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## RELIABILITY OF $V_{S,30}$ EVALUATION FROM SURFACE WAVES TESTS

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### ABSTRACT

The reliability of surface wave tests for the evaluation of  $V_{S,30}$  in seismic site characterization is assessed with respect to both uncertainty and accuracy. The discussion of uncertainty is mainly focused on the implications of solution non-uniqueness in inverse problems; only the inversion uncertainty is considered within this work, omitting other possible sources like non trivial geological settings (e.g. lateral variations) or the influence of different processing procedures. A Monte Carlo approach has been used to select, through a statistical test, a set of shear wave velocity models that can be considered equivalent with respect to fitting the experimental dispersion curve according to the information content (dispersion velocities and frequency range) and the experimental uncertainties. This set of equivalent solutions is then used to evaluate the uncertainty in the determination of  $V_{S,30}$ . Moreover, comparisons between the results obtained by surface wave tests and invasive seismic methods are reported to assess the accuracy of  $V_{S,30}$  evaluation using surface wave methods. It is shown that, given an adequate investigation depth, the solution non uniqueness is not a major concern and that the results are in most situations comparable with the ones of invasive tests providing an accurate estimate of  $V_{S,30}$ , even with simplified approaches.

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## INTRODUCTION

The weighted average of shear wave velocities in the shallowest 30m ( $V_{S,30}$ ) is often used for seismic site classification.  $V_{S,30}$  is used, for example, in the NEHRP Provisions (BSSC, 1994) to separate sites into different seismic classes and a similar classification has been adopted also in European codes (e.g. CEN, 2004). This classification is then used to determine the site-dependent seismic coefficients for earthquake-resistant design. Other uses of  $V_{S,30}$  as a relevant seismic parameter include the generation of attenuation laws for predicting ground motion parameters in seismic hazard studies (Power et al., 2008).

Different geophysical techniques, either invasive (down-hole, cross-hole, P-S logging) or non-invasive (surface waves tests or SH seismic refraction), can be used in the field to obtain  $V_{S,30}$ . It is important to underline that none of these methods provide “what can be deemed as an unbiased estimate” (Moss, 2008) and that a correct evaluation of the uncertainty of the parameter is crucial. Invasive methods are generally considered more accurate, but they are not free of uncertainty.

Surface wave tests are widely used to estimate  $V_{S,30}$  because they are cost and time effective when compared to invasive methods and they do not suffer from limitations related to site conditions that affect SH seismic refraction (e.g. presence of inverse layering or hidden layers).

Surface wave tests are based on geometrical dispersion, which makes the velocity of propagation of Rayleigh waves frequency dependent in vertically heterogeneous media. The experimentally measured dispersion curve is used for the solution of an inverse problem aimed at the identification of soil model parameters (shear wave velocities and thicknesses of a horizontally stratified medium). This paper does not attempt to provide guidelines for the selection of methods for obtaining reliable dispersion curves and for the solution of this inversion process. Rather it is focused on evaluating the accuracy and uncertainty of these data if they are used for  $V_{S,30}$  estimation.

Certainly a variety of approaches exists to determine experimentally a site-specific surface wave dispersion curve. In active source tests, waves are generated using a seismic source (Stokoe et al., 1994; Park et al., 1999; Foti, 2000), whereas passive source tests are based on the analysis of microtremors (Horike, 1985; Tokimatsu, 1995; Louie, 2001). While in active source tests it is usually very easy to generate and detect high frequency components, microtremors are typically rich in energy in the low frequency band. The resolvable frequency band affects the investigation depth (related to the maximum recorded wavelength) and the spatial resolution close to the ground surface (related to minimum recorded wavelength). A combination of both active and passive methods may be necessary to obtain a reliable evaluation of  $V_{S,30}$  (depending on the strength of the active source). Combined use of passive and active methods has been suggested to improve both resolution and investigation depth (Tokimatsu, 1995; Rix et al., 2002; Foti et al., 2007). Different studies have shown that the measurement uncertainty in active surface wave data is typically below 5% in terms of coefficient of

variation of the Rayleigh wave phase velocity (Xia et al., 2002; Marosi and Hiltunen, 2004a; Lai et al., 2005). These values are estimated from different acquisitions in the same testing configuration; hence, lateral variations in complex geological settings and errors induced by processing are not accounted for. Some attempts to propagate the measurements uncertainty on the estimated shear wave velocity profile are also reported in the literature (Marosi and Hiltunen, 2004b; Asten and Boore, 2005; Lai et al., 2005).

**Table 1. Acquisition parameters for the case histories.**

	No of active channels	Geophone spacing [m]	Sampling Rate [ms]	Time window [s]	Array length [m]	Source-array distance [m]
<b>Active Surface Wave tests</b>						
<b>Pontremoli</b>	24	1 - 2	2	4.096	24 - 72	4
<b>Saluggia</b>	24	1 - 3	1	0.4096 – 0.8192	24 - 72	3
<b>Torre Pellice</b>	24	2	1	2	46	6
<b>Combined Active and Passive Surface Wave tests</b>						
<b>La Salle</b>	24 - 48	1.5 - 2	0.5	4.096	48 - 75	2
	12 - 24	10.35 19.41	16	524.288	Circular Diameter 40 - 75	
<b>Pianola</b>	48	1	0.5	2.048	48	3
	12	12.94	8	524.288	Circular Diameter 50	
<b>Rojo Piano</b>	48	1.5	0.5	2.048	70.5	3
	12	12.94	8	524.288	Circular Diameter 50	
<b>Catania</b>	48	1.5	0.5	2.048	70.5	3
	12	12.94	8	524.288	Circular Diameter 50	
<b>Pisa</b>	24	2.5	2	4.096	60	5
	8	15.31	2	688.128	Circular Diameter 40	

Once the experimental dispersion curve is retrieved, different approaches can be used for the solution of the inverse problem aimed at the estimation of the shear wave velocity profile. Most of them are based on deterministic gradient-based inversion techniques (e.g. Hermann, 1994; Lai and Rix, 1998), so that the solution of the inverse problem is a single velocity profile. Since surface wave inversion is strongly non linear, ill-posed and mix-determined, the solution is non-unique and several velocity profiles may comply with the experimental data. The final model chosen by deterministic methods is hence only one of the possible solutions and the final result is very sensitive to the initial model. The inversion process can easily be biased by wrong choices in terms of model parameterization that lead the solution into local minima (Sambridge, 2001; Luke et al., 2003; Wathelet et al., 2004). The non uniqueness of the inverse problem solution represents one of the main causes of uncertainty in surface wave analysis. In spite of this, it is often neglected, especially when deterministic inversion algorithms are used.

Global search methods avoid the linearization of the problem and mitigate the risk to converge in a local minimum. Moreover, they can provide a population of solutions from which it is possible to statistically assess the implications of solution non-uniqueness. In the present study, a Monte Carlo approach is used to evaluate the consequences of solution non-uniqueness, accounting also for measurement uncertainties. The procedure leads to the selection of a group of shear wave velocity profiles which can be considered equally good with respect to the available experimental information (i.e. the experimental dispersion curve and its associated measurement uncertainty). This approach leads to a consistent evaluation of inversion uncertainties in  $V_{S,30}$  determination. A similar procedure has been adopted to study the influence of solution non-uniqueness in seismic site response studies (Foti et al., 2009).

In the following, a description of experimental testing and inversion procedures is reported. Then, a collection of several case histories in Italy is used to discuss the reliability and accuracy of surface wave tests in  $V_{S,30}$  evaluation. Finally, the experimental dataset is also used to provide further validation of an existing approximate formula (Brown et al., 2000) for the evaluation of  $V_{S,30}$ .

## METHODS

Eight test sites have been considered in this study. In all of them, active source surface wave data have been collected, sometimes in combination with passive source tests. Independent invasive seismic tests were also available as a benchmark at all sites. Details of the testing setups and acquisition parameters are reported in Table 1. For the active source tests, linear arrays of 24 or 48 vertical geophones with 4.5Hz natural frequency were used. The standard active source was a 5 kg sledge-hammer; a weight drop system (130 Kg from 3m) was used at Saluggia and Pontremoli sites; a self-propelled weight dropper has been used at Torre Pellice (drop height 1.6 m, total weight 750 kg). Distance from the source to the central point of the array are generally such that near field effects can be considered of minor influence; indeed the source-to-array center distance is typically larger than half of the maximum experimental wavelength

(Rosenblad and Li, 2010). Several independent acquisitions (at least 15, including also forward and reverse shots) were performed with the same acquisition setup. Dispersion curves were obtained from field data using f-k analysis (Gabriels et al., 1987; Foti, 2000) implemented in the code SWAT (Surface Wave Analysis Tool), developed in Matlab® environment at Politecnico di Torino. For the passive source tests circular arrays of 50 - 75m diameter with 8 - 24, 2Hz vertical geophones (evenly-spaced along the circumference) were used. Also in this case, several independent recordings were acquired. Dispersion curves were obtained from microtremors using the frequency domain beam former technique (FDBF) implemented in a Matlab® code developed by Zywicki (1999). Compared to linear arrays used with the ReMi method (Louie, 2001), the use of 2D arrays provides a more reliable estimate of phase velocities because it takes into account the actual direction of propagation of the microtremors, which is a-priori unknown. This aspect is crucial, especially when the sources of microtremors are not homogeneously distributed around the testing site.

To evaluate the experimental uncertainty of both active source and passive source datasets, each record (shot or microtremor registration) has been independently processed. The experimental dispersion curve for the site is given by the mean velocity value at each frequency and its related uncertainty is represented by the standard deviation. This procedure may lead to an overestimation of the uncertainty because no signal averaging is performed before calculating the standard deviation. However, on the other side, other sources of uncertainties (e.g. geometrical errors in the receiver array) are not taken into account. All together, a reasonable estimate is achieved, as confirmed also by the comparison to previous literature data obtained with different procedures (Marosi and Hiltunen, 2004).

A Monte Carlo procedure has been used for the inversion of experimental surface wave dispersion curves (Socco and Boiero, 2008). The algorithm uses scale properties of Rayleigh wave propagation (Socco and Strobbia, 2004; Socco and Boiero, 2008) to efficiently explore the model parameter space, cutting down the required number of forward simulations. The analyses for the present study were performed with a population of  $10^5$  profiles for each dataset. The forward modelling algorithm is based on the Haskell (1953) and Thomson (1950) approach and the fundamental mode solution has been considered. The misfit function compares the experimental and synthetic dispersion curves accounting also for experimental data uncertainty and problem dimensionality (number of unknown parameters with respect to available datapoints). It can be written as:

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

where  $V_t$  and  $V_e$  are respectively the theoretical and experimental phase velocities,  $\sigma_e$  contains the experimental data uncertainties,  $m$  is the number of points in the dispersion curve and  $n$  is the number of layers in the model (only shear wave velocity and thickness for each layer are considered unknown while the densities and Poisson ratios are fixed a priori). The misfit is evaluated for each profile of the population and used to select

acceptable models according to a statistical test. The statistical one tailed Fisher test (Sachs, 1984) selects all profiles that are “equivalent”, given a confidence level. For the present study, a level of confidence equal to 1% has been used. The selected models hence represent a set of possible solutions which may be considered equally probable, given the experimental data and their uncertainty, the adopted model parameterization and the level of confidence. Socco and Boiero (2008), showed that the solutions of deterministic inversions performed with different initial models fall in a wider model region with respect to the models selected by the Monte Carlo inversion. The profile set can therefore be assumed as a “picture” of the solution non-uniqueness for the specific dataset. More details on the algorithm are reported in Socco and Boiero (2008).

In the paper, results of the Monte Carlo inversion are reported using a representation based on the relative misfit. The darkest color always corresponds to the model having the lowest misfit with reference to the experimental dispersion curve. The same color is used to represent each shear wave velocity model and its associated dispersion curve.

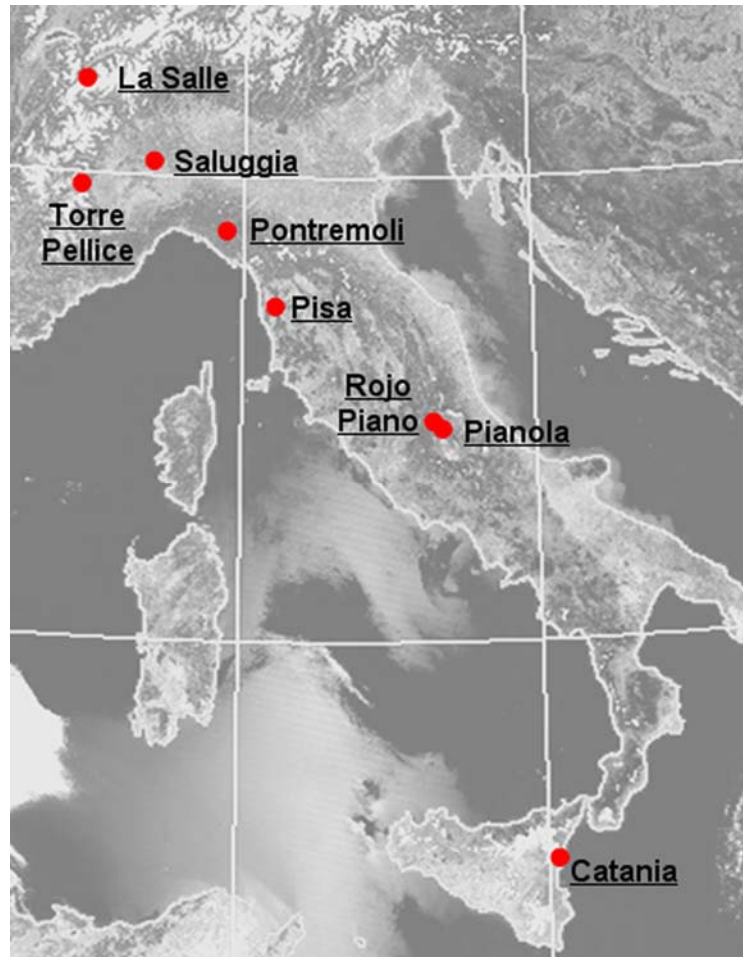
The  $V_{S,30}$  has been computed for the population of equivalent shear wave velocity profiles of each dataset. This allowed retrieving the mean  $V_{S,30}$  for each site and its associated uncertainty.

## CASE HISTORIES

The locations of the sites in Italy are reported in Figure 1. Different soil classes and soil conditions are investigated so that the dataset presents a wide range of results in terms of  $V_{S,30}$ . Either by using heavy sources in active source tests, or combined interpretation of active source and passive source data, the experimental dispersion curve has been recovered for each site in a wide frequency band; this allows a  $\lambda_{\max}$  greater than 60 m to be retrieved for all datasets. This is an essential requirement for  $V_{S,30}$  determination. The statistical results of the Monte Carlo inversion for each site are summarized in Table 2.

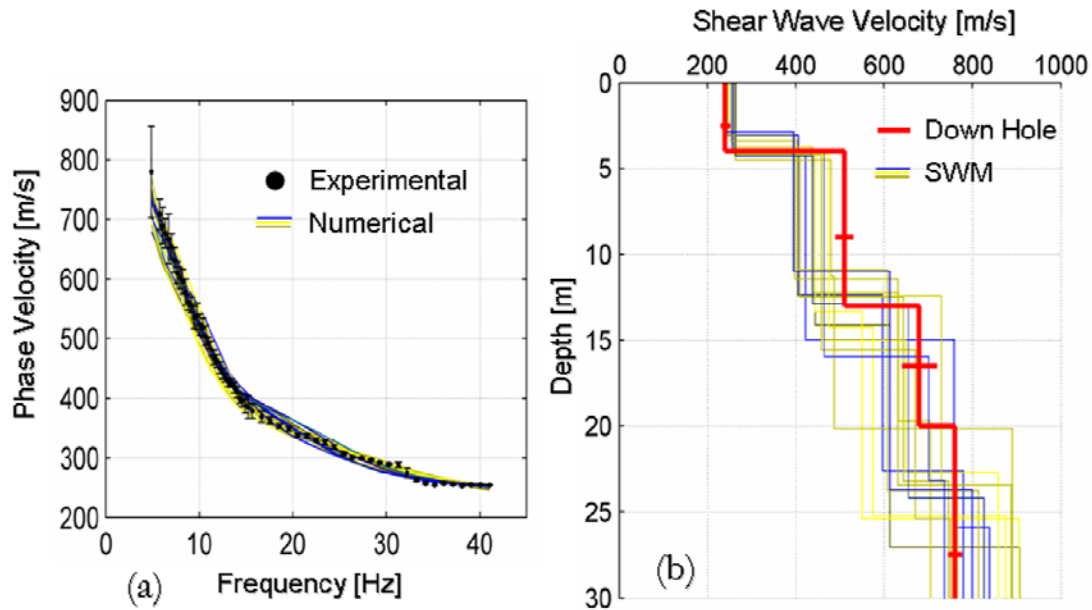
The first site is located in La Salle (Valle d’Aosta) on a wide fluvial fan (Socco et al., 2008). The expected maximum thickness of the Quaternary deposits in La Salle is around 200 m and the fan is mainly composed of fluvial deposits (sand, gravel, stone), polygenic slivers, pebbles and blocks. The experimental dispersion uncertainty in active source and passive source tests is considerably different as can be noted from the error bars reported in Figure 2a. The values of the coefficient of variation (CoV) obtained from active data (around 1%) are in agreement with other studies (e.g. Marosi and Hiltunen, 2004; Lai et al., 2005), while passive data, being based on natural seismic noise, show a higher variability (mean CoV around 4-6 %). In the frequency band in which the two dispersion curve branches are superimposed (from about 15 to 18 Hz) there is however a good consistency of the experimental phase velocity values (see also Foti et al., 2007). The CoV increases with wavelengths due to CoV frequency dependence and effect of different kinds of sources. The same trend in CoV has been noticed for the other case histories in which both types of acquisitions (active and

passive source) have been performed. Even though the site was not heavily urbanized and far from major roads, a dominant source of microtremors was recognized, likely related to some excavation works in progress about a kilometer apart from the survey area (Foti et al., 2007); in this condition of localized source, passive linear arrays methods (such as ReMi) could fail in the determination of the correct phase velocity.



**Figure 1.** Geographical location of test sites in Italy.

The 16 profiles selected by the Monte Carlo procedure are reported in Figure 2b. The results are compared to the shear wave velocity profile obtained with a down-hole test. The uncertainty in the down-hole test result is also available (Socco et al., 2008). The  $V_{S,30}$  from the down-hole test has a CoV around 3%, which is comparable to the one obtained from surface wave tests (Table 2).

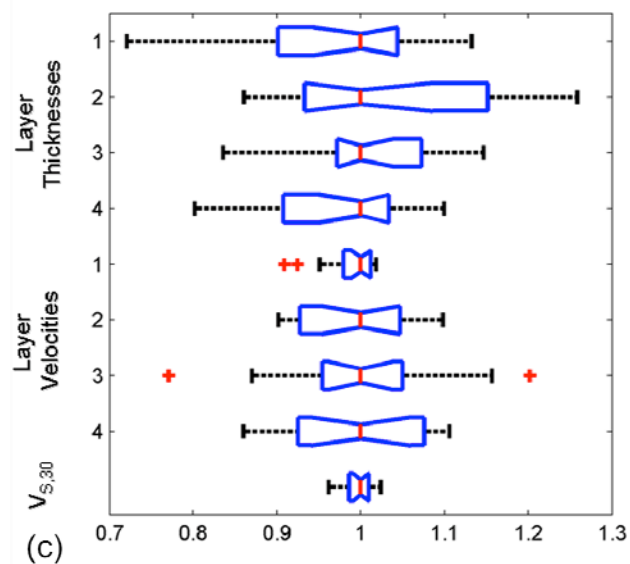


**Figure 2.** Montecarlo inversion of combined active and passive surface wave data at La Salle site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.

**Table 2. Summary of the results of Monte Carlo inversion of surface wave tests at the Italian sites and comparison with invasive test results.**

	$\lambda_{\max}$ SW [m]	No of equivalent profiles	Mean $V_{S,30}$ SW [m/s]	Std $V_{S,30}$ [m/s]	Mean CoV $V_{S,30}$ [%]	$V_{S,30}$ [m/s] Invasive
<b>Active source Surface Wave tests</b>						
<b>Pontremoli</b>	63	22	774	15.2	2.0	797 (DH)
<b>Saluggia</b>	85	39	452	7.8	1.7	380 (CH)
<b>Torre Pellice</b>	145	16	319	7.4	2.1	294 (DH)
<b>Combined Active source and Passive source Surface Wave tests</b>						
<b>La Salle</b>	155	16	491	8.2	1.7	491 (DH)
<b>Rojo Piano</b>	110	21	312	3.6	1.1	290 (DH)
<b>Pianola</b>	90	33	303	6.7	2.2	308 (DH)
<b>Catania</b>	110	24	162	3.5	2.1	195 (DH)
<b>Pisa</b>	90	25	181	2.0	1.1	176 (CH)

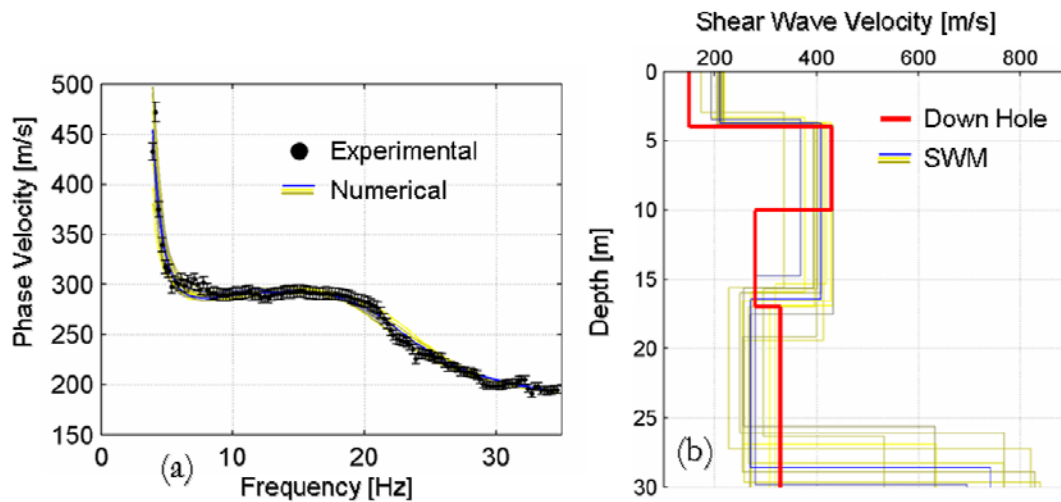
Box plots of both model parameters ( $V_S$  and thicknesses) and of the final  $V_{S,30}$  are reported in Figure 3. Values are normalized with respect to the median for a comparable assessment of reliability. Box plots identify the statistical distribution of each parameter with an area delimited by the lower and upper quartiles (middle line is the median). The notches around the median value represent an estimate of the uncertainty for box-to-box comparison. The black whiskers lines, extending from each end of the boxes for 1.5 times the corresponding inter-quartile distance, show the extent of the rest of the data. Crosses are outliers with values beyond the ends of the whiskers. Shear wave velocity of the shallowest layer presents the lowest uncertainty, as expected taking into account the resolution of surface wave tests close to the ground surface and the large amount of information in the high frequency band, which makes the estimate very reliable. It can be noticed also that the uncertainty on the global  $V_{S,30}$  is much lower than the uncertainty on each single model parameter. The reliability of a single model parameter is in fact strongly affected by solution non-uniqueness. This is a typical feature of the solution of inverse problems: several combinations of model parameters yield equally good profiles. As a consequence, a single parameter is not well resolved, but the overall model is reliable, as shown by the lower uncertainty on  $V_{S,30}$ . Similar conclusions have been obtained with respect to seismic site amplification studies (Foti et al., 2009).



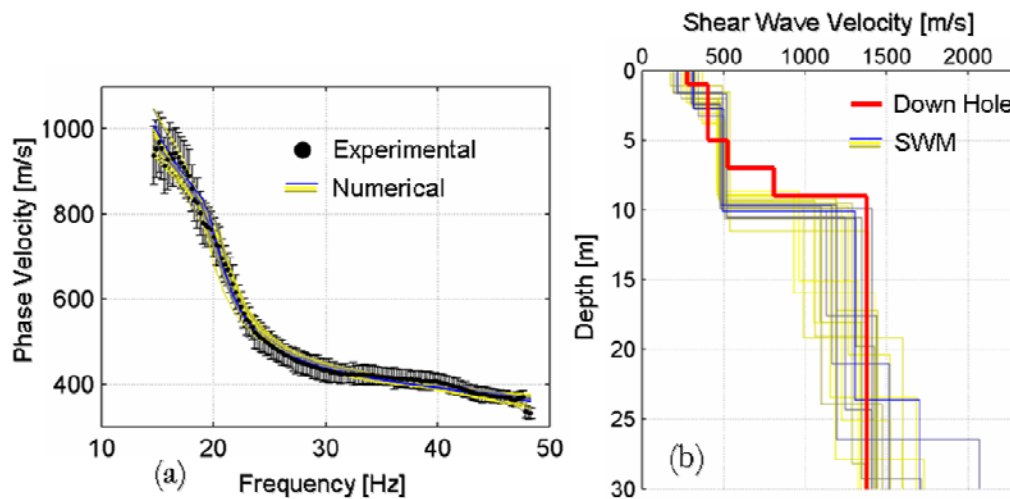
**Figure 3.** Box plots of the distributions of model parameters and  $V_{S,30}$  for the combined active and passive tests at La Salle site.

The second site is located in Torre Pellice (Socco et al., 2009); this case history is interesting since a velocity inversion is expected in the shallowest 30 m. Indeed, the geology of the site is characterized by a shallow formation of fluvial sediments with an expected variable thickness of 10 – 50 m over soft lacustrine sediments. The bedrock is

expected to be more than 100 m deep in the central part of the valley while it is shallower on the lateral portions where tests have been executed. The results, reported in Figure 4, confirm the presence of a velocity inversion relative to the contact between fluvial and lacustrine sediments (also confirmed by the down-hole test performed nearby).



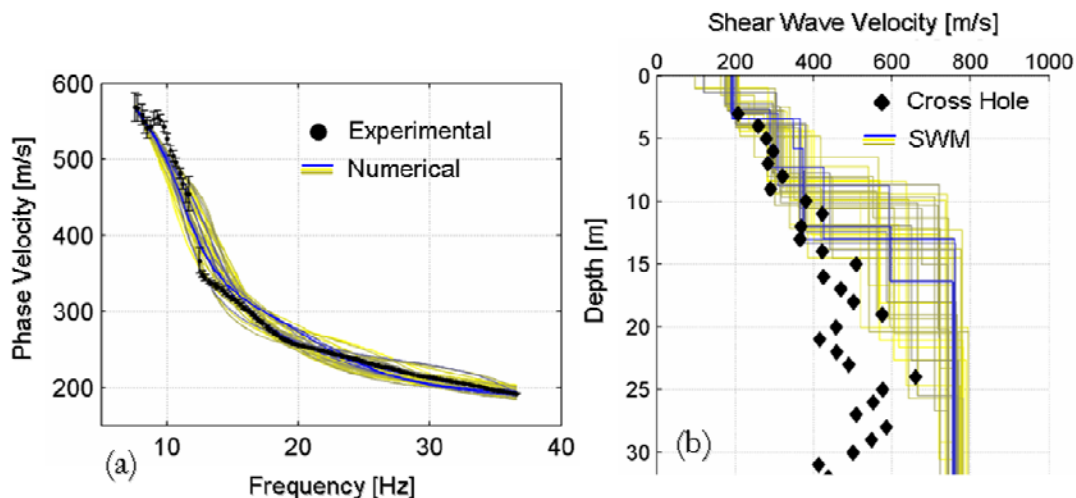
**Figure 4.** Montecarlo inversion of active surface wave data at Torre Pellice site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.



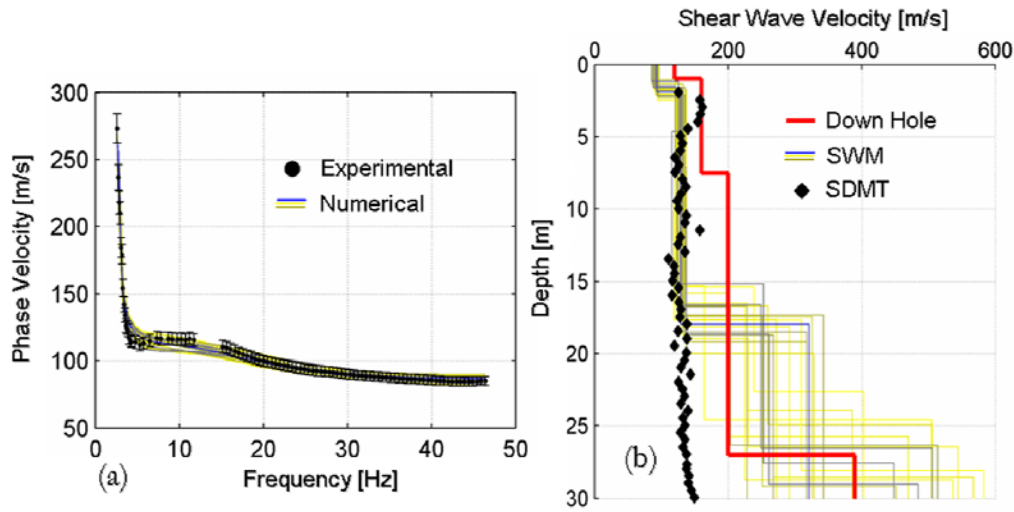
**Figure 5.** Montecarlo inversion of active surface wave data at Pontremoli site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.

The third case history is located in Pontremoli and the local geology reports the presence of relatively shallow bedrock (Foti, 2002). The sounding executed for the down-hole test indicated the presence of a deposit of gravels and sands over the limestone bedrock located approximately at 10 meters depth. Surface waves and down-hole test results are very similar at this site (accounting for the different parametrization) and the variability of profiles extracted from the Monte Carlo inversion is small (Figure 5).

The Saluggia test site (Figure 6) is located close to the Dora Baltea River, in a large flat area of fluvial sediments (Foti, 2000). The soil is composed basically of gravels and gravelly sands, with the presence of fine sand and clayey silt, in the form of lenses. For this site, the profiles selected from the Monte Carlo inversion show a higher velocity trend for depths below 15 meters with respect to cross-hole test. This reflects in a higher value of  $V_{S,30}$  (452 m/s) than the one obtained with the cross-hole test (380 m/s). The Catania test site, on the contrary, shows a lower value of  $V_{S,30}$  determined with surface wave tests compared to the invasive test (Figure 7). The Catania test site is in a wide sedimentary flat area mainly constituted by alluvial deposits (clays and silty clays) with some intercalated sands (Capilleri et al., 2009); The site is very close to the location of a station of the Italian Accelerometric Network. Results of the Monte Carlo inversion are reported in Figure 7 and compared with the results of a down-hole test at the same site (Capilleri et al., 2009) and of a Seismic Dilatometer Test (SDMT) executed in a near site (Marchetti, personal communication). In fact the SDMT site is about 3.5km away with also a few meters of difference in elevation, hence it cannot be considered for a strict comparison; however the uniformity of the alluvial deposits along the whole Catania plain (Capilleri et al., 2009) allows to compare the results at least for the shallowest layers .



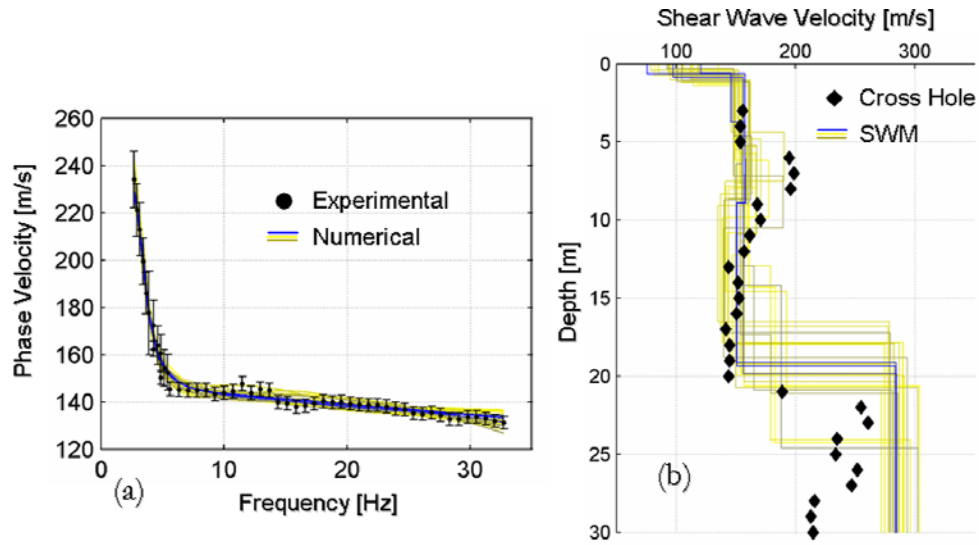
**Figure 6.** Montecarlo inversion of active surface wave data at Saluggia site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to cross-hole test result.



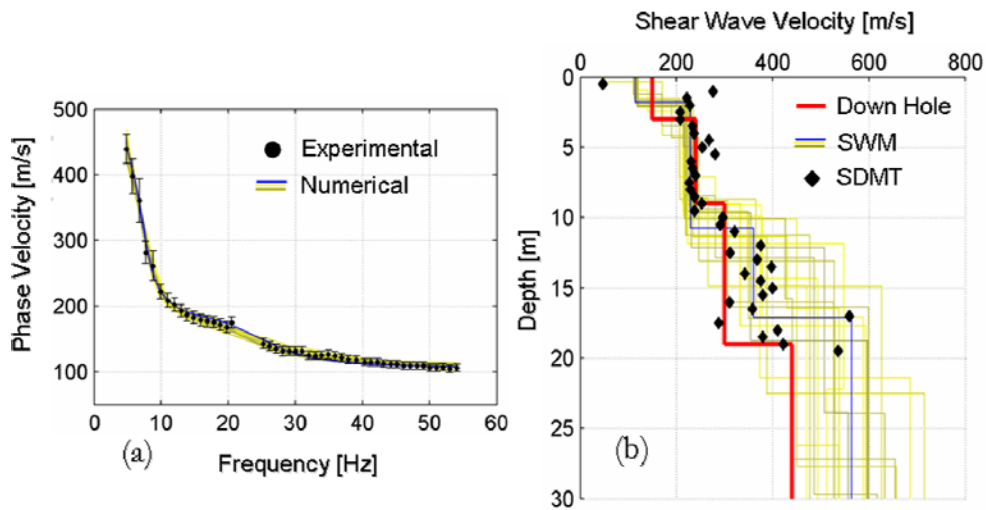
**Figure 7.** Montecarlo inversion of combined active and passive surface wave data at Catania site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole and SDMT tests results.

The Pisa site is located near the leaning tower and has been characterized within the remediation studies for the tower (Foti, 2003). The well characterized subsoil of this site is mainly constituted by clay formations with some slightly stiffer layers. The results of the Monte Carlo inversion (Figure 8) identify a velocity inversion between 5 and 10 meters which is more evident in the cross-hole test results.

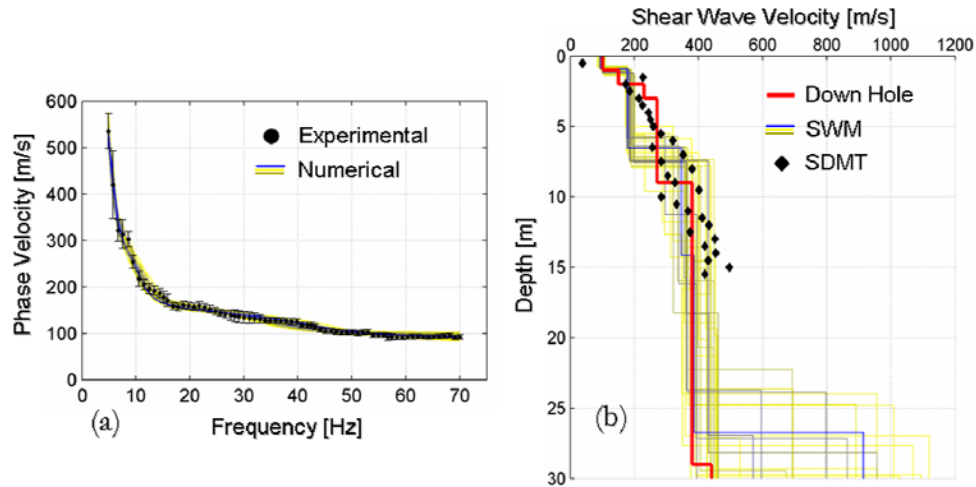
Finally two sites near L'Aquila have been characterized within the activities for the selection of new construction sites in the aftermath of the 2009 earthquake. Both sites are located on the lacustrine deposits of the Aquilian Basin, which are mainly composed by fines and sands (Monaco et al., 2010). On the basis of available geological information, at both sites the bedrock is expected to be deeper than 30m. For both sites, the results of a down-hole test and of a Seismic Dilatometer Test (SDMT) are available for comparison (Monaco et al., 2010) and are reported in Figure 9b and 10b together with the surface wave inversion results.



**Figure 8.** Montecarlo inversion of combined active and passive surface wave data at Pisa site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.



**Figure 9.** Montecarlo inversion of combined active and passive surface wave data at Rojo Piano site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.



**Figure 10.** Montecarlo inversion of combined active and passive surface wave data at Pianola site: a) Experimental and numerical dispersion curves. b) Shear wave velocity profiles from Monte Carlo analysis compared to down-hole test result.

## DISCUSSION

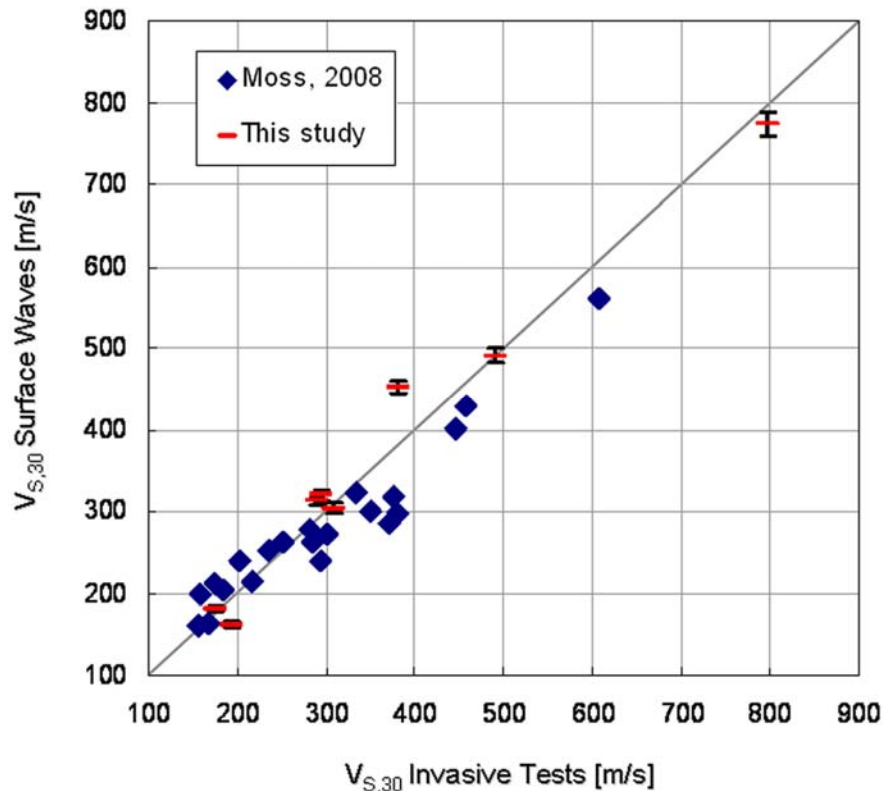
For all the sites the uncertainty on  $V_{S,30}$  (as quantified by the CoV) is more or less around 2 % (Table 2) and lower than the measurement uncertainty of the experimental dispersion curves. This indicates that if the experimental dispersion curve is sampled in a sufficiently wide frequency band, the profiles selected by the Monte Carlo inversion are equivalent in terms of both fit to the dispersion curves and  $V_{S,30}$ . A similar equivalence has been demonstrated in Foti et al. (2009) in respect of both amplification functions and response spectra within the typical framework of 1D seismic site response studies.

It is worthwhile to recall that different inversion strategies could lead to any of the profiles selected by the Monte Carlo procedure. The difference between velocity profiles can be significant, but in terms of  $V_{S,30}$  evaluation this difference collapses to very limited values.

### Comparison with invasive tests.

A comparison of  $V_{S,30}$  evaluation from invasive and surface wave data is reported in Figure 11 for the test sites presented in this study and for a series of data available in literature (Figure 3 of the paper by Moss, 2008) concerning both SASW and MASW methods. Although the comparison is generally good, Moss (2008) has underlined in his study that surface wave tests tend to overestimate  $V_{S,30}$  in soft sites and underestimate it in stiff sites. This trend however is not present in the dataset of the present study where the relationship appears closer to a one to one ratio. One of the possible explanations is given by the presence in the Moss dataset of comparisons with

P-S suspension logging, which tends to overestimate  $V_S$  in stiff materials. Data from this study shown in Figure 11 are relevant as they extend the comparison of invasive versus surface wave tests to stiffer soil conditions, even if much work is still to be done in this velocity range to confirm the observed trends. Moreover, the uncertainty bars associated with surface wave tests show the limited relevance of solution non-uniqueness in this context.



**Figure 11.** Comparison of  $V_{S,30}$  determined with invasive tests and surface wave tests.

Although the results from invasive tests are typically considered as a benchmark, there are several possible reasons for differences between surface wave tests and borehole methods. Indeed, the investigated volume is different: surface wave tests measure an average value based on the dynamic response of a large portion of the soil deposit, which can be considered more representative than local estimates obtained with invasive methods. It is also necessary to account for possible inaccuracies in borehole methods. For example, it is common experience that the down-hole test become less accurate as a function of depth due to the increased source to receiver distance and that cross-hole tests can be biased due to the effects of drilling disturbance or because of critical refraction at interfaces. Furthermore, borehole measurements are strongly influenced by material anisotropy, borehole inclination and source polarization which are rarely addressed in their interpretation. Soil disturbance can produce either a

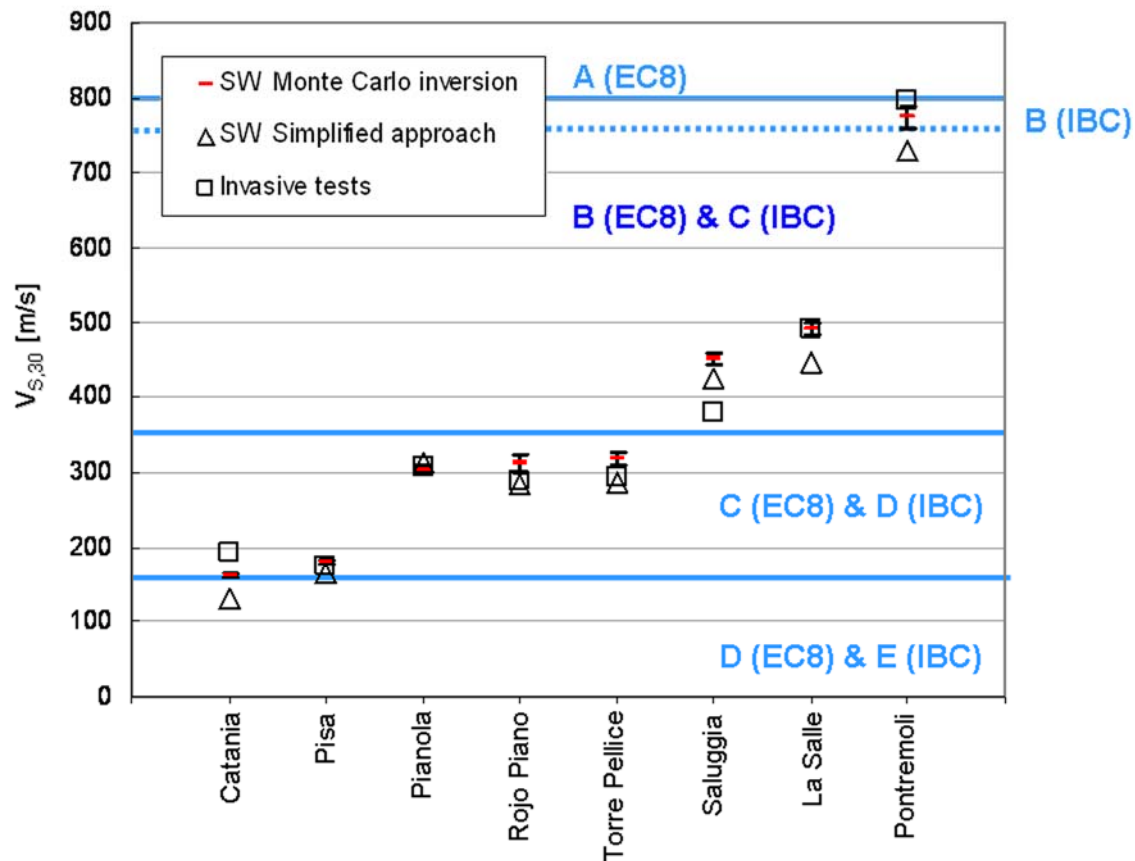
decrease or an increase in velocity due to strain softening or hardening occurring around the borehole. This effect is particularly evident at softer sites. For example, data presented in Figure 9 show that a less invasive methodology (SDMT) is more in agreement with the results of surface wave tests than the down-hole test. The same trend has been noted also at the Catania site (Figure 7). Here it is necessary to recall that the SDMT was not located at the same site as the other two tests; still, a very good correspondence for shallow clays is obtained with surface wave tests, while for higher depths (below 20 m) the difference is likely due to geological variations.

The cross-hole test at Saluggia was performed about 30 years ago with old style equipment and using a 2 borehole setup; hence, the results could be affected by errors (e.g. inaccurate triggering or borehole inclination). This fact could justify the discrepancy with respect to surface wave results (Figure 6b). On the other hand, it has to be observed that, among all the surface wave datasets, this one shows the poorest fitting of the experimental dispersion curve in the inversion (Figure 6a); hence in this case the accuracy of surface wave test may also be questionable.

#### **Simplified procedure for $V_{S,30}$ approximation.**

A preliminary estimate of  $V_{S,30}$  can be obtained directly from the experimental dispersion curve. The idea that the dispersion curve offers a consistent and simplified way of estimating the  $V_{S,30}$  has been considered by Brown et al. (2000), who proposed the Rayleigh-wave phase velocity at a wavelength of 36 meters as a valuable estimate of  $V_{S,30}$ . Their analysis is based on several case histories and the coefficient of variations of their simplified method rises to around 6 % for the different sites. Although such an approach cannot be considered as an alternative to the solution of the inversion process because this oversimplification can lead to large errors, especially for complex stratigraphical situations, it can provide a useful reference for preliminary assessments.

Results from the application of this simplified procedure for the Italian sites are compared to the outcome of the Monte Carlo inversion of surface wave data and the results of invasive tests in Figure 12. The sites have been sorted for increasing  $V_{S,30}$ . In the same Figure the boundaries proposed by IBC and Eurocode 8 for site classification are reported for reference. The simplified procedure leads to reasonable results, giving a site classification which is the same of invasive tests and surface wave inversion at most sites (neglecting the stiffest and softest sites which are borderlines). The root mean square deviation of this simplified procedure with respect to invasive tests is around 7%.



**Figure 12.** Estimates of  $V_{S,30}$  from surface wave data using the Monte Carlo inversion and the simplified approach at different sites compared to estimates from invasive methods. Also the bounds for seismic site classification according to IBC (BSSC, 1994) and EC8 (CEN, 2004) are reported.

## FINAL REMARKS

This paper has focused on the reliability of surface wave tests for  $V_{S,30}$  determination. One of the frequent criticisms of surface wave methods is related to the non-unique solution of the inverse problem. It has been, however, shown that this non-uniqueness has a reduced influence in the evaluation of  $V_{S,30}$ . The  $V_{S,30}$  is related to a global response of the soil profile, so that differences in estimated profile parameters, which are associated with small differences in the dispersion curve (equivalence problem) are of minor importance for its estimate. Indeed, even if different inversion approaches can lead to different solutions in terms of shear wave velocity profile, the

associated estimate of  $V_{S,30}$  is very similar (i.e. within approximately 2%) if the experimental data cover the necessary frequency band. This confirms the robustness of surface wave testing for estimating  $V_{S,30}$ . With respect to the accuracy, the reported case histories show that, in situations in which the maximum retrieved wavelength (either with active or passive sources) is greater than 60 meters, the final result is approximately close to the one of invasive tests. Therefore it appears that, in this condition, inversion non-uniqueness will not significantly alter the accuracy and reliability of the  $V_{S,30}$  estimate. A single deterministic profile can yield reliable results in terms of  $V_{S,30}$ , if a good fitting of experimental dispersion curve is achieved.

These considerations are confirmed both in the sites of the presented dataset and in previous literature data. With respect to the latter, the present work increases the coverage on stiff sites and provides a statistical evaluation of the uncertainty related to non uniqueness of the solution.

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