Uncertainties in VS profiles from geophysical tests and their influence on seismic ground response analyses: results from the Interpacific blind test

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Uncertainties in V_S Profiles from Geophysical Tests and Their Influence on Seismic Ground Response Analyses: Results from the Interpacific Blind Test

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ABSTRACT

The InterPACIFIC project is aimed at the assessment of the reliability of different geophysical methods (both invasive and non-invasive) for the estimation of shear wave velocity profiles. Blind tests have been performed in three different subsoil conditions. The observed variability in the results provided by several operators gives a representation of the uncertainties that has to be expected in site characterization. The implications of these uncertainties on ground response analyses are considered in the present paper.

Introduction

The ability to quantify uncertainty in shear wave velocity (V_S) is paramount to conducting realistic ground motion site response analyses. However, uncertainty in V_S has proven difficult to quantify and is often ignored by those performing geophysical tests. Indeed, those involved in dynamic site characterization generally provide a single, deterministic Vs profile without quantification of uncertainty in either layer thicknesses or velocities. As a result, those performing site response analyses often arbitrarily vary V_S by +/- 20-30% in an attempt to account for epistemic uncertainty and aleatory variability. While performed with the goal of being conservative, this approach may actually be unconservative, as the problem is one of predicting resonances at the site, which may be diluted by such a wide range of input profiles that do not meaningfully represent site conditions.

Several blind comparative studies have been performed around the world in recent years to assess the reliability of Vs profiles derived from borehole and surface wave geophysical methods. Some of these blind tests were focused only on surface-wave methods for seismic site response as the SESAME (Site Effects aSsessment from Ambient noisE) (Bard & SESAME participants, 2004) and the NERIES-JRA4 (Bard, et al., 2010; Fäh, et al., 2010; Di Giulio, et al., 2012). Another blind test was conducted by Cornou et al. (2009) to compare different methods for the analysis of microtremors and by Cox et al. (2014) for combined active and passive data.

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Other comparative studies takes into account also borehole methods as Kim et al. (2013). The latter study was conducted for a single site.

The InterPACIFIC project (Intercomparison of methods for site parameter and velocity profile characterization) was proposed to assess the reliability of both invasive and non-invasive methods for the seismic site characterization. Three different subsoil conditions were investigated to account for different geological conditions. To assess the variability of experimental results two different strategies have been devised respectively for invasive and non-invasive methods. Indeed uncertainties on invasive methods are strongly related to the availability of high quality experimental data. On the other side, non-invasive methods require the solution of a rather complex inverse problem and most relevant uncertainties are those associated to solution non-uniqueness. Different operators repeated borehole measurements while for surface wave analyses several analysts interpreted a single large experimental dataset.
After a brief description of the project and of the three sites, we discuss in detail the results at Mirandola site in Northern Italy, for which a comparison on expected ground response is also reported.

The InterPACIFIC project

In-hole and surface wave tests were conducted at specifying testing sites, each of them representative of a class of subsoil conditions: Mirandola in Italy belongs to the “soft-soil” class; Grenoble in France is representative of “stiff-soil” class with a quite deep bedrock; Cadarache in France is an “hard-rock” site, being placed on an outcropping cretaceous limestone.

At each site three companies performed and interpreted their own cross-hole, down-hole and PS-suspension loggings datasets. Several surface wave datasets, both active and passive, were acquired by the organizing team in the vicinity of the boreholes. In particular, ambient vibration acquisitions were acquired with different layout: concentric circle, triangle and L-shape, all of them were centered in the same common point, close to the boreholes. For the active measurements, both vertical and horizontal components of the propagation were recorded by adopting linear array. These datasets were then distributed to fourteen teams from around the world that performed their own surface wave analysis. It is important to highlight that no a-priori information was provided to the teams to better constraint the inversion but only a concise description of the site geology.

Mirandola site

The site was previously investigated by Emilia-Romagna authority as it hosts the station of the Italian strong-motion network that recorded the earthquake sequence of 2012. In this framework, two boreholes were drilled down to 123-m depth and hence a stratigraphy and the results from a cross-hole test were available before the beginning of the project. From these studies, a silty and clay deposit, is expected until 112 m where the seismic bedrock is found. This information was not available for the teams who analyzed the surface wave data. A simplified stratigraphy of the site is reported in Figure 1.

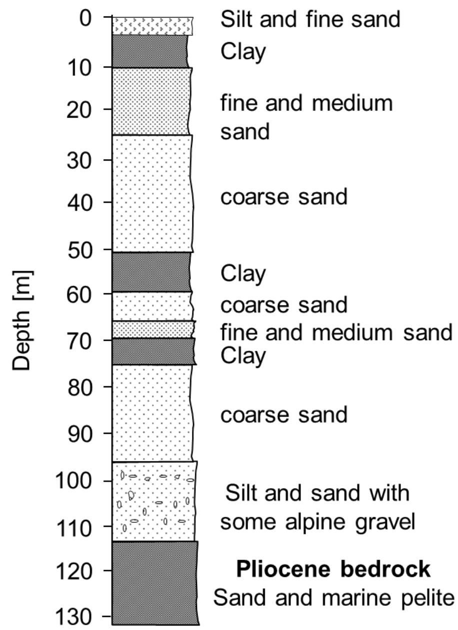

Figure 1 – Mirandola: simplified stratigraphy of the site.

As far as the borehole measurements are concerned, in addition to the three companies involved in the InterPACIFIC project, we had also the voluntary contribution of the University of Torino, that performed crosshole and downhole tests and of INGV (Italian Institute of Geophysics and Vulcanology) that performed an SDMT (Seismic Dilatometer Test). 14 teams analyzed active and passive surface-wave data by applying different strategies to retrieve the final Vs profile.

Results: Vs profiles

In Figure 2 the results of the surface-wave analyses are compared with the results from borehole measurements. The seismic bedrock was well identified by invasive methods (Figure 2a) whose results show a very low variability of the depth of this interface (between 110 and 115 m), even if some scatter is observed in the estimated S-velocity of the bedrock (690 ± 210 m/s). The results from surface-wave analysis show a greater variability of the bedrock: the depth of the interface varies between 90 and 120 m while the S-velocity is 780 ± 370 m/s. A low-velocity layer is well identified by invasive test between 48 and 65 m (Figure 2c) but not by most of the surface-wave analysis results. In addition, an interface was well retrieved by invasive tests at about 25m while the results of surface wave analysis locate such feature in between 19 and 30 m (Figure 2c). Despite the higher resolution of the invasive Vs profiles, the variability indices, estimated as the ratio between the maximum and the minimum value of each population of results (i.e. invasive results and non-invasive results), are quite similar to each other and roughly equal to 1.5 at least until 80-m depth (Figure 2b).

For each shear wave velocity profile, the equivalent V_S ($V_{S,eq}$) was computed as function of depth (z). This is the time-average of the S-wave velocity in the topmost z m of sediments and it is computed as:

$$V_{S,eq}(z) = \frac{z}{\sum_{i=1}^{N} \frac{h_i}{V_{S,i}}} \quad (1)$$

In particular the value for z = 30 m (the $V_{S,30}$), is used as a parameter for the classification of subsoil for simplified assessments of seismic site response in most seismic building codes and in several ground motions prediction equations (GMPEs). The results are reported in Figure 3 and it is interesting to observe that at z = 30 m both the two population of results have the same variability of $V_{S,eq}$ equal to 1.2.

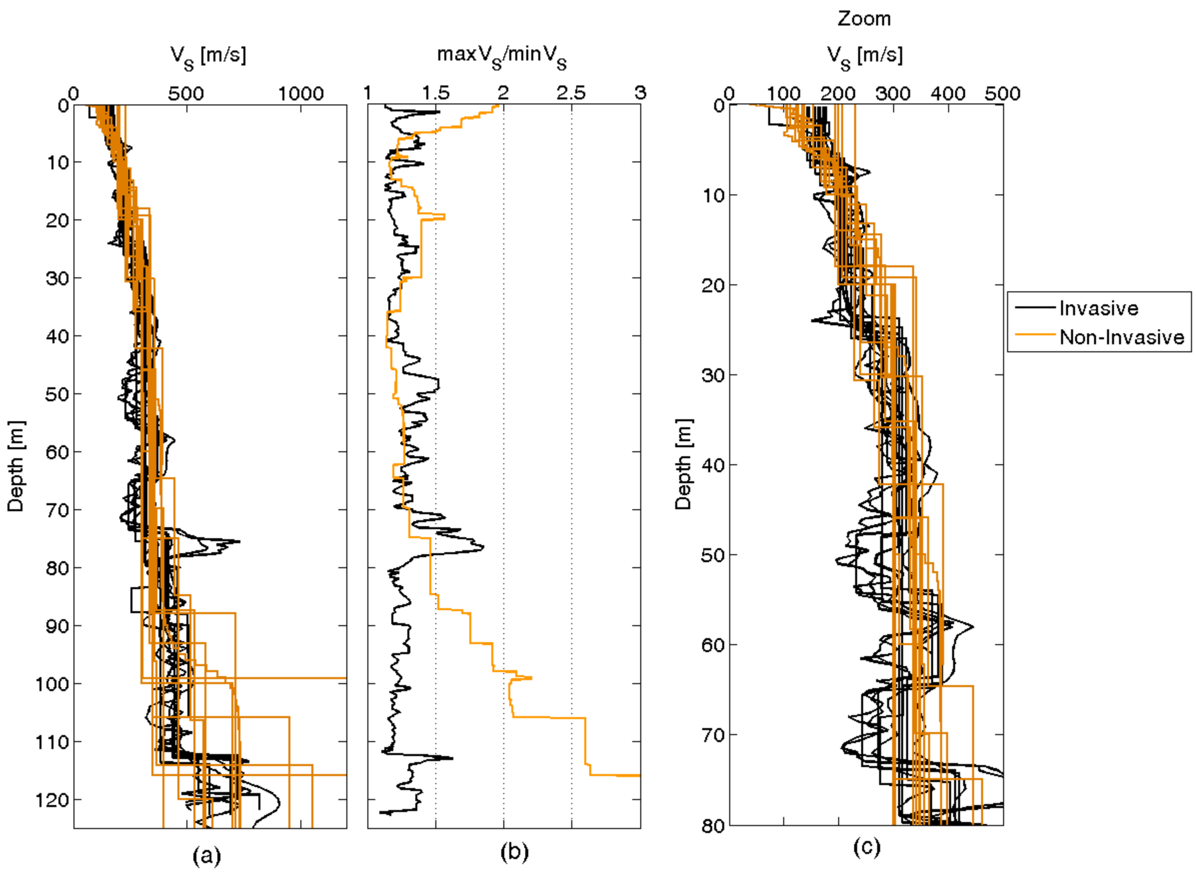

Figure 2 –Mirandola site: a) Shear wave velocity profiles from invasive (black) and non-invasive tests; b) ratio between the maximum and the minimum values of shear wave velocity for each population; c) close-up view of (a).

Seismic Site Response analyses

For a preliminary assessment of the influence of observed variability on ground response analyses, the obtained results were also compared in terms of elastic transfer function. The assumption is a horizontally layered soil deposits over a bedrock and the motion is applied within the soil profile at the top of the estimated bedrock.

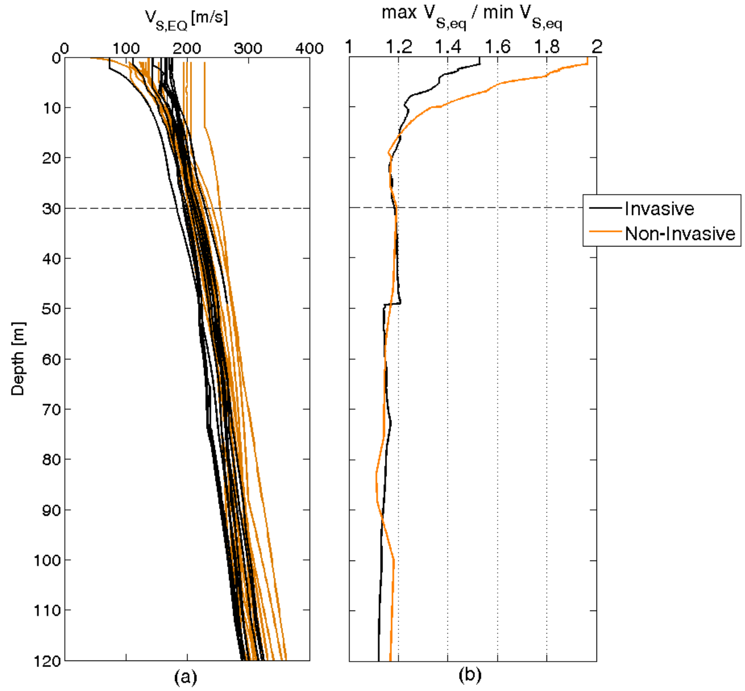

Figure 3 – Mirandola site: a) Results in terms of $V_{S,eq}$; b) the variability estimated as the ratio between maximum and minimum values of each population

The transfer functions are reported in Figure 4a, while in Figure 4c and 4b the fundamental frequency f_0 and the corresponding amplitude are reported, respectively. We observed a lower variability for the invasive results than for non-invasive results for both amplitude and f_0. In terms of average values, the calculated natural frequency is very similar, but a larger difference is observed for the corresponding amplitude. The apparent overestimation of the latter is driven by two specific profiles, which provide rather high values of amplification (see Figure 4a). These correspond to the two results of non-invasive methods that largely overestimate the velocity of the substratum (see Figure 2a).

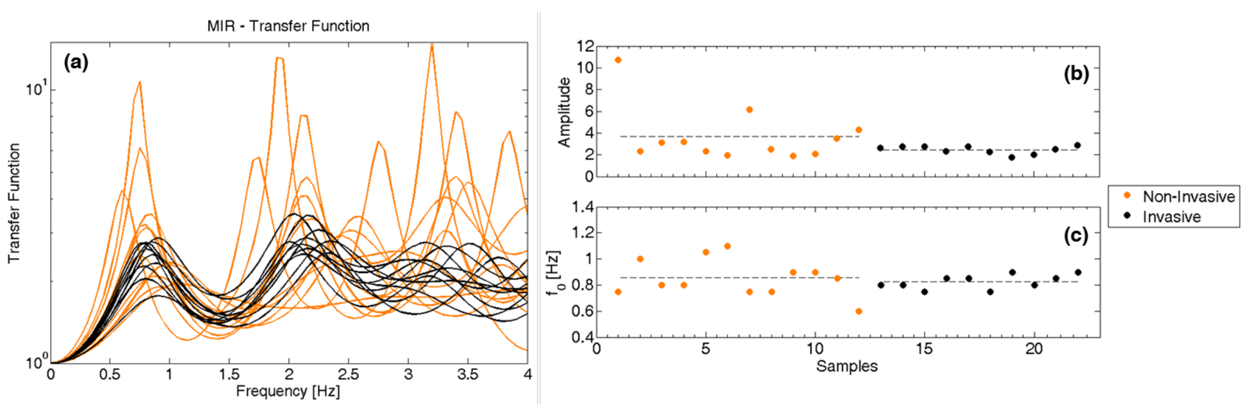

Figure 4 – a) Elastic transfer function of the obtained results; b) amplitude at the fundamental frequency f_0 (c)

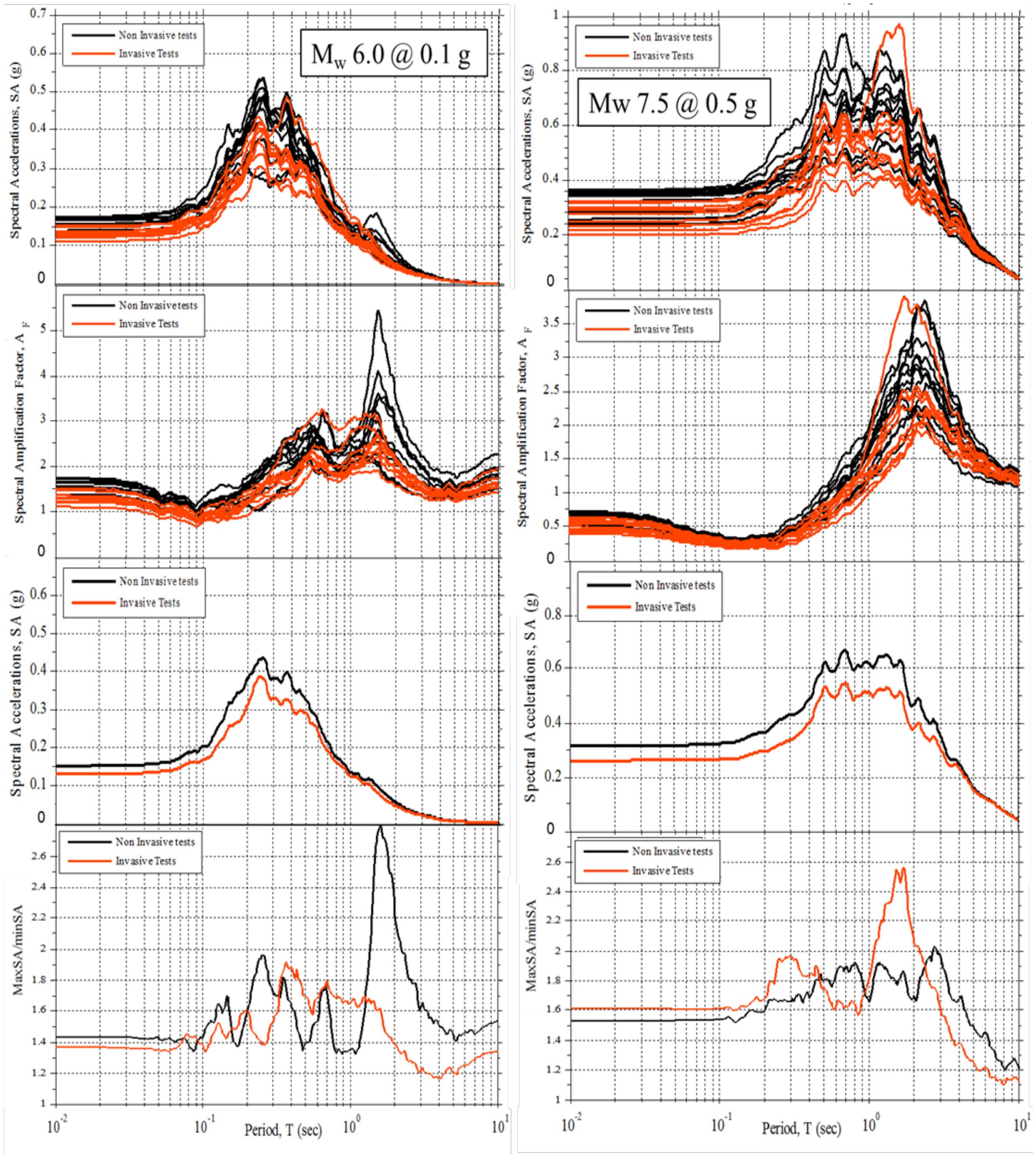

Figure 5 – Results of the linear-equivalent seismic-site-response analyses for the shear wave velocity profiles measured with invasive (borehole) and non-invasive (surface wave analysis) tests in Mirandola (from top to bottom): acceleration response spectra; spectral amplification factors; median values of the response spectra; ratio between the maximum and the minimum spectral values. Median results for two groups of 8 strong-motion records are reported: magnitude Mw equal to 6.0 and scaled to 0.1g (left column) and magnitude Mw equal to 7.5 and scaled to 0.5g (right column).

We also simulated a seismic-site response for the different shear wave velocity profiles with an equivalent linear approach. We adopted the relationship proposed by Darendeli (2001) for estimating the normalized shear modulus and damping ratio as a function of strains. The analyses have been performed for four groups of 8 strong motion records that represent different scenarios in terms of magnitude and maximum peak ground acceleration. In particular the median results for two groups of accelerograms characterized by Mw equal to 6 (scaled to 0.1g) and 7.5 (scaled to 0.5g) respectively are reported in Figure 5. The acceleration response spectra show a comparable variability of the results between the two populations of V_S profiles (invasive and non-invasive tests). On average, the response spectra for non-invasive tests are associated to higher values. This was expected as surface wave methods provided higher values for the velocity of the substratum (Figure 2a). In this respect it has to be considered that the boreholes were drilled only in the top part of the substratum. It is reasonable to expect higher values at larger depth, as obtained with surface wave analysis. The variability in the estimated site responses for the two populations of V_S profiles is expressed in the bottom part of Figure 5 as the ratio between maximum and minimum values of spectral acceleration for each population. Similar variability is observed for the two populations, with values typically below 2, except some intervals in which the ratio is dominated by the presence of a profile which give an outlier in terms of spectral response.

Comparison with the other sites

Among the three sites, Mirandola is the one for which ground response analyses can be implemented straightforwardly for both invasive and non-invasive results. Indeed in Grenoble the bedrock is very deep and cannot be reached with borehole methods, a frequent limitation due to budget restrictions in site investigation projects. Cadarache site is less significant from the point of view of seismic site response because just a thin layer is observed above the bedrock.

For Grenoble and Cadarache, the results of invasive methods were characterized by a better resolution, but the variability in terms of $V_{S,eq}$ was just slightly lower than for non-invasive methods. In Table 1 the statistic values of the $V_{S,30}$ of invasive and non-invasive results are reported for all the three sites. The statistic values are: mean, standard deviation (std) and coefficient of variation (CoV), estimated as the ratio between the mean and standard deviation. The latter is a dimensionless normalized measure of the variability of the results for a better comparison of different sites. The CoV is quite similar between invasive and non-invasive for Mirandola and Grenoble while in Cadarache the CoV of invasive results is even slightly higher than the one of non-invasive tests. Indeed, Cadarache, as any rock outcrop, is a very difficult site to study for both invasive and non-invasive methods because the weathering and fracturing of the top zones lead to lateral variability and energy scattering. The obtained CoVs may be considered as typical values of uncertainty in Vs,30 determination for soils (CoV around 5%) and for stiff rock outcrops (above 10%). Although these values required further investigation, they are in line with previous studies (e.g. Comina et al., 2011).

Table 1. Statistic values of $V_{S,30}$ (mean, standard deviation and Coefficient of Variation) computed for each site analyzed in the InterPACIFIC project

Site	Method	$V_{S,30}$ mean [m/s]	$V_{S,30}$ std [m/s]	$V_{S,30}$ CoV [-]
Mirandola	Invasive	209	12.1	0.058
	Non-Invasive	218	16.3	0.075
Grenoble	Invasive	352	18.8	0.053
	Non-Invasive	363	14.6	0.040
Cadarache	Invasive	1656	301	0.182
	Non-Invasive	1591	168	0.106

Conclusions

In the InterPACIFIC project we analyzed the variability of Vs profiles estimated through a variety of methods by different operators in three subsoil conditions. The Vs profiles obtained with invasive methods are characterized by a better resolution than the surface-wave results, but the observed variability of the results (a proxy for precision) is very similar between the two classes of methods. Also for $V_{S,30}$, invasive and non-invasive tests provide very similar average estimates with comparable variability. This observation is in line with other studies in the literature.

The site response analyses performed for Mirandola site show that the propagation of the variability observed in V_S profiles gives a similar variability also in the response spectra. A difference is observed in median values of the population of results. However it has to be recognized the different nature of the two approaches: invasive measurements are local estimates in the vicinity of the borehole(s), whereas surface wave analyses reflect average properties over the volume below the testing array. Hence the latter may likely be considered more representative of the global response of the site. Site response simulations have been conducted only for Mirandola site as in Grenoble the seismic bedrock cannot be reached with invasive tests. This is a quite frequent limitation, which can be overcome with non-invasive tests. However, the large variability of the estimates of bedrock position and velocity at Mirandola, suggests that different strategies should be devised to improve the characterization (e.g. with joint interpretation of seismic reflection surveys and surface wave analyses).

Acknowledgments

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References

Bard, P. et al., 2010. From Non-invasive Site Characterization to Site Amplification: Recent Advances in the Use of Ambient Vibration Measurements. *Earthquake engineering in Europe,* 17(Part 2), pp. 105-123.

Bard, P.-Y. & SESAME participants, 2004. *The SESAME project: an overview and main results.* Vancouver, BC, Proceedings of the 13th world conference in earthquake engineering, p. 2207.

Boore, D. M. & Asten, M., 2008. Comparison of shear-wave slowness in the Santa Clara Valley, California, using blind interpretations of data from invasive and noninvasive methods. *Bulletin od Seismological Society of America*, 98(4), pp. 1983-2003.

Comina, C., Foti, S., Boiero, D. & Socco, L., 2011. Reliability of Vs,30 Evaluation from Surface-Wave Tests. *Journal of Geotechnical and Geoenvironmental engineering*, pp. 579-586.

Cornou, C. et al., 2009. Derivation of structural models from ambent vibration array recordings: Results from an international blind test. *ESG2006,* Volume 2, pp. 1127-1219.

Cox, B., Wood, C. & Teague, D., 2014. *Synthesis of the UTexas1 Surface Wave Dataset Blind-Analysis Study: Inter-Analyst Dispersion and Shear Wave Velocity Uncertainty*. Atlanta, Georgia, Geo-Congress 2014.

Darendeli, M., 2001. *Development of a new family of normalized modulus reduction and material damping curves.* Thesis (Ph.D.) a cura di Austin, TX, USA: The University of Texas at Austin.

Di Giulio, G. et al., 2012. Case history: exploring the model space and ranking a best class of models in surface wave dispersion inversion: application at European strong-motion sites. *Geophysics,* 77(3).

Fäh, D. et al., 2010. *Guidelines for the implementation of ambient vibration array techniques: measurement, processing and interpretation,* s.l.: Neries deliverable JRA4-D9.

Idriss, I. M. & Sun, J. I., 1993. *User's manual for SHAKE91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits.* Davis Davis, California: Center for Geotechnical Modeling, Dept. of Civil and Environmental Engineering, University of California,.

Kim, D., Park, H. & Bang, E., 2013. Round Robin Test for Comparative Study of In-Situ Seismic Tests. In: R. C. &. P. Mayne, a cura di *Geotechnical and Geophysical site characterization 4.* Leiden (NL): CRC Press, pp. 1427-1434.

Moss, R., 2008. Quantifying measurement uncertantiy of thirty-meter shear-wave velocity. *Bulletin of Seismological Society of America,* 98(3), pp. 1399-1411.

Rathje, E. & Kottke, A., 2010. *STRATA.* [Online] Available at: https://nees.org/resources/strata [Consultato il giorno 11 03 2015].

Stephenson, W. J. et al., 2005. Blind shear-wave velocity comparison of ReMi and MASW Results with boreholes to 200 m in Santa Clara Valley: Implication for earthquake ground-motion assessment. *Bulletin of Seismological Society of America,* 95(6), pp. 2506-2516.