Reliability of combined active and passive surface wave methods

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Abstract

Surface wave methods, both active and passive, are often used for shallow site characterisation especially in seismic studies. They provide valuable information about the subsurface soil with relatively little economic effort. For active surveys the depth of penetration is typically limited by the amount of information in the low frequency range. Passive methods are based on the analysis of microtremors, which are characterized by an extended content of energy in the low frequency range; hence they allow for deep characterization, but typically lack resolution for shallow layers. In the present paper the combined use of active and passive data in surface wave tests is explored in order to take advantage of the complementary information given by the two methods. The experimental results for a case history, in which Down-Hole tests were available for a comparison, are presented, showing the great potential of the combined technique. Finally, the implications of data uncertainties in terms of resolution and reliability are explored using a Monte Carlo approach for the inversion process, illustrating the importance of active data to improve the characterization of shallow layers.

Introduction

Surface wave tests have a great potential for site characterization in seismic areas because they allow for the estimation of the small strain stiffness profile with reduced budget when compared with traditional seismic borehole methods.

Surface waves are easily generated and detected on the ground surface because of a combination of factors (reduced attenuation with distance, high energy content). In particular surface wave tests take advantage of a particular property of surface waves: the geometric dispersion which makes their phase velocity frequency dependent in heterogeneous media. If the Rayleigh wave dispersion curve (phase velocity vs frequency) can be retrieved from experimental data it can be successfully used for the solution of an inverse problem aimed at the identification of soil parameters. This last step is usually accomplished assuming a layered linear elastic model.

Surface wave tests are often classified as active or passive. In the latter, the data acquisition is carried on without the need for specific sources acting on the ground surface and the experimental dispersion curve is extracted from the analysis of microtremors or cultural noise. Indeed, due to the increasing amount of noise generated by human activities (e.g. highway or railway traffic) and to the presence of micro-seismic activity within the ground, passive data are always rich in energy content, especially in the low frequency range.

The origins of surface wave methods date back to pioneering works in seismology, in which the Earth's crust and mantle were characterized from analysis of surface waves generated by earthquakes [Aki and Richards, 1980]. Passive methods based on microtremors have successfully been used for the characterization of geological structures up to hundreds of metres below ground level [Horike, 1985; Tokimatsu *et al.*, 1992; Okada, 2003].

Surface wave tests have gained popularity in civil engineering since the introduction of SASW [*Spectral Analysis of Surface Waves*: Nazarian and Stokoe 1985; Stokoe *et al.*, 1994], which can be considered a particular case of active testing with a 2 station acquisition procedure. In this case the interest is typically limited to tens of metres and a higher resolution is required.

The main difference in terms of results between active and passive surface wave tests is related to the different frequency ranges in which the information can be retrieved. Indeed while in active tests it is usually very easy to generate and detect high frequency components, microtremors are typically rich in energy in the low frequency band.

Combined use of passive and active methods has been suggested as a way to avoid the limitations of each of the two methods [Tokimatsu, 1995; Rix *et al.*, 2002; Yoon and Rix, 2004]. In the present paper some results of combined active and passive tests are presented with particular attention to achievable resolution and uncertainty.

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Data acquisition and processing

The whole test procedure for surface wave testing can be described as a three step process: acquisition, processing and inversion. The data from active and passive measurements can be combined as outlined in Figure 1. While the inversion process is common to the two methods, it is worthwhile to note that the differences between active and passive tests reside in the acquisition setup and in the signal processing. These differences are mainly linked to the fact that in surveys using microtremors the source position, and hence the direction of wave propagation, is unknown so that a 2D array of sensors is required to correctly analyse the wave field at the site. As mentioned the combined use of the two methods leads to the possibility of reconstructing the experimental dispersion curve over a wide frequency range and hence getting, from the inversion process, information on the deep structure while keeping a good resolution for shallow layers.

Active data

The active data herein presented have been collected using a multistation setup with 48 geophones located along a straight line starting from the source. Multistation data can be processed using a variety of signal processing techniques [FOTI, 2005]. In the present case a transform based approach has been adopted. In particular using a 2D Fourier transform the experimental data have been transformed from the space-time domain (Fig. 2a) to the frequency-wavenumber domain (Fig. 2b), where the spectral maxima correspond to the experimental dispersion curve. In practice for each frequency f, the wavenumber k corresponding to the spectral maximum allows the estimation of the Rayleigh wave phase velocity V_R through the fundamental relationship:

$$V_R = \frac{2\pi f}{k} \quad (1)$$

The frequency range over which the experimental dispersion curve can be retrieved is governed by the length of the array and the type of source used. In order to get information for the low frequency range high energy sources and long arrays are required. On the other hand, attenuation of high frequency components of the seismic signal limits the frequency range that can be explored using long arrays. The implications concerning array length are thoroughly discussed in RIX [2005] and FOTI [2005].

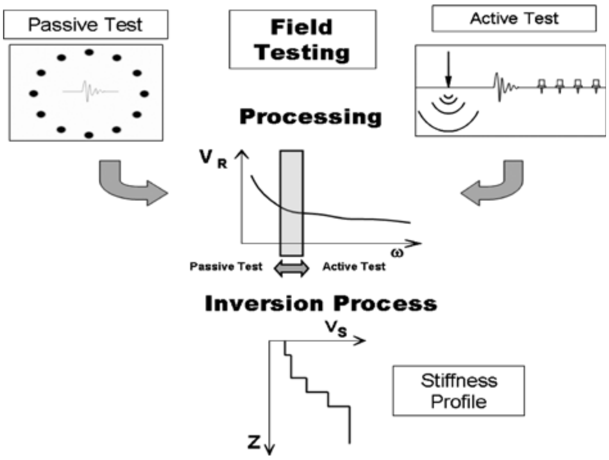

Fig. 1 – Combined interpretation of active and passive surface wave tests: schematic outline.

Fig. 1 – Interpretazione combinata di prove per onde superficiali attive e passive: schema di riferimento.

Passive data

Microtremor surveys are performed acquiring and analysing background noise caused by both hu-

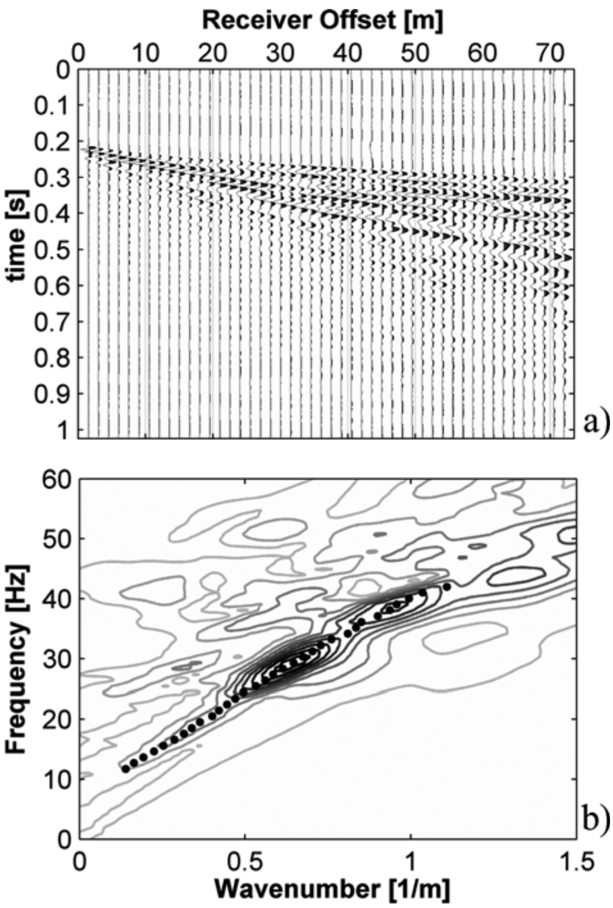

Fig. 2 – Experimental data for active surface wave test: a) Space-time domain b) Frequency-wavenumber domain (with spectral maxima).

Fig. 2 – Prove per onde superficiali attive, dati sperimentali: a) Dominio spazio-tempo b) Dominio frequenza-numero d'onda (rappresentazione dei massimi spettrali).

man activities and natural phenomena. Different experimental setups are required to detect microtremors, deploying on the ground surface a 2D array of sensors, because in this case the position(s) of the seismic source(s) is (are) unknown. In the present study circular arrays have been used. Indeed since no information is available concerning the microtremor source it is preferable to have the same "array response" for any direction (i.e. uniform space sampling).

The two techniques most widely adopted for processing microtremors are Spatial Auto-Correlation (SPAC) and Frequency-Wavenumber (*fk*) analysis [OKADA, 2003]. In the present study the *fk* method has been adopted for consistency with the technique adopted for the analysis of active data (described in the previous section).

The fk method was initially developed to detect nuclear explosions using seismic networks (e.g. CAPON, 1969). Indeed the distribution of energy in a frequency wavenumber spectrum allows the identification of the direction of arrival of different components contained in a passive measurement. Typically Rayleigh waves, because of their reduced spatial attenuation, are associated with relatively high amplitudes of vibration, hence the possibility of identifying the strongest component within the microtremors and the associated wavenumber can be used to estimate phase velocity using Equation 1. Moreover many of the sources of microtremors can be identified as acting on the soil surface and therefore surface waves are naturally considered to be their dominant component [OKADA, 2003].

In particular, several techniques can be adopted to estimate the frequency-wavenumber power spectral density function (*fk* spectra) using the theory of stochastic processes. The assumption that microtremors are stochastic processes in time and space requires data to be stationary. In the present work the Frequency Domain Beam Former (FDBF) is adopted, other more sophisticated techniques are described by ZWICKI [1999].

In FDBF the power in particular *f-k* pairs is determined by steering the array toward various directions and possible phase velocities. In this respect, also, circular or circular type arrays have been recognized as being more appropriate for *f-k* analysis [ZWICKI, 1999].

Some examples of contour plots of the spectral power density are reported in Figure 3. Each spectrum is plotted as a function of wavenumbers in two orthogonal directions for a given frequency. The origin of the axes coincides with the centre of the acquisition array. The position of the maximum energy peak identifies therefore the direction of arrival of the main perturbation with respect to the

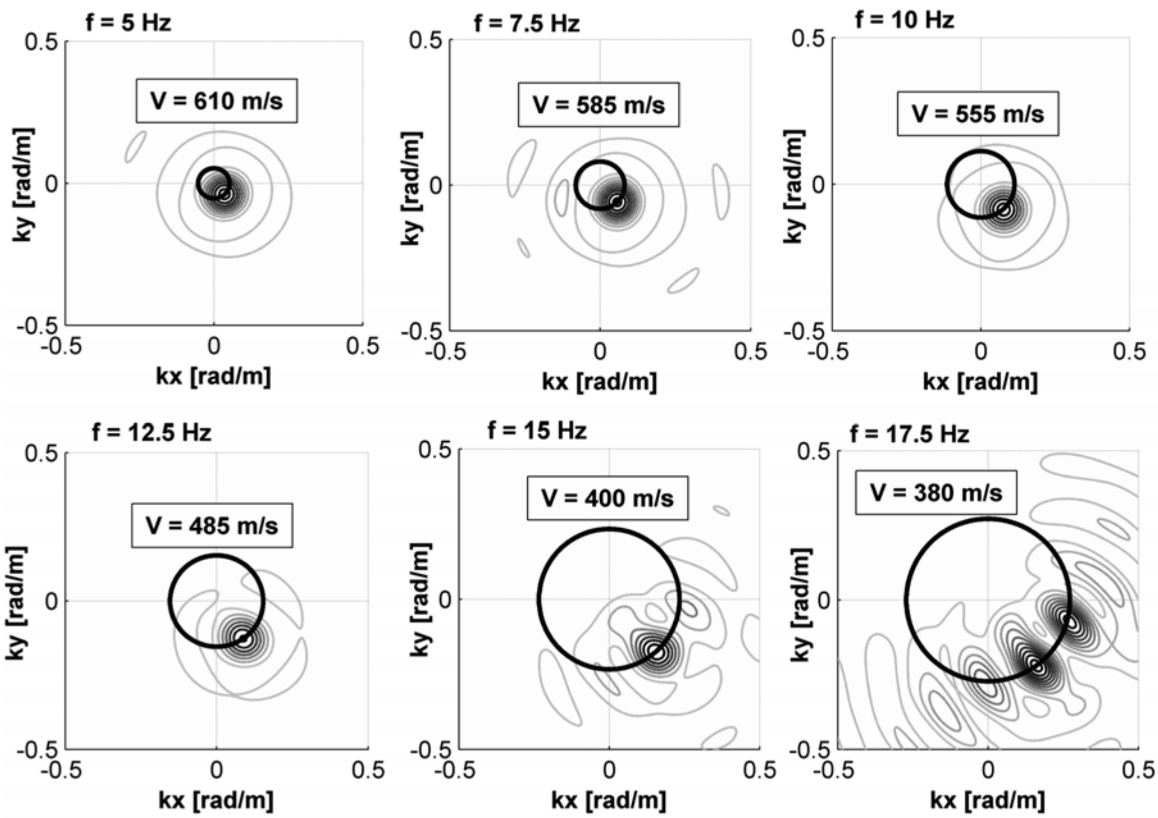

Fig. 3 – Microtremor analysis: contour plots of the spectral power density at selected frequencies.
Fig. 3 – Prove per onde superficiali passive: esempi di curve di livello della densità spettrale.

centre of the array and allows for the identification of the associated velocity of propagation using Equation 1. On top of each spectrum a circle is plotted: it represents the phase velocity (*V*) corresponding to the wavenumber at peak and to the frequency value. The identification of phase velocities is repeated for all the frequencies in the range of interest in order to evaluate the experimental dispersion curve for Rayleigh waves.

The position in space of the peak in the spectrum also allows the identification of the direction of propagation of the highest energy component and hence the position of the actual source of the Rayleigh wave. In the example reported there is a great consistency in the direction of arrival. The main source of microtremors is identified as construction activity in an area a few hundreds of metres from the site. This example also shows the great potential of the technique to identify sources of vibration, which can be useful for studies related to mitigation of vibrations [COMINA and FOTI, 2007].

Another point that is worth mentioning is related to the position of secondary peaks in the spectrum. Indeed peaks generated by different sources and hence impinging on the array from different directions should be placed along the same "velocity circle" if the subsoil is laterally homogeneous. Marked deviations from such behaviour are likely to be associated with lateral variation and should be treated with caution because typically a horizontally layered medium is adopted for the inversion process in analysis of surface waves.

Site description and test results

The site is located in La Salle (Valle d'Aosta) on a wide fluvial fan, mainly composed of gravels and sands with some silt content. A borehole logged up to 50m from the ground surface for the execution of one of the Down-Hole tests reports layers of gravelly sands and silty sands with gravel. Surface wave tests have been performed at five different locations, three of which are reported in this paper.

For the active test a linear array of 48, 4.5Hz vertical geophones spaced 1.5 m apart, has typically been used. The source was a 10kg sledge-hammer. Dispersion curves have been obtained using *fk* analysis implemented in the package SWAT, which has been developed in Matlab® environment at Politecnico di Torino.

For the passive test a circular array of diameter 75m with 12 or 24, 2Hz geophones equi-spaced along the circumference has been used. Dispersion curves have been obtained using the frequency domain beam former technique (FDBF) implemented in a Matlab® code developed by ZYWICKI [1999].

The results obtained at two of the five sites are reported in Figures 4 and 5. The experimental dispersion curves (Figs. 4a and 5a) have been obtained combining information from active and passive measurements resulting in a wide frequency range. The inversion process has been performed using a damped and weighted least square algorithm, implemented in the computer code SURF, developed by HERRMANN [1994].

In Figures 4b and 5b the inverted shear wave velocity profiles are reported together with the results from Down Hole tests performed at the two sites,

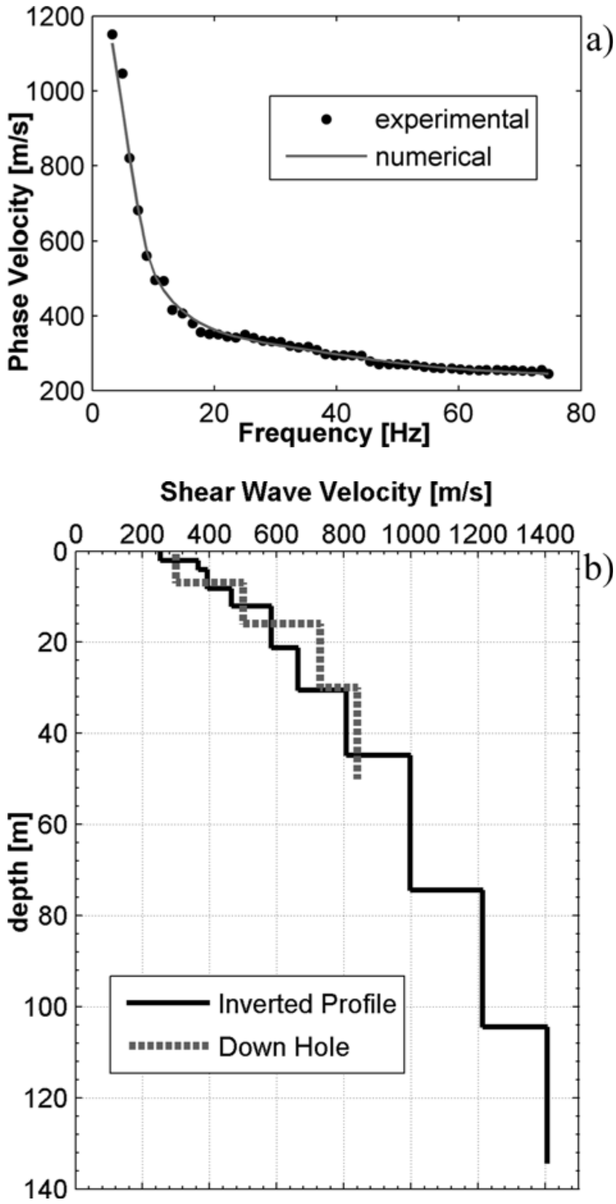

Fig. 4 – Site 1: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles (Surface Wave Method and Down Hole Test).
Fig. 4 – Sito 1: a) Curve di dispersione numerica e sperimentale. b) Profilo di velocità delle onde di taglio (Prove per onde superficiali e Down Hole).

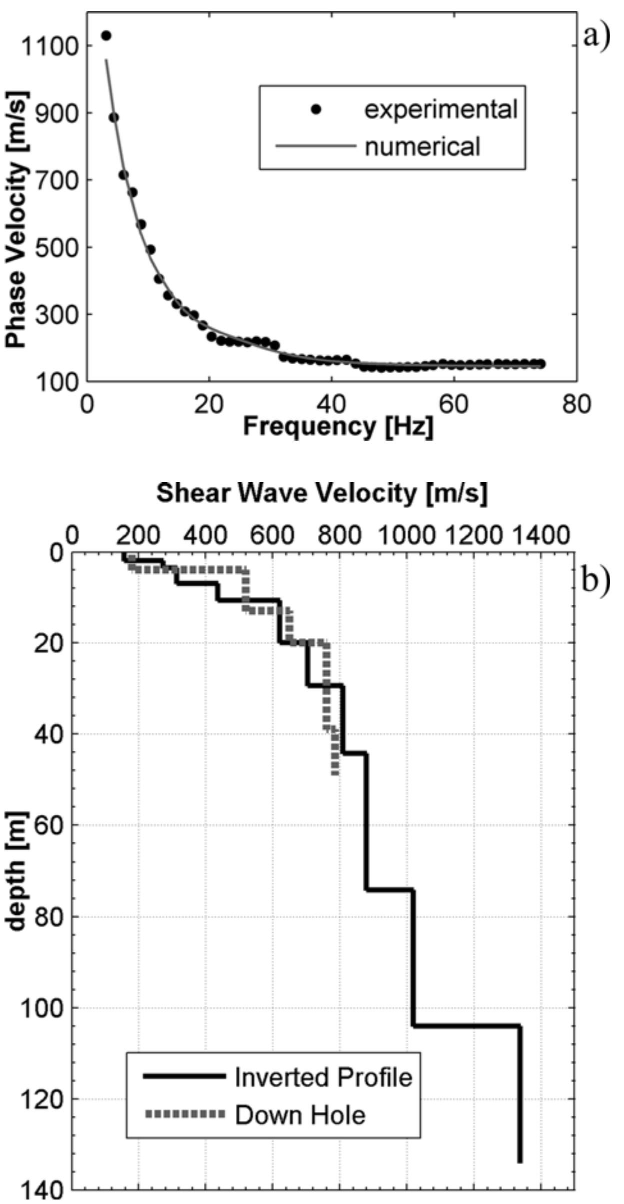

Fig. 5 – Site 2: a) Experimental and numerical dispersion curves. b) Shear wave velocity profile (Surface Wave Method and Down Hole Test).
Fig. 5 – Sito 2: a) Curve di dispersione numerica e sperimentale. b) Profilo di velocità delle onde di taglio (Prove per onde superficiali e Down Hole).

showing the good agreement with surface wave results for the depth over which the two experimental datasets are available.

Reliability analysis

In order to evaluate the influence of uncertainties in the experimental data, several tests with the same configuration have been performed both for active and passive methods at a third site. The different sets of data have then been independently interpreted in order to assess the variability of the results. This procedure allows for the evaluation of uncertainty related to background noise but other effects, such as errors in the geometry, cannot be assessed, so that the measured reliability is a partial estimate of the overall one.

Examples of active and passive experimental datasets are reported in Figures 2 and 3 respectively. The whole set of experimental dispersion curves obtained for both active and passive tests is reported in Figure 6a while Figure 6b reports the corresponding mean values and standard deviations. It is worth noting that the levels of uncertainty in active and passive tests are very different. This is more clearly evident in Figure 7 which shows the coefficient of variation of the experimental data, defined as the ratio between standard deviation and mean value of the phase velocity at each frequency. The values of the coefficient of variation obtained from active data are in line with other studies [MAROSI and HILTUNEN, 2004; LAI *et al.,* 2005].

The deterministic inversion of the mean values of the experimental dispersion curve based on the

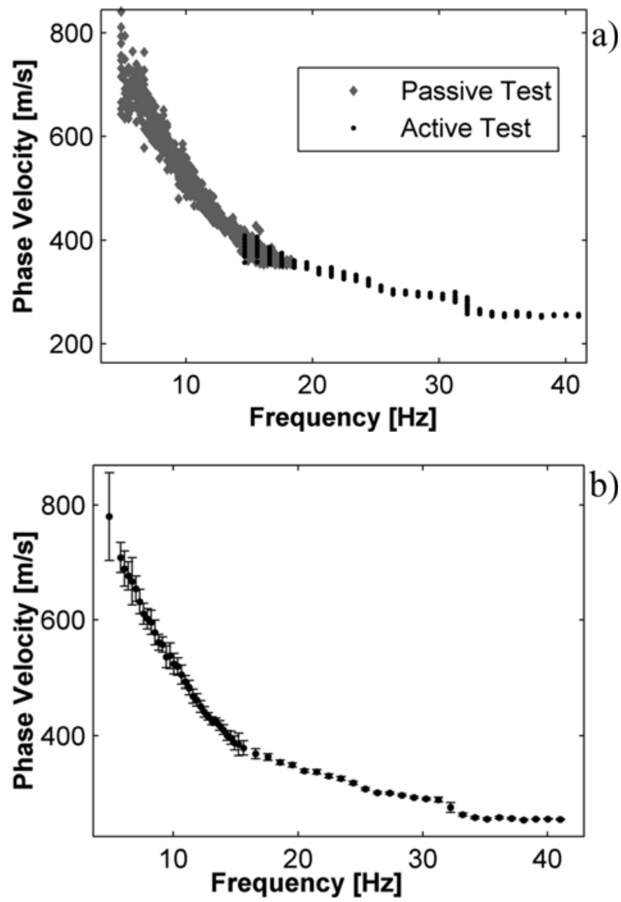

Fig. 6 – Experimental dispersion curve at site 3: a) scatter of data for active and passive tests; b) mean values and standard deviation of phase velocity.
Fig. 6 – Curva di dispersione sperimentale per il sito 3: a) dispersione dei dati per prove attive e passive; b) valore medio e deviazione standard della velocità di fase.

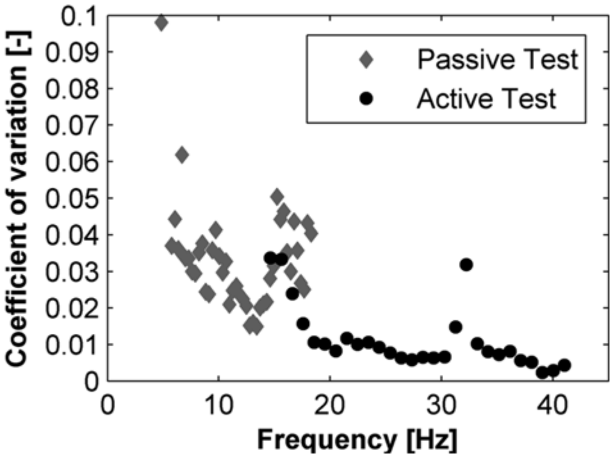

Fig. 7 – Coefficient of variation of phase velocity vs frequency for active and passive data (Site 3).
Fig. 7 – Coefficiente di variazione della velocità di fase nei confronti della frequenza per prove attive e passive (Sito 3).

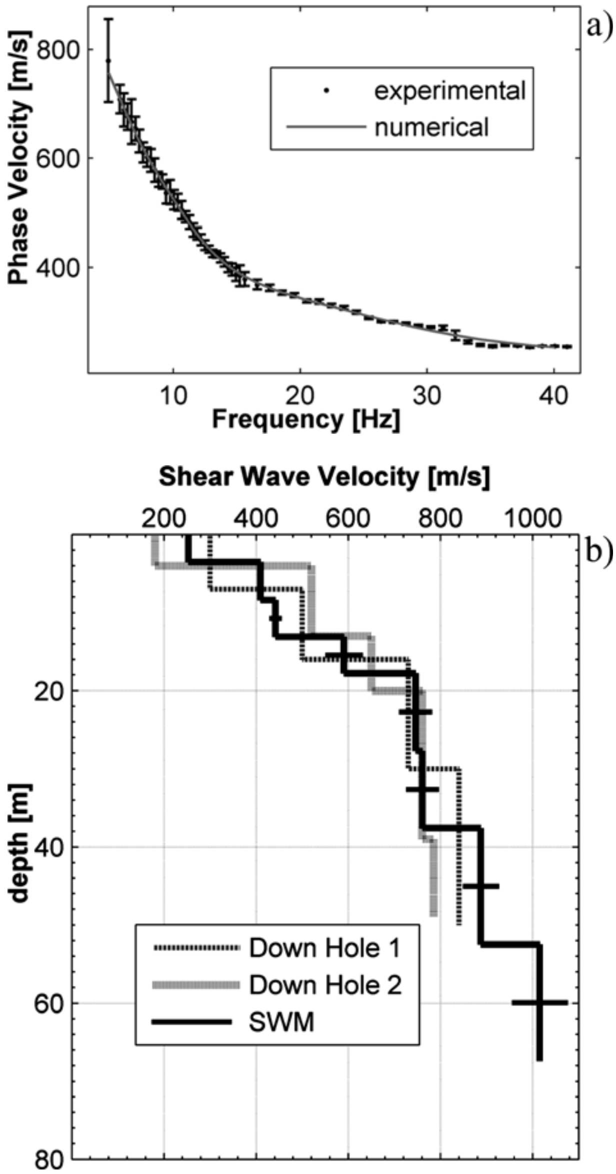

Fig. 8 – Least square inversion of surface wave data (Site 3): a) Experimental and numerical dispersion curve. b) Shear wave velocity profile and corresponding uncertainty from Surface Wave Method compared with Down Hole Test results.
Fig. 8 – Inversione ai minimi quadrati dei dati attivi e passivi (Sito 3): a) Curve di dispersione numeriche e curva sperimentale. b) Profilo di velocità delle onde di taglio, e corrispondente incertezza, da prove per onde superficiali rispetto alle prove Down Hole.

weighted damped least square algorithm [HERRMANN, 1994] is reported in Figure 8. Since for this site no borehole for DHT was available, results from DHT at the other sites are reported as references. The actual distance between each of the three sites is about 1km, so that a direct comparison is not possible, but, considering the nature of the sediments the analogy between the profiles appears to be meaningful.

In order to obtain the standard deviation of the final shear wave velocity profile the standard deviation of the Rayleigh wave phase velocities can be incorporated in the inversion process using a linearization in the neighbourhood of the final solution [TARANTOLA, 2005]. In this study the procedure described in LAI *et al.* [2005] has been adopted in this respect and the corresponding error bars on the velocity profile are reported in Figure 8b.

It can be noted that the low uncertainty associated with active data in the high frequency range leads to very low uncertainties in the velocity estimate for shallow layers, while for deeper layers the higher uncertainty of passive data leads to higher uncertainties in the shear wave velocity. The coefficient of variation of shear wave velocity varies from less than 1% for shallow layers to about 6% for deeper layers showing that the inversion process is not affected by error magnification.

In order to study in more detail the implications of uncertainties in the measurements a different strategy has been adopted using a global search method based on a Monte Carlo procedure for the inversion. The objective of this study is not just the solution of the inverse process, but an evaluation of a number of profiles which can be considered statistically equivalent with respect to the uncertainty in the experimental data. Indeed any inversion process is ill-posed and the non-uniqueness of the solution implies the existence of several equivalent models that fit, with the same precision, the data [TARANTOLA, 2005]. In practice, several shear wave velocity profiles can be associated with numerical dispersion curves which present the same statistical distance from the experimental one.

A population of 10^5 synthetic models has been randomly generated having defined the number of layers and the starting upper and lower boundary for each model parameter. For each model, the fundamental mode curve is computed using the Haskell and Thomson approach [THOMSON, 1950; HASKELL, 1953].

The misfit function between experimental and numerical dispersion curves is then evaluated for each random profile, accounting for the data uncertainty and the statistical number of degrees of freedom. The misfit function considered in the present study is:

$$\chi^2 = \frac{\sum_1^m (V_t - V_e)^2 \cdot \sigma_e^{-2}}{m - (2 \cdot n + 1)} \quad (2)$$

where V_t and V_e are respectively the theoretical and experimental phase velocities, σ_e contains the data uncertainties, m is the number of points in the dispersion curve and n is the number of layers above the half-space in the model.

The misfit is evaluated for each profile and normalized with respect to the lowest. The χ^2 ratio is then used in a Fisher test [SACHS, 1984] such that, having set a certain level of confidence, all the models that can be considered statistically equivalent at that level are selected. The result of the inversion is therefore a group of models having a misfit on the dispersion curve lower than a certain variable threshold, determined on the basis of the level of confidence [BOIERO *et al.*, 2006]. Well resolved parameters produce a small range of variations while badly resolved parameters can assume virtually any value within a wide range.

For the present study a level of confidence equal to 1% has been used: the result of the inversion is therefore a group of models defining a region in the model space within which the "true one" falls at 99% of probability. The results of the inversion of the experimental dispersion curves with this approach are reported in Figure 9. In particular Figure 9a shows all the numerical dispersion curves corresponding to the selected profiles (reported in Fig. 9b) compared with the experimental one, showing the equivalence of these profiles with respect to experimental data. The relative misfit representation adopted for the equivalent profiles (Fig. 9b) shows the absolute difference between each profile misfit and the lowest misfit, so that the darkest colour corresponds to the profile having the lowest misfit. The value of the relative misfit is not itself a meaningful physical parameter, but it shows the range of variation for the models accepted by the statistical test and it is useful to represent the group of models with a hierarchy of quality of fit. In Figure 9a is also reported, for comparison, the deterministic inversion and its associated standard deviation.

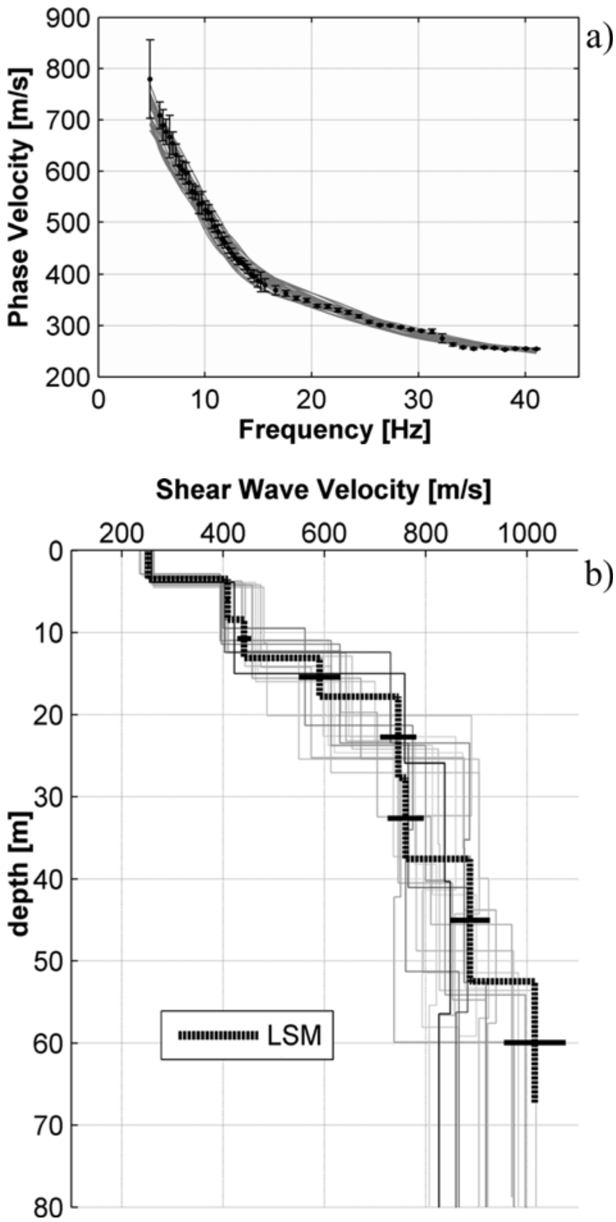

Fig. 9 – Statistical Monte Carlo analysis of active and passive surface wave data (Site 3): a) Experimental and numerical dispersion curves. b) Equivalent shear wave velocity profiles from Monte Carlo analysis compared with the result of least square inversion (LSM).

Fig. 9 – Analisi statistica con metodo Monte Carlo dei dati da prove attive e passive (Sito 3): a) Curve di dispersione numerica e sperimentale. b) Profili di velocità equivalenti delle onde di taglio confrontati con il risultato dell'inversione ai minimi quadrati.

It is noticeable that a very high level of resolution is attained for shallow layers, while the variability of the experimental dispersion curve in the low frequency range causes a much higher degree of uncertainty for deeper layers. This is partially due to the fact that the resolution of surface waves inevitably decreases with depth and partially to the higher

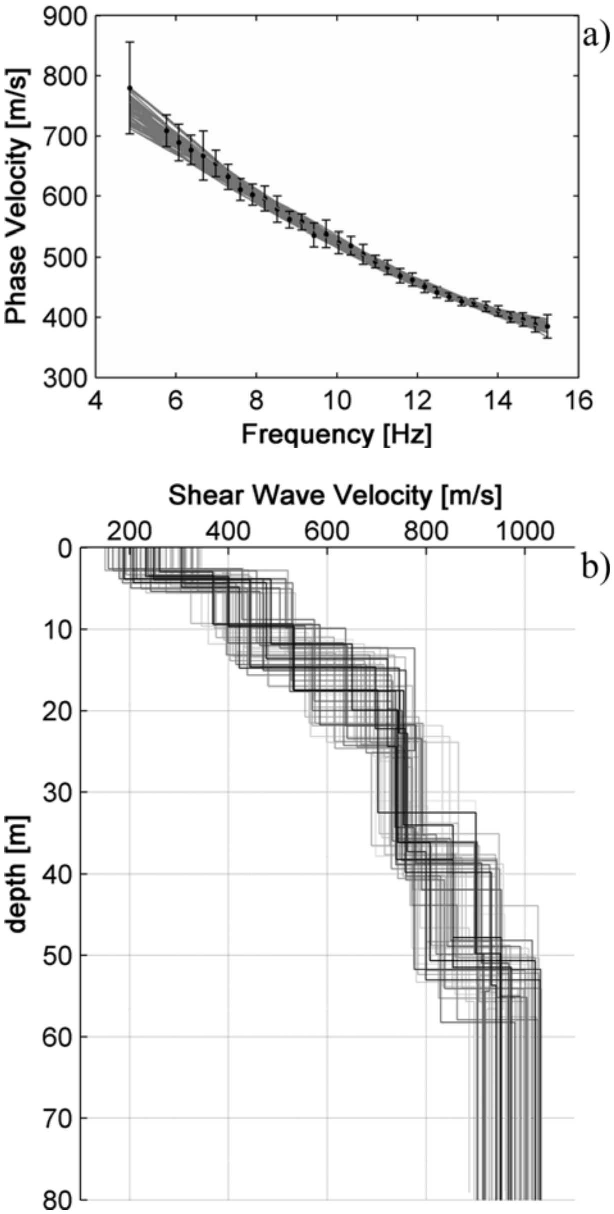

Fig. 10 – Statistical Monte Carlo analysis of passive surface wave data (Site 3): a) Experimental and numerical dispersion curves. b) Equivalent shear wave velocity profiles from Monte Carlo analysis.

Fig. 10 – Analisi statistica con metodo Monte Carlo dei dati da prove passive (Sito 3): a) Curve di dispersione numeriche e curva sperimentale. b) Profili di velocità equivalenti delle onde di taglio.

experimental uncertainty in the passive tests (Fig. 7).

In order to assess the influence of data obtained from active tests in the combined interpretation of surface waves, the Monte Carlo inversion has also been applied to the subset of experimental data which was obtained from the passive tests. The results reported in Figure 10 show that the resolution at shallow depth is strongly affected and also that the shallow layers are not well resolved in this case.

Considering typical engineering applications (e.g. seismic site effect evaluation) the level of uncertainty for shallow layers obtained from passive tests only would not be acceptable. Moreover it has to be considered that the information related to shear wave velocities of shallow layers plays a central role in the inversion process so that the reconstructed profile for deeper layers is also influenced by near surface uncertainties.

Final remarks

The experimental datasets reported in the present study show the effectiveness of combined active and passive surface wave tests in estimating the shear wave velocity profile at a site, combining high resolution at shallow depth with the ability to obtain information for deep strata. The comparisons with Down-Hole Test results confirm the accuracy of surface wave methods and the consistency of the obtained profiles.

Microtremor analysis is a very promising tool for subsurface exploration, allowing the extension of soil characterization for depths of up to tens or hundreds of metres. However, passive data are affected by higher degrees of uncertainty, so the statistical analysis presented here shows that this, combined with the intrinsic nature of surface wave tests, leads to poorer resolution at depth. On the other hand, the high quality information associated with active data and the corresponding high resolution of surface waves at shallow depth leads to very reliable results close to the ground surface.

Given these considerations, the reliability analysis has illustrated the absolute necessity of adding active data to microtremor analysis in order to provide shear wave velocity data for engineering applications, especially where good resolution at shallow depth is of paramount importance.

Acknowledgements

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Affidabilità dell'interpretazione combinata di prove per onde superficiali attive e passive

Sommario

Il metodo delle onde superficiali, con prove sia di tipo attivo che passivo, è spesso usato per la caratterizzazione del sottosuolo, in particolar modo in studi rivolti all'analisi della risposta sismica locale. Esso infatti è in grado di fornire informazioni utili sulle caratteristiche del terreno a fronte di una spesa contenuta. Per le prove di tipo attivo la profondità di indagine è solitamente limitata dalla quantità di informazione deducibile a bassa frequenza. D'altro canto le prove di tipo passivo, poiché basate sull'analisi di microtremori, sono solitamente caratterizzate da un maggiore contenuto di energia a bassa frequenza e permettono di indagare profondità superiori a scapito della risoluzione negli strati più superficiali. Il presente articolo propone un utilizzo combinato delle prove per onde superficiali attive e passive in modo da trarre vantaggio dalle informazioni complementari ottenute con i due approcci. Si riportano i risultati sperimentali di un caso di studio, per il quale erano disponibili per un confronto i risultati di prove Down-Hole, mostrando le grandi potenzialità dell'interpretazione combinata. Infine le implicazioni relative all'incertezza dei dati in termini di risoluzione e affidabilità sono state esplorate utilizzando un approccio di inversione di tipo Monte Carlo, evidenziando l'importanza delle prove di tipo attivo per la caratterizzazione degli strati più superficiali.