferimento non è stata trovata.**a. The profiles are similar and consistently present a velocity inversion in the shallow layers.

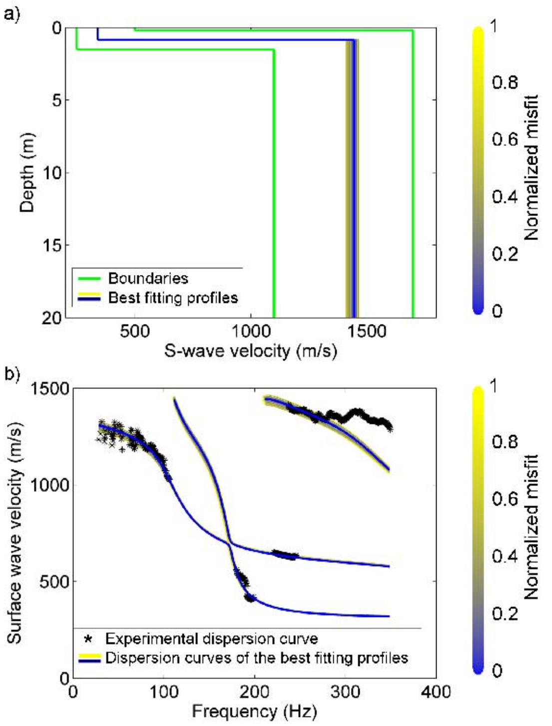

Figure 2 Ispica Site: a)Best fitting profiles; b) Dispersion curve of soil profiles compared with the experimental dispersion curve.

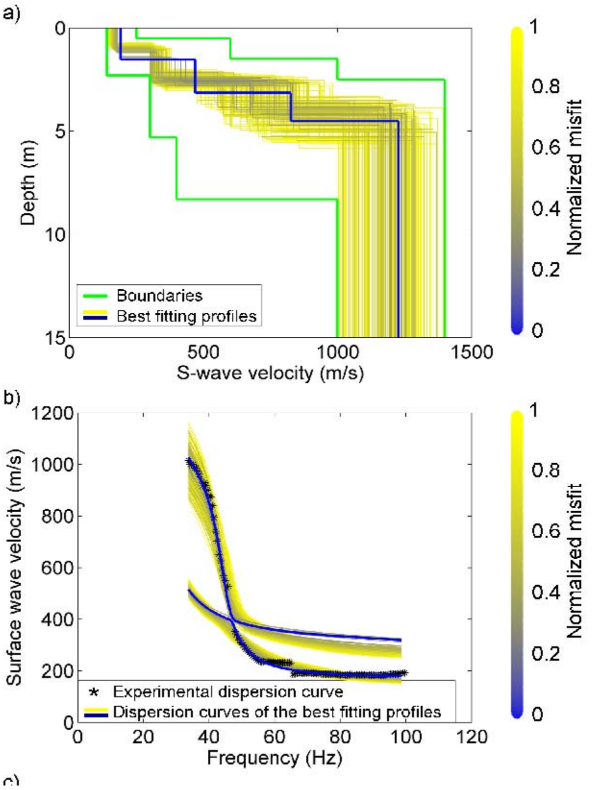

Figure 3 Santa Croce Site: a)Best fitting profiles; b) Dispersion curve of soil profiles compared with the experimental dispersion curve.

The accelerometric station in Ispica (Sicily) lies on a thin fill soil which leans on a very shallow limestone bedrock (outcrop evidences have been observed near the station). The dispersion curve (Figure 2b) is quite noisy and obscure because of the very strong velocity contrast between the two layers. Nevertheless all of the profiles selected by the inversion code (Figure 2a) indicate a strong S-wave velocity contrast at about 0.8 m depth, so that the interface between the upper fill soil and the lower limestone bedrock is clearly determined. The inversion result is reliable and in agreement with our a priori information on the site. With a mode numbering based algorithm it wouldn't be possible to attribute a priori any of the four branches of the experimental dispersion curve to a particular mode.

At Santa Croce site (Sicily) the superficial layer is an uncultivated soil with a substantial sand content laying over a shallow compacted limestone bedrock. The retrieved dispersion curve (Figure 3b) consists of three branches, all of them showing a phase velocity decrease with frequency. The best fitting profiles from the Monte Carlo inversion (Figure 3a) are similar and show a progressive increase in S-wave velocity with depth until the bedrock is reached. The selected dispersion curves attribute the first branch of the experimental curve to the first higher mode and the second and third branches to the fundamental mode.

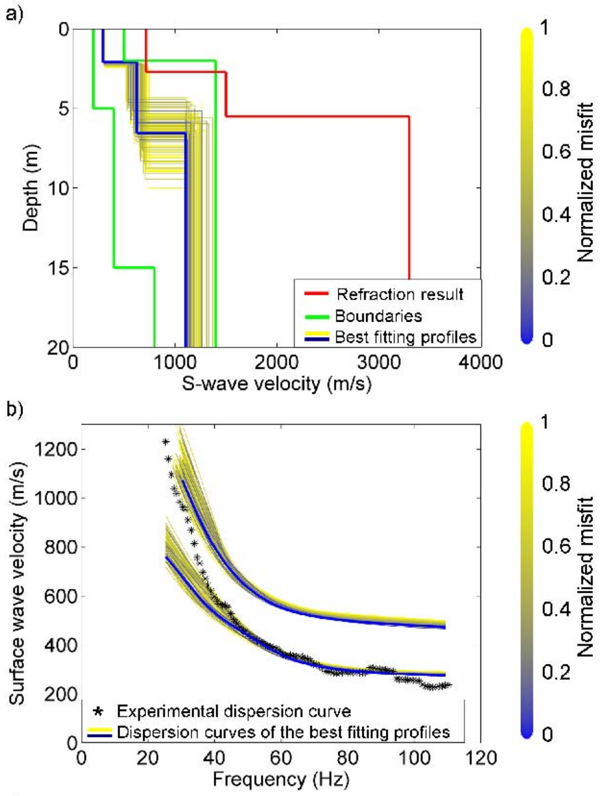

Figure 4 Varese Ligure Site: a)Best fitting profiles; b) Dispersion curves of soil profiles compared with the experimental dispersion curve.

In Varese Ligure (Liguria Region), a top cover lies on a "flysch" formation mainly constituted by marbly limestones with outcrop evidences near the accelerometric station. The apparent dispersion curve coherently shows a decrease of the S-wave velocity as the frequency increases, but likely the curve follows the first higher mode at low frequencies, “jumping” to the fundamental mode from 40 Hz on (Figure 4b). The profiles which minimize the misfit function are represented in Figure 4a. For this site a P wave refraction survey is also available on the same array. The layering results compare well with surface wave inversion. The first interface under soil coverage can be attributed to altered “flysches”.

For each site we simulated the seismic site response for the best fitting velocity profiles using the code Shake91 [11]. The results of amplification functions obtained for each site are reported in Figure 5 using the same color representation of the corresponding profiles. In the same figure, approximate estimates of the resonance frequency and amplitude for each profile are also reported. They have been computed by modelling a homogeneous layer over bedrock, assuming the mean slowness as the average parameter for the soil layers.

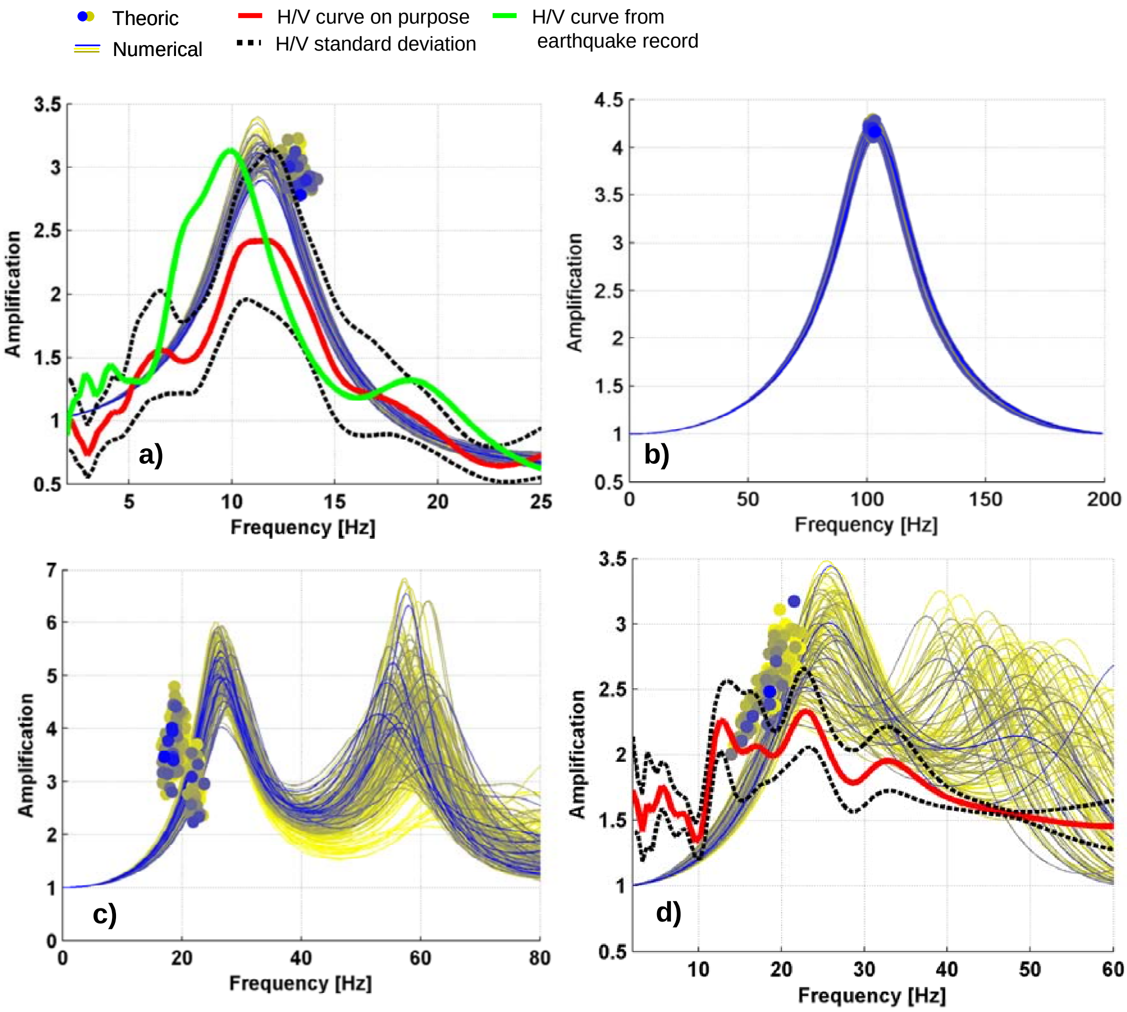

Figure 5 Amplification functions for the soil profiles at each site compared to the theoretical resonance frequencies and, when available, to H/V spectral ratios: a) Sestri Levante; b) Ispica; c) Santa Croce; d) Varese Ligure.

Amplification functions and site resonance frequency can be also experimentally extracted from the Horizontal to Vertical Spectral Ratio (H/V) method. This method, also termed Nakamura's method [13], makes use of ambient vibrations recorded with a three-component station [14]. The spectra of the horizontal and vertical components of ambient vibrations are calculated and their ratio is evaluated. For sites conditions where there is a strong velocity contrast, a clear peak will occur in the H/V curve that closely corresponds to the fundamental frequency of the site. For two of the sites in the present study H/V spectral ratio curves have been evaluated and are also reported for comparison in Figure 5. Data for H/V analyses have been acquired with 2 Hz triaxial geophones and processed by means of the open source code Geopsy (www.geopsy.org). The parameters used for window selection are in accordance with recommended values developed in the SESAME project [14]. Since high resonance frequency is expected at the sites, the use of relatively high frequency geophones and short recording windows (1048 s) is not a major concern. For the Sestri Levante site, comparison is also made with the H/V curve extracted, using a similar procedure, from a real earthquake record available at the accelerometric station (Figure 5). The seismic event (5.4 magnitude at about 90 km epicentral distance from the station) originated in the Parmesan Apennines.

DISCUSSION

The sites of the present study are characterized by dispersion curves whose inversion requires the necessity to take into account high propagation modes. In all four sites a shallow seismic bedrock is expected and in one of them very probably a velocity inversion occurs. It is then very likely that the four apparent dispersion curves do not follow the fundamental mode but they may "jump" from one mode to another. As the applied inversion method does not require mode numbering, we can attribute every branch of the experimental dispersion curve to a particular propagation mode without any a priori assumptions.

The calculated amplification functions (Figure 5) show that the uncertainty in the inversion process (number of profiles selected by the Monte Carlo inversion) is of minor importance in the evaluation of the site response characteristics of the sites. Indeed the amplification functions of all of the profiles selected by the inversion procedure are very consistent and lead to the identification of very similar shapes and a clear resonance frequency (main peak of the amplification function). The only profile that seems critical at higher frequencies is the Varese Ligure one which however shows a clear resonance peak (Figure 5d) despite the high uncertainty in the location of the second interface (Figure 4a).

The resonance frequency is underestimated by the approximate theoretical value in a normal dispersive condition (Figure 5c – d) and overestimated when a velocity inversion is present (Figure 5a). These aspects have to be evaluated when the mean velocity value of the sediments is intended to be extracted from peak resonance frequency only [15].

For seismic classification purposes, $V_{S,30}$ cannot be considered a representative parameter for shallow bedrock situations. The mean shear velocity of the soil deposits ($V_{S,h}$) and the fundamental frequency can be considered alternative classification parameters [1, 2]. To statistically evaluate the uncertainty in the profile parameters (velocities and thicknesses) and in the lumped classification parameters ($V_{S,h}$ and fundamental frequency), box plots for the distribution of each parameter are reported in Figure 6 for two sites. Values are normalized with respect to the median to allow a direct comparison. In both case histories the uncertainty in the lumped classification parameters is lower than the uncertainty on single model parameters. The uncertainty in the fundamental frequency is always higher than the one on the average velocity. At the Sestri Levante site (Figure 6a) this difference is particularly noticeable due to the increased uncertainty in layer thicknesses whereas at Varese Ligure site (Figure 6b) the higher uncertainty in the second interface position does not directly reflect on lumped parameters.

The correspondence between the simulated amplification functions and the H/V experimental curve is quite good especially for the Sestri Levante site, even if this site is characterized by non-trivial stratigraphic conditions (Figure 5a). The small difference with the earthquake resonance peak can be attributed to bedrock depth variations since our dataset has been acquired, due to logistic problems, a few tens of meters apart from the station. In the Varese Ligure site, on the contrary, a lower peak seems also to be present in the H/V curve but the main peak is in agreement with simulated data (Figure 5d).

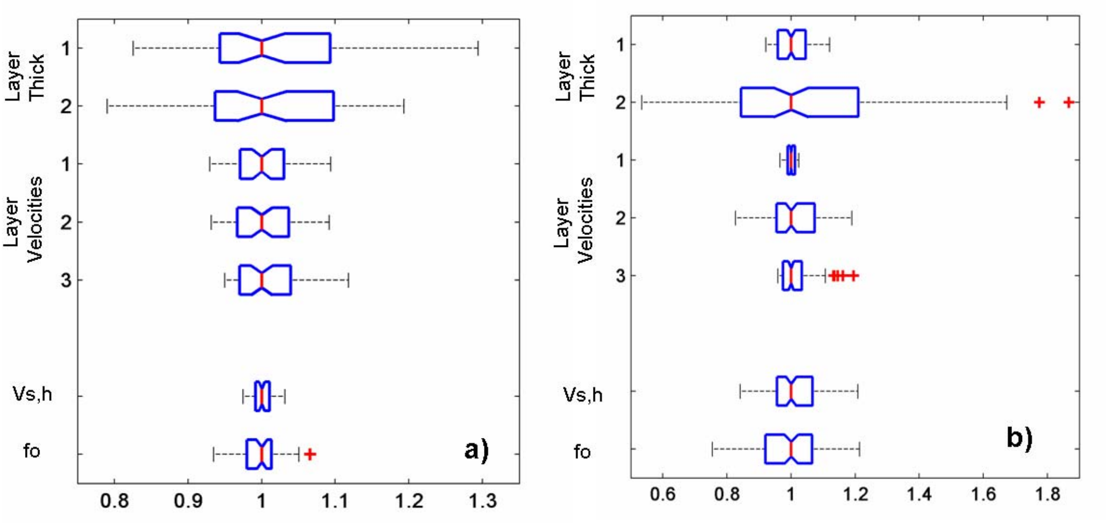

Figure 6 Box plots representing the uncertainty in the profile parameters (velocities and thicknesses) and in the local site response characteristics ($V_{S,h}$ and fundamental frequency) for a) Sestri Levante and b) Varese Ligure sites.

CONCLUSIONS

In this work a Monte Carlo algorithm for surface wave inversion based on a multimodal misfit function is applied. The algorithm is tested inverting dispersion curves which present transitions of the apparent dispersion curve to higher modes both in the low and high frequency ranges. It has been shown that high quality profiles can be extracted with this procedure even in non trivial stratigraphic conditions and when only disconnected branches of the experimental dispersion curve are available. The results are evaluated with comparisons with independent measurement (H/V) and with statistical analyses.

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REFERENCES

[1] K. Pitilakis, Ch. Gazepis, A. Anastasiadis, Design response spectra and soil classification for seismic code provisions, Proceedings of the ETC-12 Athens Workshop, January 20th 2006, Athens, Greece.

[2] G. Bouckovalas, A. G. Papadimitriou, D. Karamitros, Compatibility of EC-8 Ground Types and Site Effects with 1-D Wave propagation theory, Proceedings of the ETC-12 Athens Workshop, January 20th 2006, Athens, Greece.

[3] R.E.S. Moss, Quantifying measurement uncertainty of thirty-meter shear-wave velocity, Bulletin of the Seismological Society of America, Volume 98 No. 3 (2008) 1399 – 1411.

[4] C. Comina, S. Foti, D. Boiero, L.V. Socco, Reliability of $V_{S,30}$ evaluation from surface waves tests, Journal of Geotechnical and Geoenvironmental Engineering, in press. (2010).

[5] S. Foti, C. Comina, D. Boiero, L.V. Socco, Non uniqueness in surface wave inversion and consequences on seismic site response analyses, Soil Dynamics and Earthquake Engineering, Volume 29 Issue 6 (2009) 982 993.

[6] K. Tokimatsu, S. Tamura, H. Kojima, 1992, Effects of Multiple Modes on Rayleigh Wave Dispersion Characteristics, Journal of Geotechnical Engineering 118, No. 10 (2002) 1529 – 1543.

[7] S. Foti, Numerical and experimental comparison between two-station and multistation methods for spectral analysis of surface waves, Rivista Italiana di Geotecnica Vol. 36(1), ISSN: 0557-1405 (2002) 11 – 22 .

[8] M. Maraschini , F. Ernst, S. Foti, L.V. Socco, A new misfit function for multimodal inversion of surface waves, Geophysics, Volume 75, Issue 4, pp. G31-G43 (2010).

[9] M. Maraschini, S. Foti, A Monte Carlo multimodal inversion for surface waves, Geophysical Journal International, in press. (2010).

[10] C.G. Lai, S. Foti, G.J. Rix, Propagation of Data Uncertainty in Surface Wave Inversion, Journal of Environmental and Engineering Geophysics, 10(2) (2005) 219-228.

[11] I.M Idriss, J.I. Sun, Shake91 User's Manual, University of California at Davis (1992).

[12] S.L. Kramer, Geotechnical Earthquake Engineering, Prentice Hall, New York 1996.

[13] Y. Nakamura, A method for dynamic characteristic estimation of subsurface using microtremor on the ground surface, Q. Rep. Railway Technical Research Institute 30(1) (1989) 25 – 33.

[14] P.Y. Bard, SESAME team, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations measurements, processing and interpretations, http://sesame-fp5.obs.ujf-grenoble.fr (2005).

[15] B. Rosenblad, R. Goetz, Study of the H/V spectral ratio method for determining average shear wave velocities in the Mississippi embayment, Engineering Geology, Volume 112, Issues 1-4 (2010) 13-20.