4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1410

INVERSION OF LOCAL S-WAVE VELOCITY STRUCTURE FROM AVERAGE H/V RATIOS AND COMPARISON WITH CROSS-HOLE MEASUREMENTS

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ABSTRACT

H/V spectral ratios from microtremors can be used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio. Constraints are needed in order to restrict the range of solutions and the inversion is applied to sites where the thickness of the unconsolidated sediments is approximately known from borehole information. Therefore this H/V technique can be used to complement measurements from other S-wave measurement techniques or to constrain inversions for S-wave velocity profiles for example from ambient vibration array measurements. We focus in this experiment on the comparison between the results from the H/V method to estimate S-wave velocities and cross-hole measurements for two sites in Greece. The two examples shown here provide one comparison with good agreement and one with no satisfactory agreement between the results from the H/V method and the cross-hole measurements. Two methods are first applied to compute average H/V ratios, a classical method based on the Fourier transform of the recordings and a method based on frequency-time-analysis (FTAN). In a second step, models are searched for which the ellipticity of the fundamental mode Rayleigh wave explains the observed H/V ratio. A third step involves numerical simulation of H/V spectral ratios for the inverted models, and a selection of the models that qualitatively explain the observed amplitude of the H/V peak. In this work the aforementioned methodology is applied for two sites in Greece, namely, Nestos and Edessa.

Keywords: S-wave velocity, H/V spectral ratio, ambient noise data.

INTRODUCTION

H/V spectral ratios from microtremors can be used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio (Yamanaka et al., 1994, Satoh et al., 2001; Fäh et al., 2001). Constraints are needed in order to restrict the range of solutions, and the inversion is applied to sites where the thickness of the unconsolidated sediments is approximately known from borehole information. Within the uncertainty, the inverted structures generally agree well with the results from other S-wave measuring techniques such as down-hole and cross-hole measurements, and the analysis of ambient vibrations measured on an array (Fäh et al., 2003). Therefore this H/V technique can be used to check measurements from other S-wave measurement techniques or to constrain inversions for S-wave velocity profiles for example from ambient vibration array measurements.

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We focus in this experiment on the comparison between the results from the H/V method to estimate S-wave velocities and cross-hole measurements for two sites in Greece. S-wave cross-hole measurements involves body waves in the frequency range above 30Hz, which on one hand allows to map sub-surface interface variations, but on the other hand operates in a frequency range above the frequency band of interest in engineering seismology. High-frequency waves may be strongly affected by small-scale lateral heterogeneities, and the measured velocities may not necessarily coincide with S-velocities in the frequency band below 10 Hz. The two examples shown here provide one comparison with good agreement and one with no satisfactory agreement between the results from the H/V method and the cross-hole measurements.

METHOD, SITE DESCRIPTION AND DATA

Two methods are first applied to compute average H/V ratios: [1st] A classical method based on the Fourier transform of the recordings using the 'H/V processing' module of the JSESAME software (SESAME project, 2004a, 2004b); in this case the following steps were applied on the ambient noise data; (a) offset correction, (b) computation of Fourier spectra in all three components (E–W, N–S, UP), (c) application of a cosine taper, (d) smoothing of the Fourier amplitude spectra by a Konno-Ohmachi algorithm (Konno and Ohmachi, 1998). [2nd] A method based on frequency-time nalysis (FTAN) (Fäh et al., 2001).

In a second step, models are searched for which the ellipticity of the fundamental mode Rayleigh wave explains the observed H/V ratio (Fäh et al., 2001).

A third step involves numerical simulation of H/V spectral ratios for the inverted models, and a selection of the models that qualitatively explain the observed amplitude of the H/V peak (Fäh et al. 2003).

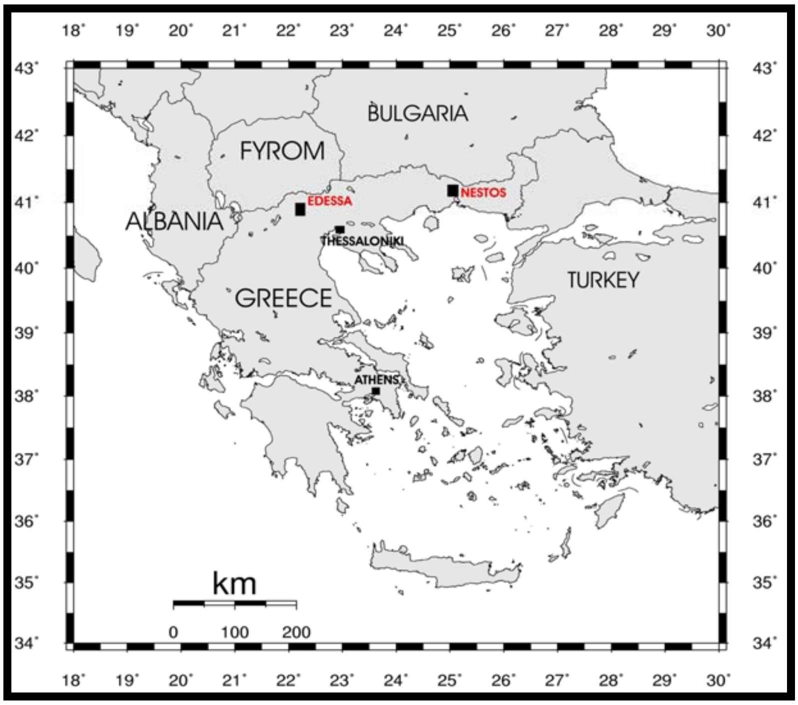


Figure 1. Map of Greece indicating the two test sites Nestos and Edessa where ambient noise and cross-hole measurements were acquired.

Our test sites are two locations in northern Greece, the site NESTOS and the site EDESSA (Fig. 1), where S-wave profiles where obtained from cross-hole measurements every 2m up to 64m depth and up to 20m depth, respectively.

At site NESTOS three profiles (CH2, CH3, CH5) have been measured that are located within a distance of 380 m (ITSAK-Gazetas, 2003). At each site 30 minutes of ambient vibration measurements have been recorded using CityShark 24bits A/D recorder with Lenartz 3D/5sec sensor. Site geology is shown in Fig. 2 consisting of fluvial deposits containing clean sand and silty sand in a medium-dense to loose state overlaying weathered gneiss of unknown thickness (ITSAK-Gazetas, 2003; Klimis et al. 2004).

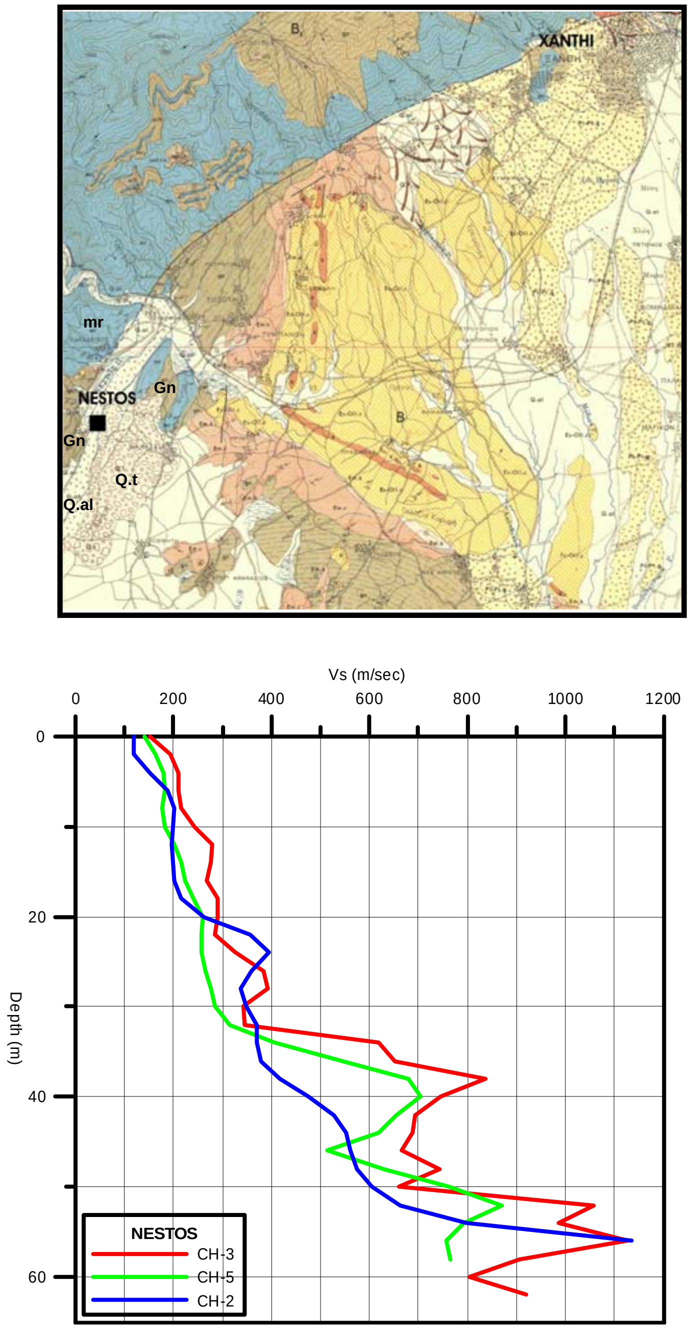


Figure 2. *(Top)* **Regional surface geology in the vicinity of Nestos site [black square] (Q.al , Q.t : Fluvial deposits, Gn: Gneiss, mr: marble) and** *(Bottom)* **shear wave velocity profile from cross-hole measurements within a distance of 380m (ITSAK and Gazetas, 2003, Klimis et al., 2004).**

The local geology of the city of Edessa is quite complex. Ophiolithic formations, flysch and limestones and schists are found in the vicinity of the city. The most striking geological characteristic underlying the city is a thick layer of travertine (porous rock) with a maximum thickness of about 100m (Pitilakis et al. 1992). A thin layer of lacustrine and continental deposits with a thickness varying from a few to about 30m, is overlying the travertine. Borehole at the site under investigation showed 15.3m deposits overlain a 4m layer of weathered travertine (AUTH-ITSAK-YPEXODE, 1996).

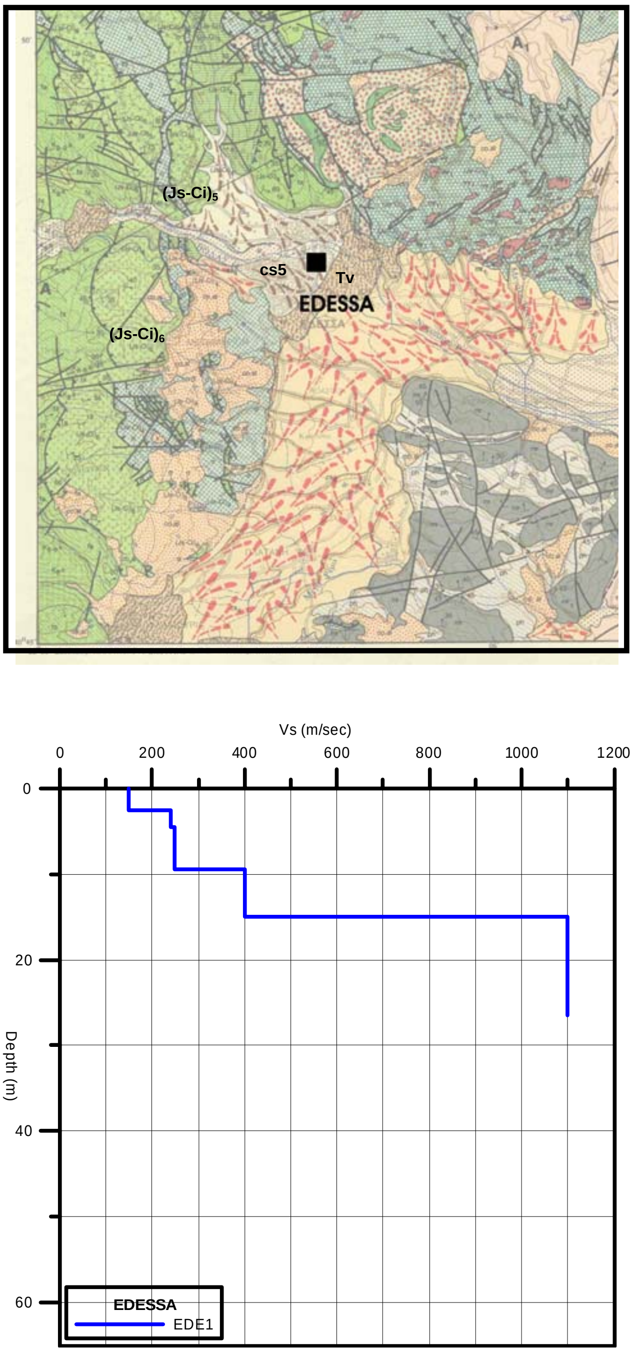


Fig 3. *(Top)* **Regional surface geology in the vicinity of Edessa site [black square] (cs5: Recent Torrential Cones, Tv: Travertine, $(Js\text{-}Ci)_6$:Volcano-sedimentary series of Messimeri, $(Js\text{-}Ci)_5$: Volcanic Formation) and** *(Bottom)* **shear wave velocity profile from cross-hole measurements. (AUTH-ITSAK-YPEXODE, 1996).**

RESULTS FOR THE SITE OF NESTOS

For the site NESTOS CH2 several inverted structures obtained from the H/V method are shown in Figure 4a, with the corresponding ellipticity of the fundamental mode Rayleigh wave overlaid to the H/V ratios of the measurements in Figure 4b. The red curve in Figure 4a corresponds to the S-wave velocity obtained from cross-hole measurements. The inversion applied in the H/V method is resolving with good accuracy the soft-sediment structure, but does not allow an accurate estimate of the velocity of the bedrock. The scatter in the velocity models from the H/V method is increasing with depth. The ellipticities are all in good agreement with the observed H/V ratios, as does the ellipticity obtained for the model from cross-hole measurement (Fig 5). From the amplitude of the H/V ratio at the fundamental frequency of resonance (Fig.4b) it is concluded that the bedrock has rather low velocities below about 1400m/s, with a considerable thickness of more than 300 meters.

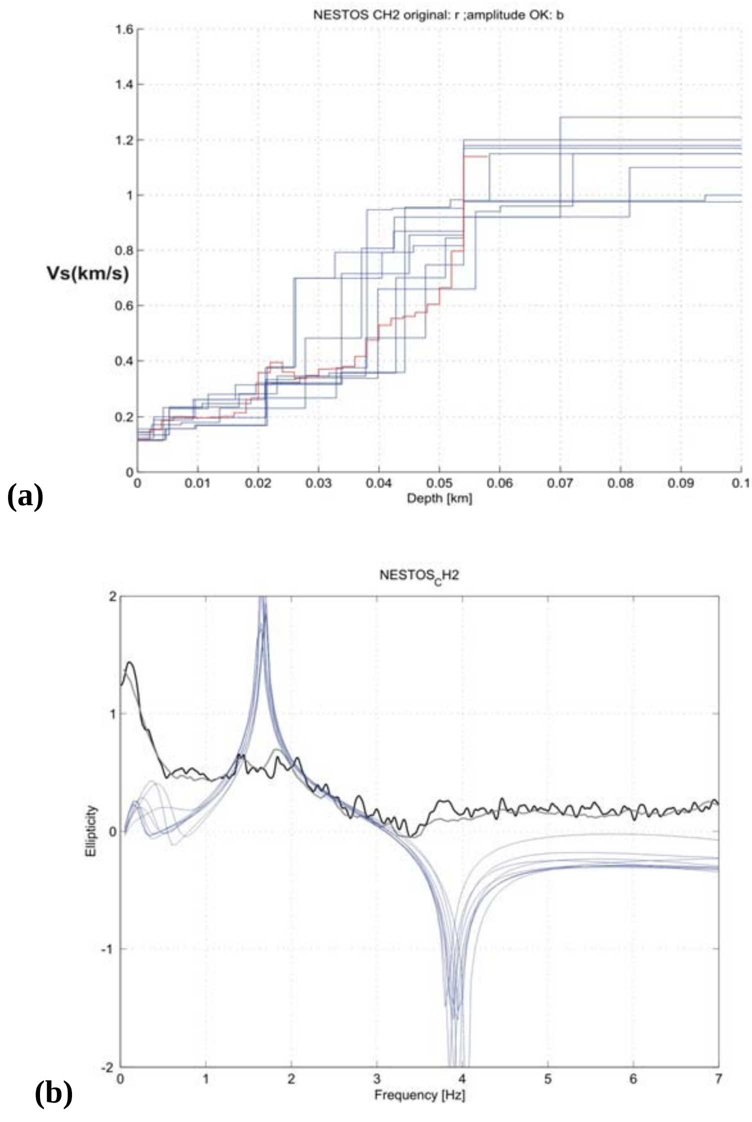


Figure 4 (a). Structural models obtained from the different inversions of the observed H/V ratios (blue lines) at site NESTOS CH2, compared to the model obtained from cross-hole measurements (ITSAK-Gazetas, 2003) (red line). (b) Comparison between H/V ratios of observed noise at site NESTOS CH2 (thin black line: classical method; thin gray line: FTAN based) and the ellipticity of the fundamental-mode Rayleigh waves for the inverted structures (blue curves).

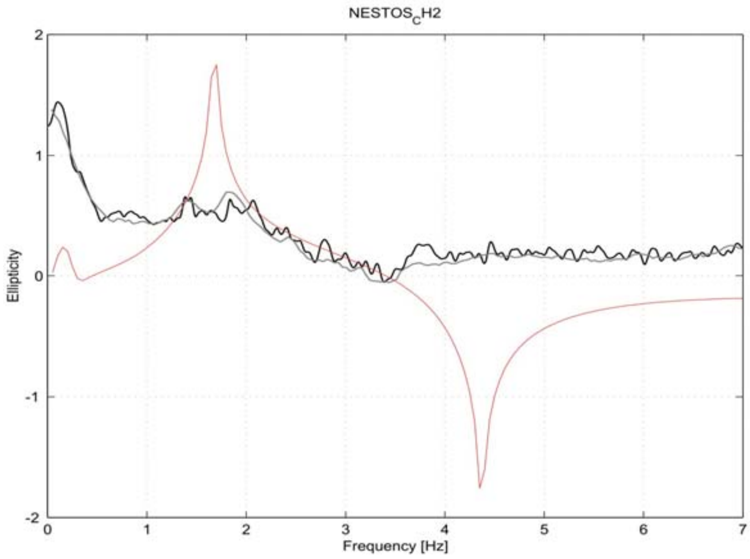
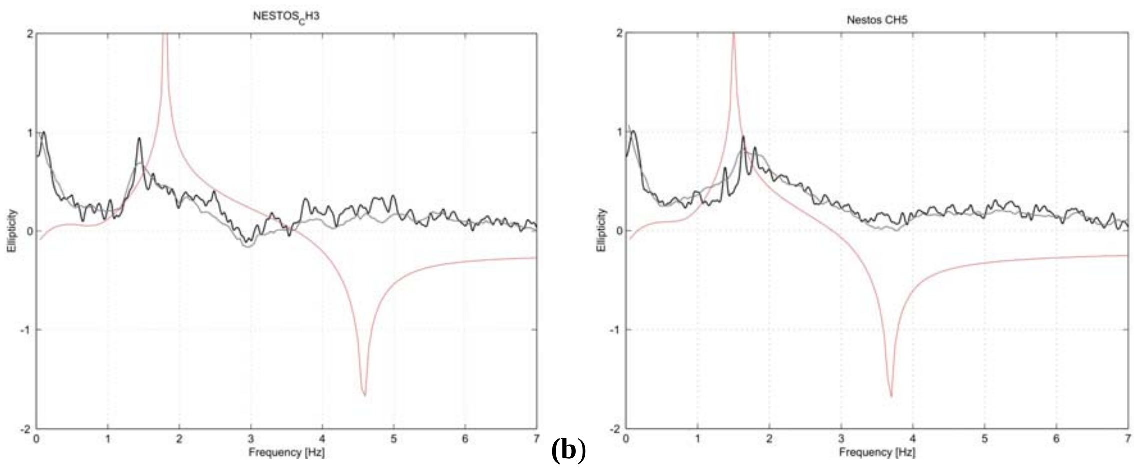


Figure 5. Comparison between H/V ratios of observed noise at site NESTOS CH2 (thin black line: classical method; thin gray line: FTAN based) and the ellipticity of the fundamental-mode Rayleigh wave for the model obtained from cross-hole measurements (red curve).

For sites NESTOS CH3 and CH5 (see Fig. 6), the comparison between ellipticity of the S-wave model from the cross-hole measurements and the measured H/V ratio is not as good as for site CH2. Reasons could be the high lateral variability of the soft sediments and the frequencies of the waves used in the cross-hole measurements. These differences are still within the accuracy of the cross-hole method. Another reason could be that the working hypothesis in the H/V method is not completely fulfilled, namely, the dominance of the fundamental mode Rayleigh wave in the observed ambient vibration wave-field is not ensured.

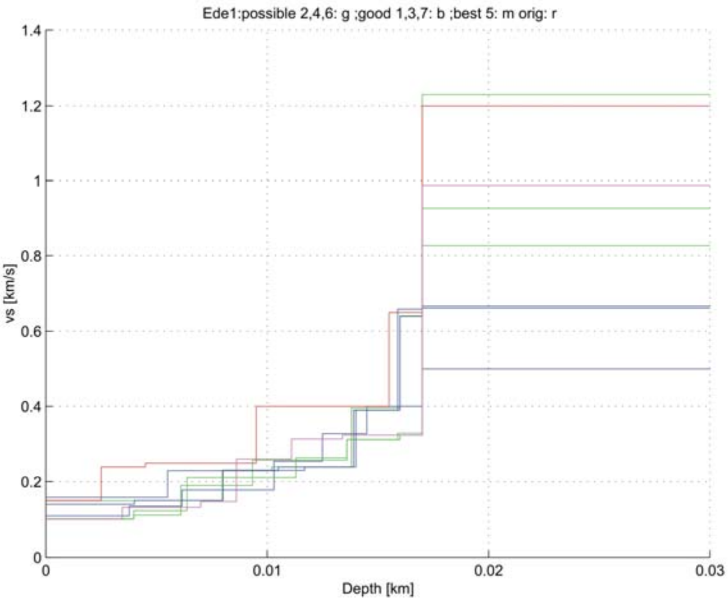


(a) **(b)**

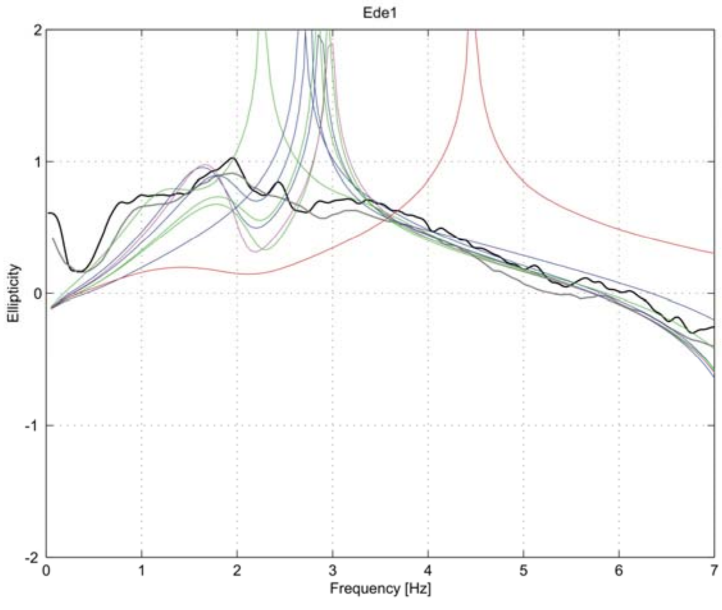
Figure 6 (a). The same as in Figure 5 but for site NESTOS CH3, (b) The same as in Figure 5 but for site NESTOS CH5.

RESULTS FOR THE SITE EDE1

For the site EDE1 several inverted structures obtained from the H/V method are shown in Figure 7a, with the corresponding ellipticity of the fundamental mode Rayleigh wave overlaid to the H/V ratios of the measurements in Figure 7b.



(a)



(b)

Figure 7. (a) Structural models obtained from the different inversions of the observed H/V ratios (green lines: possible models; blue lines: good models; magenta line: preferred model) at site EDE1, compared to the model obtained from cross-hole measurements (AUTH-ITSAK-YPEXODE, 1996) (red line). (b) Comparison between H/V ratios of observed noise at site EDE1 (thin black line: classical method; thin gray line: FTAN based) and the ellipticity of the fundamental-mode Rayleigh waves for the inverted structures (green lines: possible models; blue lines: good models; magenta line: preferred model). The red curve is the ellipticity obtained for the model from the cross-hole measurements.

For the inversion, the thickness of the soft sediments has been fixed, using the borehole information at this site (see Fig. 3) with a slightly different bedrock velocity. From the comparison between synthetic and observed amplitudes of H/V ratios at the fundamental frequency of resonance we distinguish between possible models (in green), good models (in blue) and a preferred model (in magenta). The good models have the best fit between ellipticity curve and H/V spectral ratio and the preferred model has a sufficiently large velocity contrast between sediments and bedrock to explain the observed H/V spectral ratio. The red curve in Figure 7b corresponds to the result from the cross-hole measurements. The ellipticities from the models obtained from the inversion of the H/V curves from ambient noise data are obviously all in good agreement with the observed H/V ratios. This is not the case for the model from cross-hole measurement (Fig 7b). This disagreement cannot be explained anymore with the variability of S-waves in the soft sediments. As it is obvious there is no correlation between the cross-hole (CH) results and the ambient noise data from the ellipticity curves. The elipticity curves presented in Figure 7b are from the inversion of the ambient noise data except from the red colour curve that correspond to the CH data. The green colour elipticity curve that is closer to the resonance, ie. 2Hz could be considered as the best solution that correspond to a shear wave velocity model with lower velocity for the upper sedimentary layers compared to the CH velocity model, green and red colour model on Figure 7a, respectively. This site requires a revision of the local structural model since one could state that the CH results should be under reconsideration. Either S-wave velocities are much lower as given in Figure7a, or the interface between soft sediments and bedrock is at larger depth. Travertine is a porous rock, and probably has a rather low S-wave velocity. The real rock interface may be at the volcanic-sedimentary floor, but this depth is not known. By defining this interface at larger depth, the inversion applied in the H/V method would result in higher S-wave velocities.

DISCUSSION AND CONCLUSIONS

In this paper H/V spectral ratios from microtremors are used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio.

It seems that for sites that can be approximated by a layered structure the applied method gives reasonable results. This is probably due to the fact that the ellipticity of Rayleigh wave - in the frequency band between the fundamental frequency of resonance of the soft upper layers - and the first minimum of the average H/V spectral ratio is determined by the layering of the sediments (Fäh et al., 2003).

However, H/V spectral ratio results can be reliably used to reveal the soil structure in the upper layers if the bedrock depth is satisfactorily resolved from borehole or other method data.

In addition, the basic assumption of the dominance of Rayleigh wave ellipticity curve in the observed data should be further investigated in order to ensure that the peak in H/V spectral ratio is related to the fundamental mode of Rayleigh wave. Separation of Rayleigh waves should be introduced and application of the technique in time series with high percentage of Rayleigh waves should be exercised.

ACKNOWLEDGEMENTS

This work has been financially supported by the SESAME EC project (ENVG1-CT-2000-00026) and NERIES-JRA4 (“Infarst-2.1 [I3], EC Contract No. 026130)

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