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FTAN METHOD FOR THE DETAILED DEFINITION OF VS IN URBAN AREAS

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SUMMARY

Detailed shear wave velocity profiles with depth can be obtained from the non-linear inversion (Hedgehog method) of the dispersion curve of group velocity of Rayleigh wave fundamental mode extracted with FTAN method.
In this paper we present some results of FTAN measurements in italian urban areas with different soil and rock environments and high seismic risk. Comparisons are also shown with SASW and down-hole measurements. These results put in evidence that, even in engineering geophysics, FTAN method is a powerful tool as detailed Vs profiles can be obtained in highly urbanized areas with only one receiver on the ground surface.

INTRODUCTION

Shear dynamic parameters are of fundamental interest in earthquake engineering. Most engineering structures are founded on soil deposits that are far from being rigid bodies. Laboratory measurements cannot be assigned to soil deposits because of the different volumes and frequencies involved. Detailed shear wave (Vs) velocities are obtained from down- and cross-hole tests, which are expensive because of drilling costs; instead, they can be measured from refraction seismic surveys by studying the dispersion of Rayleigh surface waves. Rayleigh group velocities are related to the signal energy, while phase velocity measurements are intrinsically undetermined. FTAN (Frequency Time Analysis) method is based on the study of surface wave (both Rayleigh and Love) group velocities and is successfully used in seismology.
Aim of this paper is to show what a powerful tool is the FTAN method even in seismic engineering problems. We present some field tests in sedimentary and volcanic deposits of italian urban areas (Figure 1), carried on in the framework of national research projects for the study of the local seismic response [1,

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2, 3, 4, 5, 6, 7, 8 and 9]. Measurements have been selected to show the main advantages of FTAN method in complex geological settings of noisy urban areas and archaeological sites.

Figure 1
Location of the examined Italian urban sites.

FTAN METHOD

Rayleigh waves are artificially generated by the vertical impact of a 20 kg weight on the ground, for receiver distances less than 50m, and by bullets of gunpowder (5-10g) fired into the ground for longer distances (about 250m). Signals are recorded along refraction seismic surveys by vertical geophones with 4.5 Hz and 1 Hz resonant frequency, damping 70%, for the shorter and the larger distances, respectively. After correction for the instrument response, a signal is processed by FTAN method to extract the group velocity dispersion curve of the Rayleigh fundamental mode. FTAN represents a significant improvement, due to Levshin et al. [10, 11], of the multiple filter analysis originally developed by Dziewonski et al. [12] and can be applied to a single channel to measure group velocity even when there is higher modes contamination. This method employs a system of narrow-band Gaussian filters, with varying central frequency, that do not introduce phase distortion and give a good resolution in the time-frequency domain. For each filter band the square amplitude of the inverse FFT of the filtered signal is the energy carried by the central frequency component of the original signal. Since the arrival time is inversely proportional to group velocity, for a known distance, the energy is obtained as a function of group velocity at a certain central frequency. The process is repeated for different central frequencies. A FTAN map is the image of a matrix whose columns are the energy values at a certain period and the raws are the energy values at constant group velocity. A sequence of frequency filters and time window is applied to the dispersion curve for an easy extraction of the fundamental mode. The floating filtering technique, combined to a phase equalization, permits to isolate the fundamental mode from the higher modes [13]. The dispersion curves obtained in such a way can be inverted to determine the S-wave velocity profiles versus depth. A non-linear inversion is made with the Hedgehog method developed by Valyus et al. [14] and discussed in detail by Panza [15]. An initial model represented by a set of parameters (shear and compressional wave velocities and densities in a layered earth) is considered. Perturbing a chosen set of model parameters within a preassigned volume in the parameters space, phase or/and group velocities are computed. These theoretical velocities are then compared with the corresponding experimental ones. If the root mean square error of the entire data set is less than a value defined a priori on the base of the quality of the data and if, at each frequency, no individual computed velocity differs from its experimental counterpart by more than an assigned error, depending upon the quality of the measurements, the model is accepted as a solution. A representative solution is then chosen as having an error closest to the average error computed for the entire solution set, unless other information suggests a different choice.

FTAN AND SASW METHODS

Among non destructive methods commonly used in engineering geophysics we mention SASW (Spectral Analysis of Surface Waves) based on the computation of phase velocities between the signals recorded at two vertical receivers, in the frequency range of coherence equal to one [16]. The main problem is the counting of the correct cycle number. We make spectral analysis with MATLAB software and use the unwrap function to get the correct phase angle. Anyway, as usual in noisy areas, the phase spectra present rapidly changing values and this prevents the good use of unwrap subroutine to detect phase jumps and, hence, the right number of cycles. As comparison between FTAN and SASW methods, we present measurements carried out in a typical lithostratigraphy of the eastern district of Napoli (Figure 1), characterized by volcaniclastic soils (pozzolana) and rocks (various types of tuffs) with different percentage of hardening and alteration because of weathering and rill-wash processes. Moreover, the eastern area of Napoli was a marsh, recently drained both for urban development and for the reduction of water supply. The sub-soil, reconstructed from several drillings, is mainly formed by man-made ground, alluvial soils (ashes, stratified sands, peat), loose and slightly cemented pozzolana, yellow tuff and marine sands [17]. Such a complex geological pattern, together with the high population density and the need of detailed Vs profiles with depth for the mitigation of seismic risk, requests the use of non conventional spreadings with receivers not regularly distributed on the surface.

The signals recorded at 50, 60, 70, and 80m offsets were analysed to obtain FTAN maps from which group velocity dispersion curves of the fundamental mode have been obtained for each signal (Figure 2a). The phase velocities have been determined by computing the difference between the phases of FTAN maps for 50 and 80m offsets. The phase velocities have been computed also with SASW method [16] for spreadings with receiver spacing of 10, 20 and 30m (Figure 2c). The inversion of the average group velocity with the Hedgehog method has resulted in Vs profiles ranging 130-220m/s to a maximum depth of 15m (Figure 2b). The representative solution is characterized by a velocity decrease to 185m/s at 10m of depth, corresponding to the presence of the peat layer. Phase velocities have been computed for all the Hedgehog solutions and they are confined between two FTAN phase velocities (Figure 2c). The comparison between phase velocities computed for the Hedgehog solutions, and those obtained by FTAN and SASW methods evidences the good agreement in the period range of 0.03-0.05s, for short source-receiver distances. Instead discrepancy is evident with SASW phase velocities for larger distances, due to the ambiguity in the determination of the number, N, of the cycles.

FTAN AND DOWN-HOLE MEASUREMENTS

Comparisons between FTAN measurements and down-hole tests have been extensively done [9] and are shown in two sites with different geological settings, that is at Nocera Umbra, in central Italy, heavily damaged by 1997-99 seismic sequence, and Agnano, southern Italy, in the western district of Napoli (Figure 1).

Nocera Umbra has an historical centre built on different types of scaglia formation (rossa, variegata and cinerea), surrounded by ancient walls characterized by a cover of man-made ground consisting of heterogeneous gross pieces and clayey material. FTAN measurements with 24 and 28m source-receiver distances have been done inside the historical centre, at the Caprera square, on scaglia rossa formation (Figure 3a). Down-hole test has been carried out few hundred metres far, close to the ancient walls, in S. Martino street.

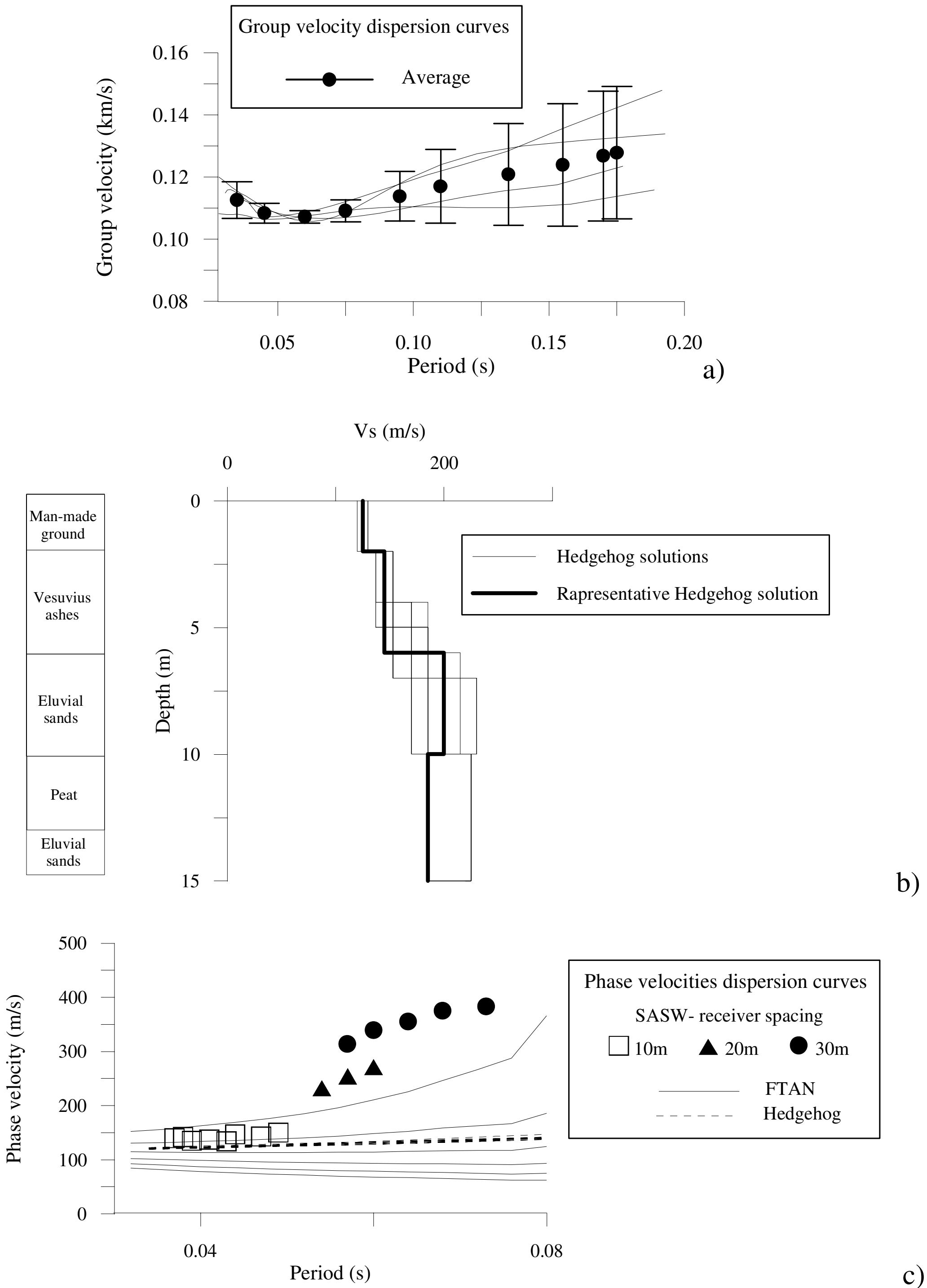

Figure 2

Dispersion curves of Rayleigh group velocities relative to receivers with 50, 60, 70 and 80 m offsets. The average dispersion curve is also shown (full dots) with 2σ error bar (a). The Vs models obtained from the Hedgehog non-linear inversion of FTAN measurements in the eastern district of Napoli. The stratigraphic sequence is typical of this area (b). Phase velocities computed with FTAN, between signals at 50 and 80 m offsets, and SASW methods. Phase velocities computed for Hedgehog solutions are also shown (dot line) (c).

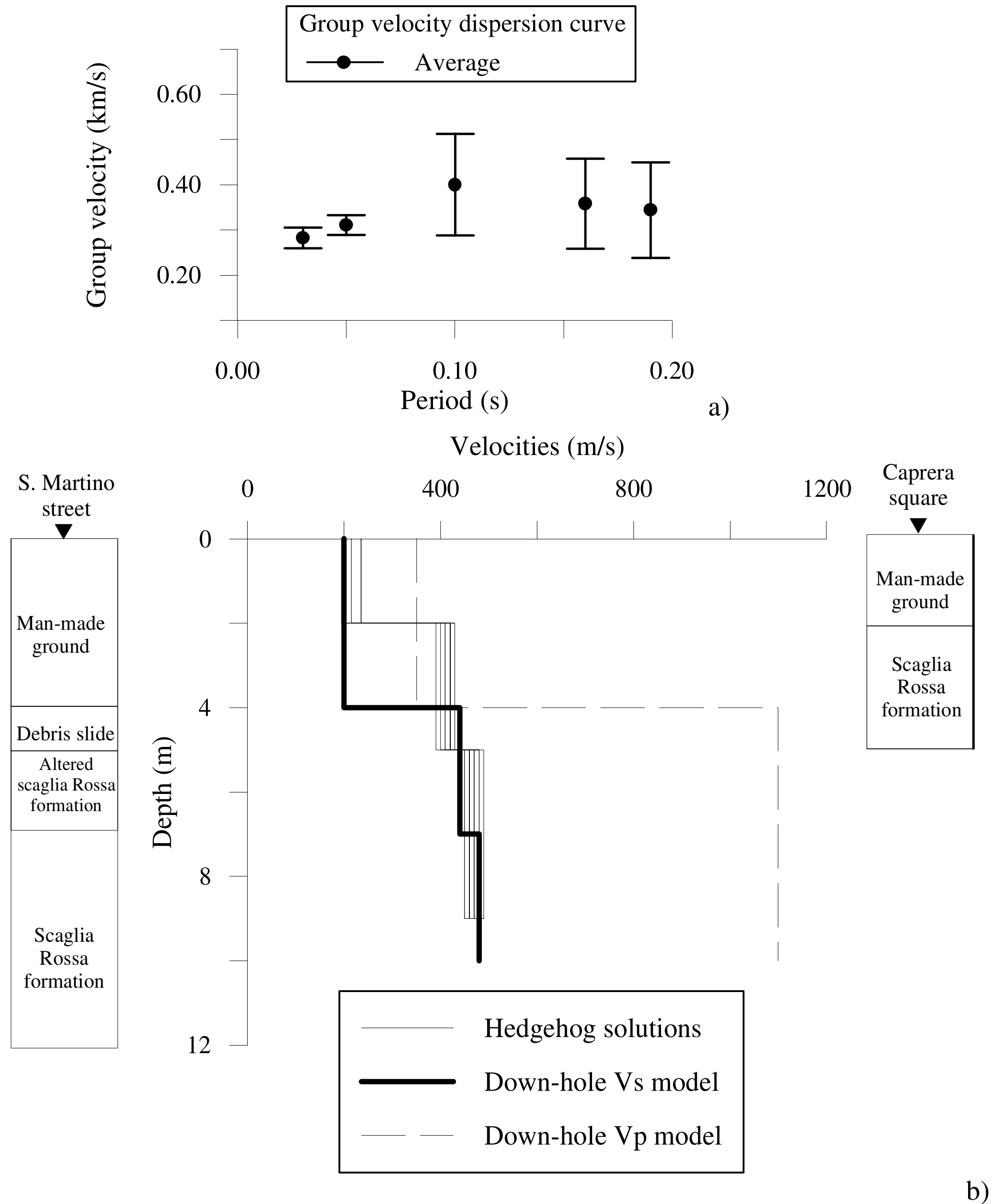

Figure 3
Comparison between down-hole profile (St. Martino street) and the Vs models, inverted from average FTAN group velocity (a) with Hedgehog non-linear method, in the historical centre of Nocera Umbra (Caprera square) (b).

The Hedgehog solutions are characterized by Vs values of 190-230m/s for the man-made ground, in very good agreement with down-hole measurements (Figure 3b). The scaglia rossa formation is characterized by Vs of 390-490m/s, at the Caprera square, in agreement with down-hole Vs of 440-480m/s (Figure 3b). The Vp down-hole measurements vary from 350m/s, in the shallower 4m of man-made ground to 1100 m/s in the scaglia rossa formation (Figure 3b). The very good agreement between Hedgehog solutions and down-hole measurements imply that the investigated soils are laterally homogeneous.

The second site is located at Agnano, in the western part of Napoli (Figure 1), characterized by pyroclastic material with intercalations of peat material with thickness up to 15-20m (Figure 4). The set of Hedgehog solutions has been compared with down-hole tests performed in close drillings (S10 and S14 in the figure 4b) [18], about 1km distant. As observed in numerous sites in Napoli, the presence of large scoriae and lavic lapilli in the pyroclastic soils is responsible of down-hole Vs higher than cross-hole ones, often with spurious spikes clearly depending on the soil composition [9]. Taking also into account the distance between down-hole and FTAN measurements, we can conclude that the agreement is good, and that the average Hedgehog solution, having sampled some tens of metres, is more appropriate in studies of seismic amplification effects.

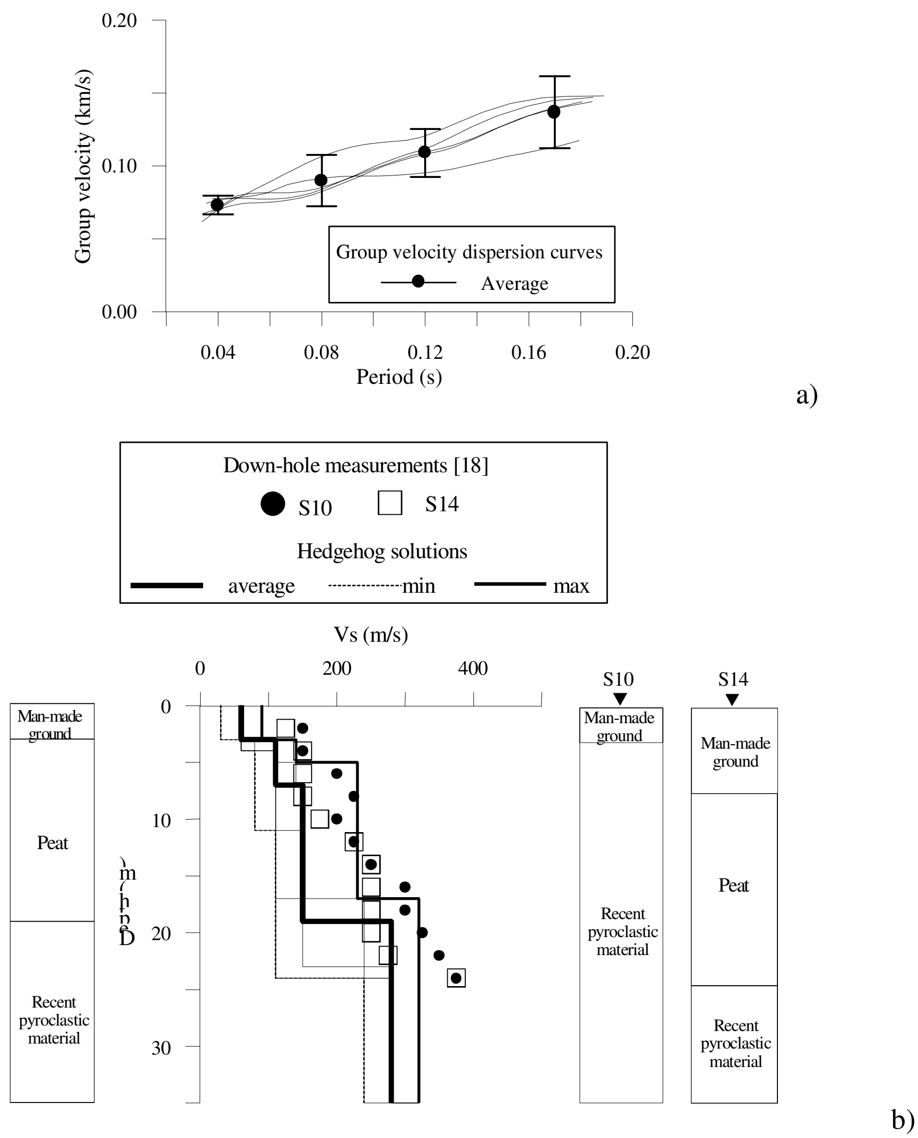

Figure 4

Comparison between down-hole Vs measurements at S10 and S14 drillings [18] and the Vs models inverted from average FTAN group velocity (a) with Hedgehog non-linear method at Agnano, Napoli (b). The stratigraphic sequence is hypothesized according to the two drillings.

SAMPLING DEPTH

The depth of investigation obviously depends on the seismic velocities of the subsoil. As an example, we show the Vs models (Hedgehog solutions) obtained at Siracusa (Epipoli site), Sicily (Figure 1) for a maximum source-receiver distance of 200m. The stratigraphy, deduced from the geological map, is characterized by a volcanic cover on a thick sequence of calcareous sandstones. The Vs models, up to 260m of depth, are characterized by Vs ranging 1.1-1.7 km/s, which can be attributed to volcanic material, and velocities increasing from 0.8-0.95 km/s to 1-1.6 km/s, in the layer of calcareous sandstones. Hence, depending on the high Vs, for the same period range (0.02-0.30s) we could investigate very deep compared to the profile length (Figure 5).

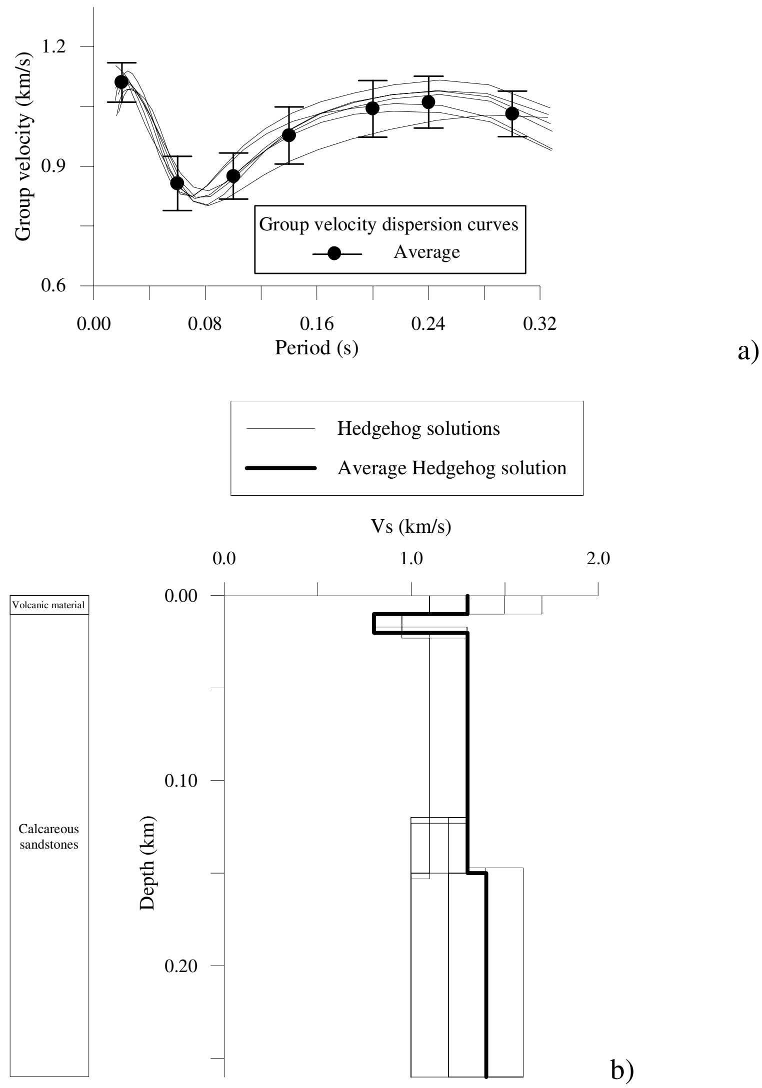

Figure 5
Vs models (Hedgehog solutions) obtained at Epipoli, Siracusa (b) from the inversion of the group velocity dispersion curve (a). The stratigraphic sequence is hypothesized according to the geology of the investigated area.

FTAN AND ARCHAEOLOGICAL SITES

Particular attention is required for the definition of detailed Vs profiles in restoring ancient monuments, as you need non destructive methods and non regularly spaced receivers. As an example, we present the FTAN-Hedgehog results obtained at St. Nicolò l'Arena church, located in the historical centre of Catania (Sicily) (Figure 1). Stratigraphy, based on a close drilling, outside the church, is characterized by man made ground material on alternating layers of Etna bubble lavas, ashes and lapilli, with variable thickness. The FTAN average dispersion curve has been obtained from the analysis on recordings at 50, 60 and 70m from the source (vertical impact of a 20kg weight), being 70m the maximum possible distance (Figure 6a). The representative Vs model, 40m thick, is characterized, below a 1m thick pavement, by a layer of man made ground with Vs of 210m/s, and a layer of volcanic soil with Vs slightly increasing from 360 to 380m/s (Figure 6b).

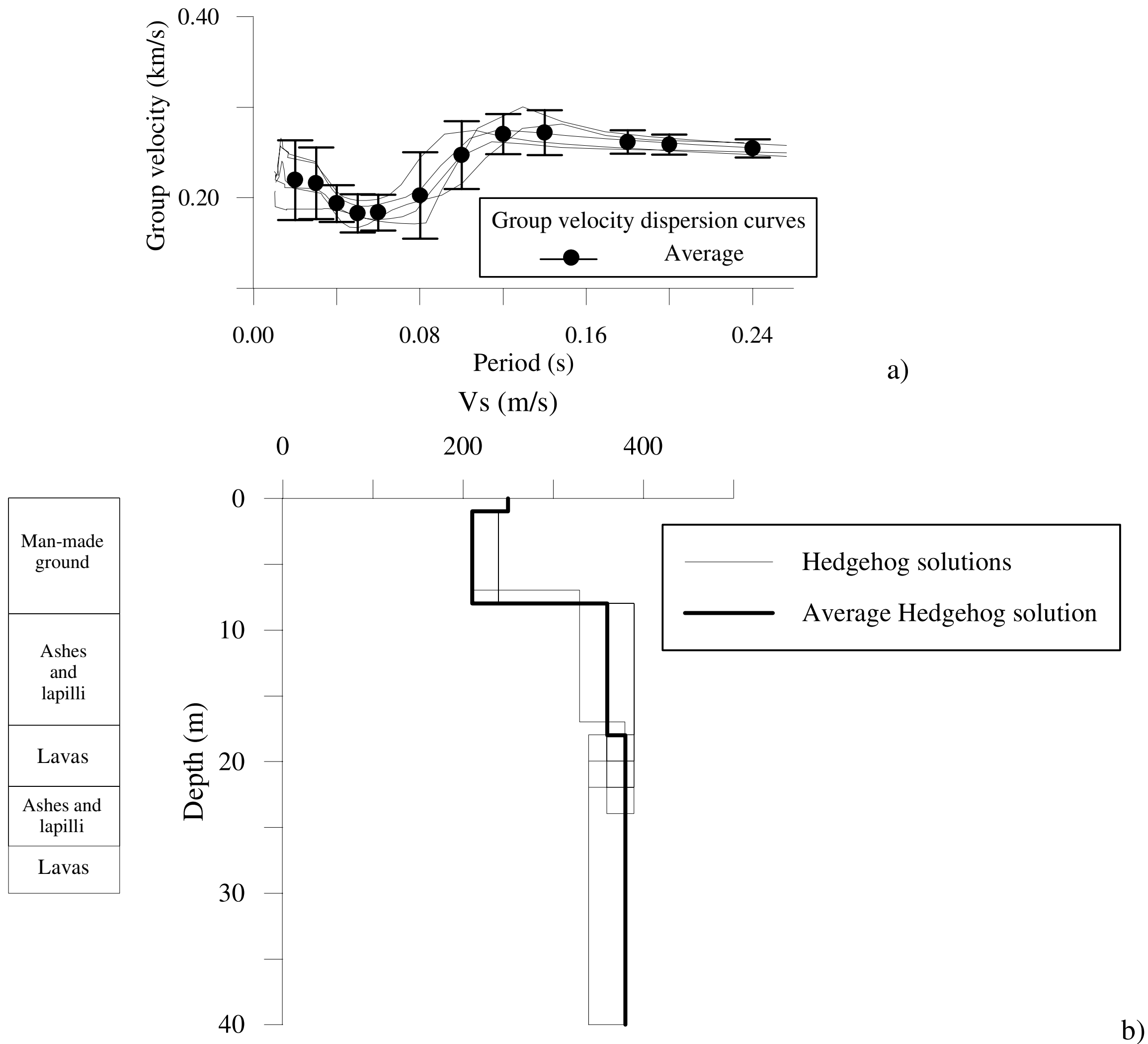

Figure 6
Vs models (Hedgehog solutions) obtained at St. Nicolò l'Arena church, Catania (b) from the inversion of the group velocity dispersion curve (a). The stratigraphic sequence of a close drilling is also shown.

FTAN AND LIQUEFACTION SUSCEPTIBILITY

In the framework of the Catania Project supported by GNDT (Gruppo Nazionale per la Difesa dai Terremoti) FTAN measurements have been carried out in the shore sands of Catania (Figure 1), at La Plaja beach, to define their detailed shear wave velocity profiles and to evaluate potential liquefaction phenomena. In particular, the Catania Project aimed to define a risk scenario of Catania for a dangerous earthquake like that happened in 1693 (M=7-7.5) which caused extensive structural damages and thousands of victims.

The investigated site is characterized by fine sands with thin intercalations of gravelly sands having a mean grain size between 0.24mm (in the uppermost 10 m of thickness) and 0.13mm. The water level is around 2m below the ground surface. Geotechnical data put in evidence a sharp decrease of the cone penetration resistance values q_{c1}, corrected for the overburden pressure and fine content [19], corresponding to a change of relative density Dr from 75% to about 40%. This trending seems to be correlated with Vs Hedgehog solutions that show an increase of velocities at 2-3m of depth, then a decrease of them at about 5m of depth, and again an increase at about 11m of depth [20] (Figure 7).

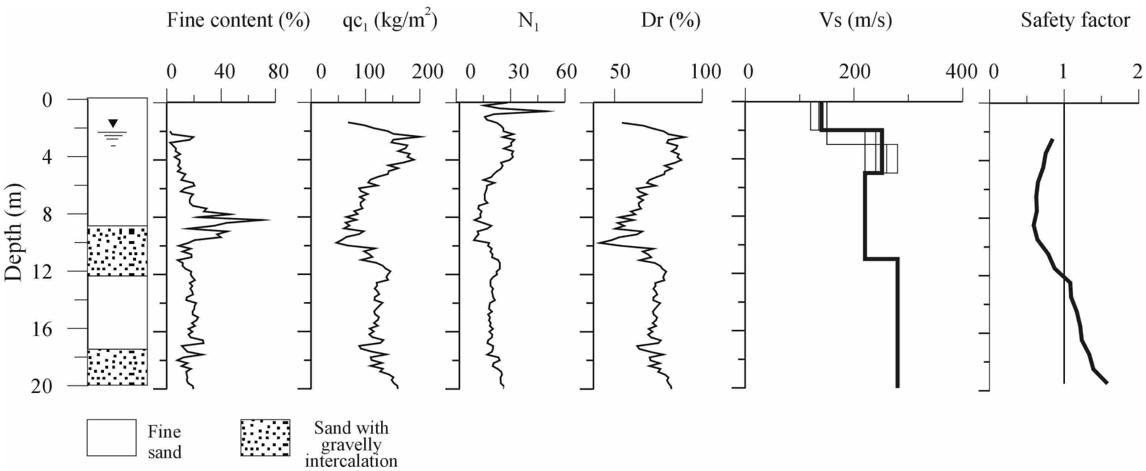

Figure 7

Analysis of the liquefaction susceptibility of the shore sands at La Plaja beach with the safety factor empirical method [21, 22] for the scenario earthquake (M=7-7.5) [23]. The values of cone penetration resistance qc_1 have been corrected for overburden pressure and fine content; the blow count number N_1, corrected for pressure, has been computed from the qc_1 by the empirical correlation from Tatsuoka et al. [22] and Meyerhof [25]. The Vs models (Hedgehog solutions) and the average model (thick line) are shown [20]. The stratigraphic sequence is representative of the investigated area.

The liquefaction susceptibility of the shore sands at La Plaja beach has been evaluated in terms of safety factor, F, defined as the ratio between the cyclic strength and the cyclic stress ratio. At each depth, liquefaction is said to happen if F is less or equal to 1. The shear stress induced in a soil element during an earthquake is approximately equal to the amplitude of the maximum shear stress, normalized to the effective vertical stress, and it can be computed by the procedure proposed by Seed and Idriss [21]. The cyclic strength corresponding to the shear stress required to cause initial liquefaction can be evaluated from correlations between the cyclic strength of laboratory tests, performed on undisturbed soil samples, and the values, N, of the penetration resistance, such as that established by Tatsuoka et al. [22]. The liquefaction susceptibility has been evaluated for the scenario earthquake computed for 2D structural models by Romanelli and Vaccari [23]. The seismogram computed in the 1D reference model

(a_{max}=0.45g) has been attributed to the outcropping seismic basement and then SHAKE program [24] has been utilized to compute shear stress along the seismic soil profile defined by FTAN and Hedgehog methods. It results that shore sands down to 10m of depth become susceptible to liquefaction, instead at higher depths, the F factor is higher than 1, and it is in agreement with improving geotechnical and geophysical properties at depths higher than 12m (Figure 7). Therefore, the analysis of the geotechnical data and shear seismic velocities and the assumption of realistic scenario earthquakes put in evidence a high probability of liquefaction occurrence of the shore sands of La Plaja beach for a magnitude 7-7.5 earthquake. This is also in agreement with historical information.

CONCLUSIONS

Geotechnical design routinely requires that in situ shear wave velocity be determined to evaluate stiffness of the ground. This study shows that the analysis of the dispersion of Rayleigh waves is a low cost and powerful tool to define Vs profiles. Methods which are based on group velocity dispersion curve must be preferred to those based on phase velocity since the latter are intrinsically undetermined, in the frequency range considered, because of the difficulty to determine exactly the number of cycles to be used. Moreover strong energy higher modes, close to the fundamental mode time window, could make more complex the phase velocity measurements. Group velocity based techniques overcome the problem. FTAN method is suitable in engineering geophysics and provides accurate group velocity measurements. The method permits an easy identification and isolation of the fundamental mode and, when necessary, of the first higher modes. The extracted group velocity dispersion curve is inverted using a non-linear technique (Hedgehog). The examples shown in this paper evidence the advantages of the FTAN method as it is rigorous and does not require any drilling or particular spreadings, hence it is particularly suitable in urban areas.

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