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InterPACIFIC project: comparison of invasive and non-invasive methods for seismic site characterization. Part II: inter-comparison between surface-wave and borehole methods.

F. Garofalo[1,*], S. Foti[1], F. Hollender[2], P.Y. Bard[3], C. Cornou[3], B.R. Cox[4], A. Dechamp[5], M. Ohrnberger[6], V. Perron[2], D. Sicilia[7], D. Teague[4], C. Vergniault[7].

1: Politecnico di Torino, Torino, Italy.

2: French Alternative Energies and Atomic Energy Commission (CEA), Cadarache, Saint-Paul-lez-Durance, France

3: Univ. Grenoble Alpes/CNRS/IRD/IFSTTAR, ISTerre, F-38000 Grenoble, France.

4: University of Texas, Austin, Texas USA

5: French Alternative Energies and Atomic Energy Commission (CEA), Bruyères le Châtel, Arpajon, France

6: University of Postdam, Postdam, Germany

7: EdF (Electricité de France), CEIDRE-TEGG, Aix-en-Provence, France

*: currently at Eni upstream and technical services, Italy.

Corresponding author: Sebastiano Foti

sebastiano.foti@polito.it

Corso Duca degli Abruzzi, 24

10129 Torino, Italy

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Abstract

The InterPACIFIC project was aimed at assessing the reliability, resolution, and variability of geophysical methods in estimating the shear-wave velocity profile for seismic ground response analyses. Three different subsoil conditions, which can be broadly defined as soft-soil, stiff-soil, and hard-rock, were investigated. At each site, several participants performed and interpreted invasive measurements of shear wave velocity (Vs) and compression wave velocity (Vp) in the same boreholes. Additionally, participants in the project analysed a common surface-wave dataset using their preferred strategies for processing and inversion to obtain Vs profiles. The most significant difference between the invasive borehole methods and non-invasive surface wave methods is related to resolution of thin layers and abrupt contrasts, which is inherently better for invasive methods. However, similar variability is observed in the estimated invasive and non-invasive Vs profiles, underscoring the need to account for such uncertainty in site response studies. $V_{S,30}$ estimates are comparable between invasive and non-invasive methods, confirming that the higher resolution provided by invasive methods is quite irrelevant for computing this parameter.

1 Introduction

The assessment of reliability of experimental techniques typically requires an investigation of their accuracy (ability to obtain the true target value) and precision (repeatability). Most often the number of repetitions of a measurement at a site are not sufficient for an estimation of precision. With regards to accuracy, the "true" value of the measured quantity is unknown for natural systems.

The shear-wave velocity (V_S) profile is typically obtained using either in-hole seismic measurements (referred to herein as invasive methods) or ground surface measurements such as surface-wave methods (referred to herein as non-invasive methods). Because of budget restrictions in typical site-characterization projects, only a single technique and a single realization of the test are generally available. It is therefore quite difficult in practice to estimate the "true" uncertainty in a parameter which has a significant influence on seismic site response analyses.

For invasive methods, the measurement is performed inside the medium. This strategy poses the issue of placing the source and/or the receiver into the ground. This is usually achieved by drilling a hole in which the instruments are placed. Nevertheless, other strategies can be used to place instruments into the ground, avoiding the necessity of drilling a hole. This is the case for the Seismic Cone Test and the Seismic Dilatometer Test, in which the receivers are driven into the ground by pushing a rod. Among invasive methods, the Cross-Hole Test is widely considered the most reliable as the measurements are performed locally at any specific depth along short travel paths. However, a comparative study by Jung et al. [1] showed that Cross-Hole results are very close to those of other invasive methods. Because they are based on local measurements at multiple depths, invasive methods exhibit minimal decreases in resolution with increasing depth (within limits of investigation depth associated to the equipment). For this reason they are commonly considered more reliable than non-invasive methods and their results are often considered as benchmark values.

Non-invasive methods are based on measurements performed along a single boundary of the medium (i.e., the ground surface). Their main advantage is that the sources and receivers do not need to penetrate the medium. On the other hand, measuring along a single boundary leads to a decreasing resolution with increasing distance from the ground surface (i.e., with depth). Surface-wave methods have become quite popular to evaluate the V_S model not only because they are time and cost effective, but also because they can be applied to a variety of ground conditions [2]. A major criticism of surface wave methods is that the surface-wave inverse problem is strongly non-linear and affected by solution non-uniqueness [3]. This leads to interpretation ambiguities since several possible V_S profiles are solutions to the inverse problem [4].

Since early 2000's, when surface-wave methods became popular in near-surface geophysics and geotechnical engineering, several researchers have compared surface-wave analysis results with borehole measurements to validate the technique (e.g. [5-10]). In recent years systematic comparative studies between invasive and surface-wave methods have been produced. The Institute of Geological and Nuclear Sciences (New Zealand) sponsored a blind trial of ambient noise versus cone penetrometer and seismic refraction data in glacial sediments near Wellington harbour [11]. Boore and Asten [12] reported a similar study for two sites in California with constantly increasing velocity with depth. However, all six sites in this blind test, which are in the Santa Clara Valley, California, are quite similar to each other and lack strong gradients in subsoil stiffness. Brown et al. [7] compared V_S profiles inferred from surface-wave methods and in-hole measurements at 10 sites, but only a single determination was available for each technique. A study with multiple realizations of surface-wave and borehole methods was proposed by Kim et al. [13], however, only a single site was investigated and hence the study was related only to a specific subsoil condition (shallow bedrock at 15-m depth).

The main scope of the InterPACIFIC (Inter-comparison of methods for site parameter and velocity profile characterization) project is to assess the reliability/variability of seismic site characterization methods (in-hole and surface-wave methods) for estimating the shear-wave velocity profile. A series of blind tests has been organized in which several participants performed both invasive and non-invasive techniques at each site without any a-priori information about the site. In contrast to aforementioned comparative studies, three different subsoil conditions were selected as test sites: a soft-soil, a stiff-soil and a hard-rock site. In this paper the results from the invasive methods are first compared in order to assess the intra-method variability (i.e., the variability among the results obtained by different participants using a single borehole method, or the repeatability of the test) as well as the inter-method variability (i.e., the variability among the results obtained for various in-hole tests). Next, the results of the surface-wave methods (discussed in the companion paper [14]) are compared with the in-hole results. When comparing invasive and non-invasive methods, it is important to note that the results from invasive methods refer only to the soil column immediately around the borehole(s), while the results from surface-wave methods are representative of the whole volume underling the array(s). Thus, differences in Vs are expected between the two classes of methods simply based on the "sampling" of different volumes of a vertical and lateral heterogeneous material.

The test sites considered in this study are: Mirandola (MIR) in Italy ("soft soil" class); Grenoble (GRE) in France ("stiff-soil" class); and Cadarache (CAD) in France ("hard-rock" class). At each site, at least two boreholes were available to perform the in-hole measurements. Both active and passive surface-wave data were collected with arrays in the vicinity of the boreholes to achieve a meaningful comparison between the results from invasive and non-invasive methods. Different teams of engineers, geophysicists and seismologists, were invited to take part in the project. In order to ensure that each participant performed a blind test, the same experimental non-invasive datasets were provided to all of the teams with very little information about the sites ([14]). For the invasive methods, different companies repeated the measurements in order to assess the repeatability with different acquisition strategies and equipment.

2 Test-sites

Mirandola is located in the Po river plain, Italy. The Secchia river, a stream of the Po river, flows north-south on the west side of the site. The area was affected by a couple of strong earthquakes in May 2012 [15]. The station of the Italian Accelerometric Network placed in Mirandola provided strong-motion records in the vicinity of the epicentre for both shocks. For this reason, Emilia-Romagna authority planned a specific site investigation. Specifically, two boreholes placed 6.8 m from each other were drilled to a depth of 125 m. A simplified stratigraphic log is reported in Figure 1. The site is characterized mainly by alluvial deposits with alternating sequences of silty-clayey layers of alluvial plain and sandy horizons. The geological substratum (i.e., "bedrock") consists of marine and transitional deposits of lower-middle Pleistocene age and it was found at a depth of 118 m in the borehole. The water table was detected at a depth of approximately 4-m.

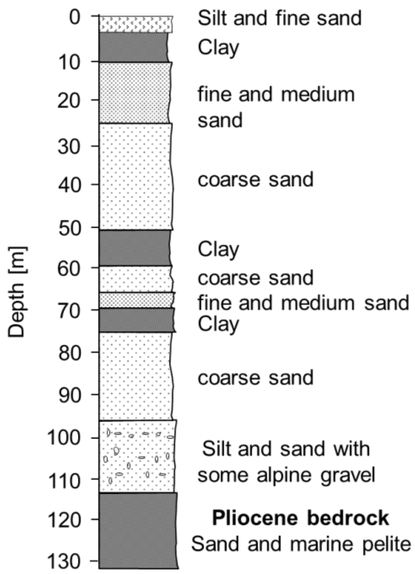

Figure 1 – Soil stratigraphy at Mirandola site (MIR).

The Grenoble site is located in the French Alps (the southeast region of France) in the vicinity of the "Institut Laue Langevin" nuclear research facility. The site is flat and is characterized by recent alluvial deposits (mainly sands and gravels) on a Quaternary lacustrine clayey/marly deposit, overlaying a Mesozoic bedrock. The expected depth of the contact between the alluvial and lacustrine deposits is a few tens of meters. The expected depth of the interface between lacustrine deposits and the bedrock is 500 to 800 meters [16]. For the InterPACIFIC project, three in-line boreholes were drilled up to a 50-m depth with an inter-hole distance of 4.5 m. A simplified stratigraphic log of the near surface is reported in Figure 2. A deposit of sands and gravels was found until 22 m. Part of this layer is saturated since the water table was found at a depth of approximately 4-m. Beneath this depth is a deposit of low plasticity clay, which extends with only minor interruptions of fine sand until 50-m depth (end of the borehole).

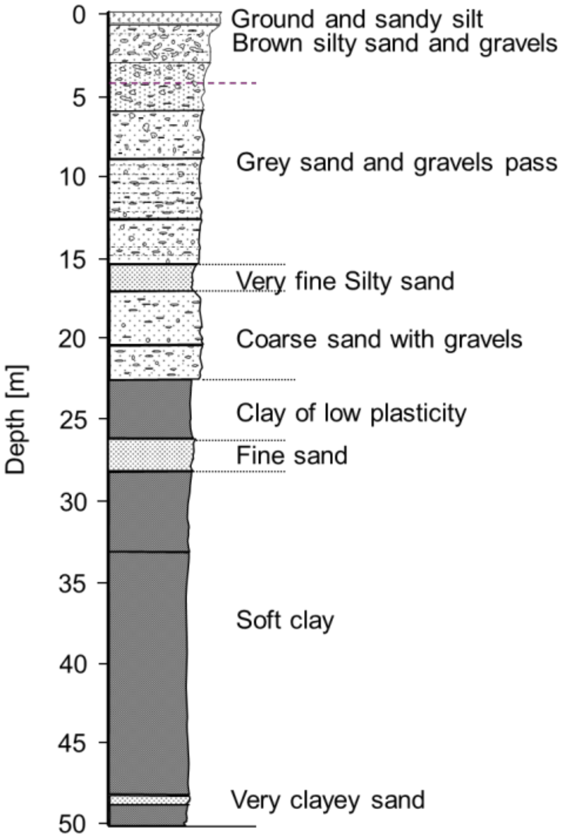

Figure 2 – Soil Stratigraphy at Grenoble site (GRE)

The third site is in Saint-Paul-les-Durance (South-East of France), within the CEA Cadarache research centre. The test site is located on the top of a hill, but it is expected to exhibit minimal topographic effects because of the mild slope inclination. Cretaceous limestone outcrops near the test-site. For the InterPACIFIC project, three in-line boreholes were drilled up to a 50-m depth with an inter-hole distance of 4.5 m. Figure 3 shows a simplified stratigraphy of the site. The subsoil is mainly composed of limestone. A few thin interlayers were encountered but are of little interest for the project. At a depth of roughly 25 m a transition to a less weathered material is identified.

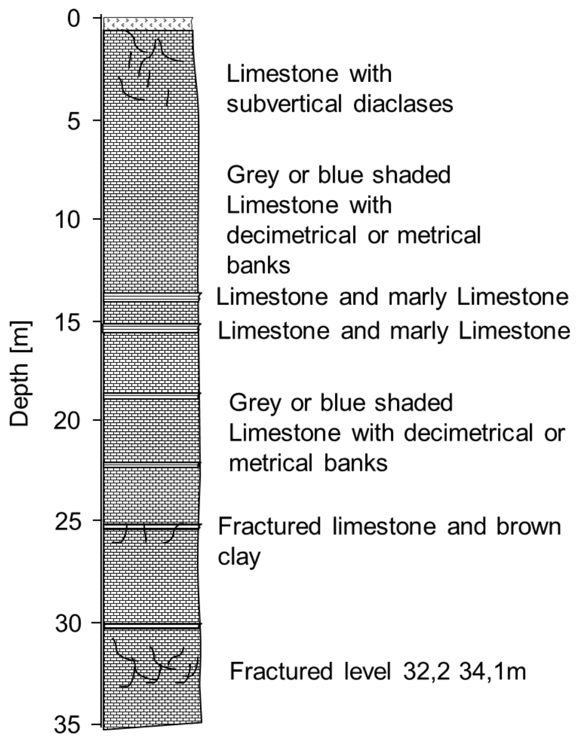

Figure 3 – Soil stratigraphy at Cadarache site (CAD)

At each site, the available results were examined to assess the ability of each method to detect specific features of the Vs profile. The variability of the different results as a function of depth were quantified as the coefficient of variation (COV), which is defined as the ratio of the standard deviation of the data normalized by the mean. It is noted that statistics like COV are less reliable when the sample size is limited. However, the COV value still provides an indication of the variability, and it is commonly used to quantify differences in Vs profiles for subsequent analyses like site response studies. Furthermore, COV values were also used to quantify variability in the non-invasive methods presented in the companion paper [14]. Thus, it is also used for consistency when comparing the invasive and non-invasive results compiled in this study.

Comparisons are reported also in terms of time-averaged S-wave velocity ($V_{S,z}$), which is computed as:

$$V_{S,z} = \frac{z}{\sum_{i=1}^{N} \frac{H_i}{V_{S,i}}} \qquad (1)$$

where N is the total number of layers to a depth of z m. $V_{S,30}$ (where z = 30 m in Eq. 1) is the parameter used for seismic soil classification for simplified assessments of seismic site response in most modern seismic codes and in several Ground Motion Prediction Equations (GMPEs). Moreover, $V_{S,z}$ can be used to compare the expected site amplification for two different shear wave velocity profiles [17].

3 Invasive methods

The following section focuses on the invasive methods. After a brief description of the methods used in the InterPACIFIC project, the results of the different techniques and different teams are compared.

3.1 Methods

Cross-Hole (XH), Down-Hole (DH), P-S Suspension Logging (SL), and Seismic Dilatometer Test (SDMT) were used in the InterPACIFIC project. All of these methods are based on local measurements, which implicitly assume a 1D subsoil model and do not capture lateral variation.

3.1.1 Cross-Hole (XH)

XH methods are based on the measurement of the S- or P- wave travel-time between the source and one or two receivers (typically 3D geophones), which are located at the same depth in different boreholes (Figure 4). The seismic velocity is then computed as the ratio between the distance and the travel-time. High quality signals make it possible to accurately evaluate travel-times. As the interpretation technique is straightforward and does not require the solution of complex inversion processes, the reliability depends mainly on the accuracy of the measurement and in the precision of the instrumentation.

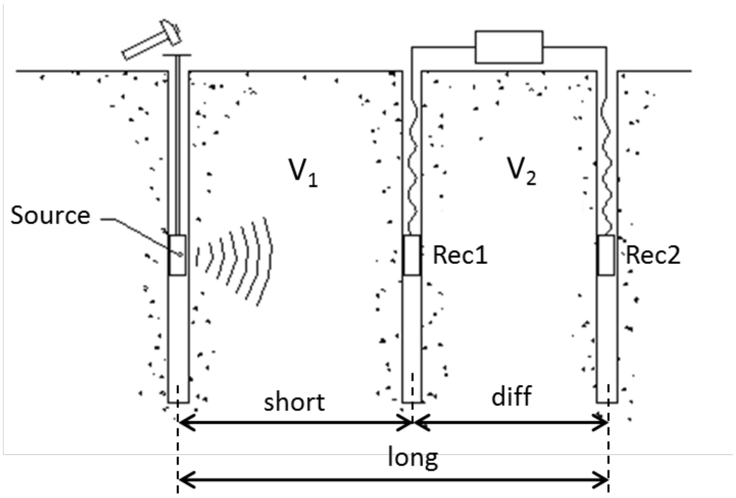

Figure 4 – XH scheme with three boreholes.

The main sources of experimental uncertainty in this method are related to: the determination of the first-break time (arrival time at the receiver); the evaluation of the distance between the boreholes as a function of depth; the accuracy of the triggering system, and the 1D layered model assumption. The latter means that the subsoil is assumed to be laterally homogeneous and that the detected first arrival is associated to a seismic wave travelling along the straight path from the source to the receiver. This assumption may fail when a strong contrast of mechanical properties occurs between adjacent layers and the critical refraction at the interface plays a significant role. The consequence is the generation of a head-wave that travels faster than the direct wave, leading to an overestimation of velocity. A methodology to avoid the critical refraction problem is reported in the standard ASTM D4428/D4428M-07 [18]. As far as the measurement uncertainty is concerned, Callerio et al. [19] showed that the uncertainty of the first break travel-time is quite constant with depth, while the uncertainty on the deviation assessment of boreholes increases with depth. As a consequence, the performance of a XH test heavily depends on the measurements of borehole deviation, which should be performed quite carefully, especially when also P-waves are of interest. Of all sources of uncertainty in XH testing, the accuracy of the trigger system is most critical. A faulty trigger may introduce a systematic error into all measurements. Usually the error is a delay on the activation of the source, leading to an underestimation of travel-time and hence an overestimation of velocity. Measurements are affected by this type of error when a two-borehole configuration is adopted. If three boreholes are used, the travel-time is estimated as the difference between the travel-time at the furthest and closest receivers, which eliminates any triggering error. For this reason the three-borehole configuration is preferred according to ASTM standards [18].

If three boreholes are available, three different estimates of the wave propagation velocities can be considered (Figure 4):

- XH-short: path between the source and the first receiver;
- XH-long: path between source and the second receiver;
- XH-diff: inter-receivers path. This is the value typically considered as the most reliable result, as the trigger time is not involved in the evaluation.

3.1.2 Down-Hole (DH)

In the Down-Hole (DH) test, one or more receivers are located in a borehole while the source is activated on the ground surface (Figure 5). Standards [20] and guidelines [21] are available for the execution and interpretation of the test.

In alternative configurations, the receivers are located in the rod of the Cone Penetration Test (Seismic Cone - SCPT) [22] or of the SDMT [23]. The DH measurements are collected during the penetration of the cone or of the dilatometer and no borehole is required. These approaches allow a significant saving of cost and time because boreholes typically have to be cased and grouted to avoid collapses and to guarantee a good coupling between the subsoil and the instruments.

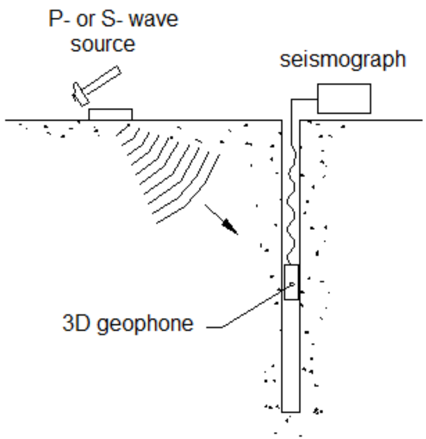

Figure 5 - DH scheme

In the interpretation it is necessary to take into account the travel path of the seismic wave as it is affected by the variability of the mechanical properties with depth. The interpretation can be performed with different methods:

- Interval method: the travel-time interval between two receivers is evaluated;
- Linear interpolation of the vertical travel time measurements over depth intervals (slope method);
- Inversion of the first-break travel-time with a model that takes into account the curvature of the seismic rays

The first method is conceptually the simplest one. It can either be performed using a true-interval (i.e., when two receivers are recorded at different depths simultaneously) or a pseudo-interval (i.e., when a single receiver is recorded incrementally at different depths). The true interval method is much preferred, but less commonly applied. Interval methods do not require any sophisticated interpretation technique and provide good resolution with depth. However the estimation is very sensitive to measurement errors, in particular those associated with the determination of the first-break travel-time. Because the two measured points are quite close to each other (usually 1 m), the difference of travel-times is quite small and the measurement error is magnified (particularly when using pseudo intervals). With the second method, the estimation is more robust but it is affected by the subjective model parameterization by the operator. Number and thickness of the layers are typically chosen on the basis of stratigraphic information from the borehole log and an assessment of the linearity of the trends of arrival travel-times with depth. The third method is more theoretically sound than the former, but the reliability of the solution is affected by the complexity of the inverse problem. Typically some form of regularization has to be introduced in order to force convergence of automated inversion algorithm and non-uniqueness of the solution can be a serious issue.

Kim et al. [24] conducted a comparative study to assess the reliability of the DH test. In this study, 6 operators acquired their own measurements in the same borehole and interpreted the data with both the linear interpolation and the curved-raypath inversion techniques. The analysts took into account the a-priori information available for the site to calibrate the discretization of the model. Consequently, the results of the linear-interpolation were in good agreement with each other. The operators adopted thin layers for the inversion to avoid a-priori assumptions on layering. As a consequence, a much larger scatter of the results was obtained with curved ray-path inversion than with linear interpolation. These results confirm the robustness of the linear interpolation technique, which gives more precise results (good repeatability), even if it is in principle less accurate (because resolution is affected by the interpolation over thick layers and ray curvature is neglected).

3.1.3 P-S suspension logging (SL)

The P-S suspension Logging (SL) system estimates the average seismic velocity of the soil surrounding a single borehole [25]. The SL is an interesting alternative to XH and DH measurements, as it allows investigations to significant depths with a single uncased borehole. The system consists of a single probe in which a source generates a seismic wave that travels in the vicinity of the borehole. The probe consists of two receivers located 1 m apart from each other and an underlying source (Figure 6). The probe is lowered down the borehole to characterize the subsoil at different depths. This technique requires the borehole to be filled with water. Uncased boreholes provide the best conditions for the measurements. The presence of casing reduces the signal-to-noise ratio, especially for steel casing. This technique can be used up to very large depths (hundreds of meters) as the source is always close to the receivers.

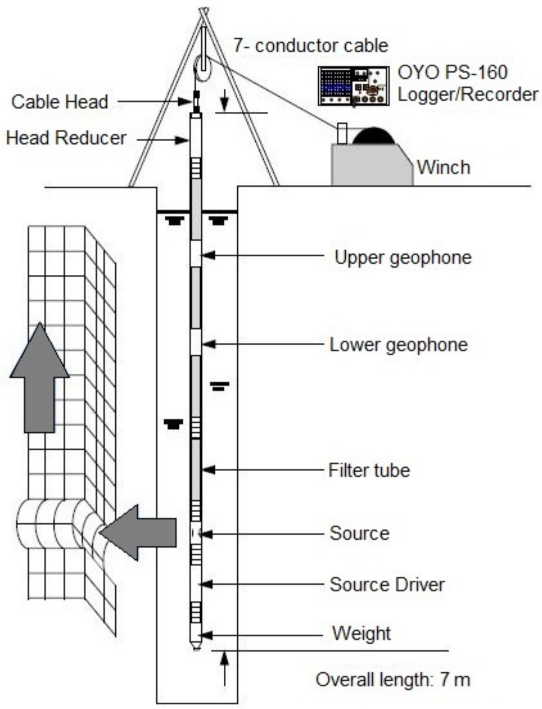

Figure 6 – P-S Suspension logging scheme [26]

3.2 Results

At all three sites, three different companies performed in-hole measurements (addressed as Team 1, Team 2 and Team 3 in the following). Each company performed XH and DH measurements with their own equipment. Additionally, Team 1 performed the S-wave velocity DH measurements at each site using two different orientations of the iron beam seismic source (East-West EW and North-South NS). The SL testing at each site was performed only by Team 1. They analysed the direct travel-time between the source and the first receiver (SL S-R1) and the differential travel-time between the two receivers (SL R1-R2). For all the three sites, a team of the University of Texas at Austin (Team 4 in the following) re-interpreted the DH experimental data acquired by Team 1, providing an alternative estimate of wave propagation velocity profiles.

Additional invasive measurements were performed at Mirandola by other participants including: a team from Università di Torino and Politecnico di Torino (UniTo-PoliTo) who acquired and interpreted both XH and DH data (Team 5 in the following); results from a XH survey were made available by Regione Emilia Romagna (RER, the Local Territorial Authority); and the Istituto Nazionale di Geofisica e Vulcanologia (INGV, National Institute of Geophysics and Volcanology of Rome, Italy) performed a SDMT.

A specific quality control assessment has been performed on the in-hole data, as outlined in the following section. Nevertheless, the scope of the present paper is to quantify uncertainties resulting from typical practice and not to assess the best practice.

3.2.1 Quality control of borehole measurements

Each team was responsible for the choice of the most appropriate equipment and testing procedure based on the site conditions and local geology. A site-by-site data quality control was performed in order to validate the results provided by the different teams. A discussion of the best testing equipment and procedures is not included, as the scope of the present study is to assess the uncertainty associated with the state of the practice. For this same reason, no attempt is made to determine the most reliable result for each site. Only the most relevant findings of the data quality control are discussed in order to justify the discarding of any dataset clearly affected by gross errors.

Several issues that can adversely impact the invasive test results were considered in the quality control study. For example, tube wave effects can corrupt the downhole data. Furthermore, XH results are very sensitive to the accuracy of the deviation survey, which is performed to monitor the distance between boreholes at depth. These issues adversely impact the raw data and cannot be corrected after testing is complete. Conversely, analysis issues such as the picking of arrival times (first-breaks) or the layering in the downhole interpretation can be mitigated by repeating the analysis of the data.

The most relevant issue was observed with respect to the DH surveys. Figure 7 shows an example (Grenoble site) of the picking of first arrival travel-time of the downhole data performed by the three teams. Note that the two traces shown at each depth correspond to the source impacts in the left and right directions, which should show opposite phase polarity upon the first arrival of the S-wave. The two S-wave seismograms on the left and central panels of Figure 7 show a clear reversal in phase polarity of S-waves corresponding to shots in left and right directions, and the picking is coherent with this wave opposition. The seismograms of the team on the right panel of Figure 7 show that the opposite phase polarity was not exploited and the picking is inconsistent with the other two teams (e.g., arrival time of approximately 50 ms at 50 m depth versus approximately 150 ms for the other two teams). The downhole results provided by this team were clearly affected by a gross error, which was likely caused by recording tube waves in the borehole. Thus, the shear wave velocities provided by this team are actually tube waves and largely overestimated. This inconsistency was also observed at the Mirandola and Cadarache sites. Tubes waves can typically be avoided by pumping the water out of the top 10-15 m of the borehole prior to DH testing. Furthermore, if due diligence were performed when analysing the data such results would be discarded since velocities much higher than expected values for soils were obtained. For these reasons, the DH results from this team are shown in the figures below, but are not used in the calculation of statistics to quantify the variability in results presented in the following sections.

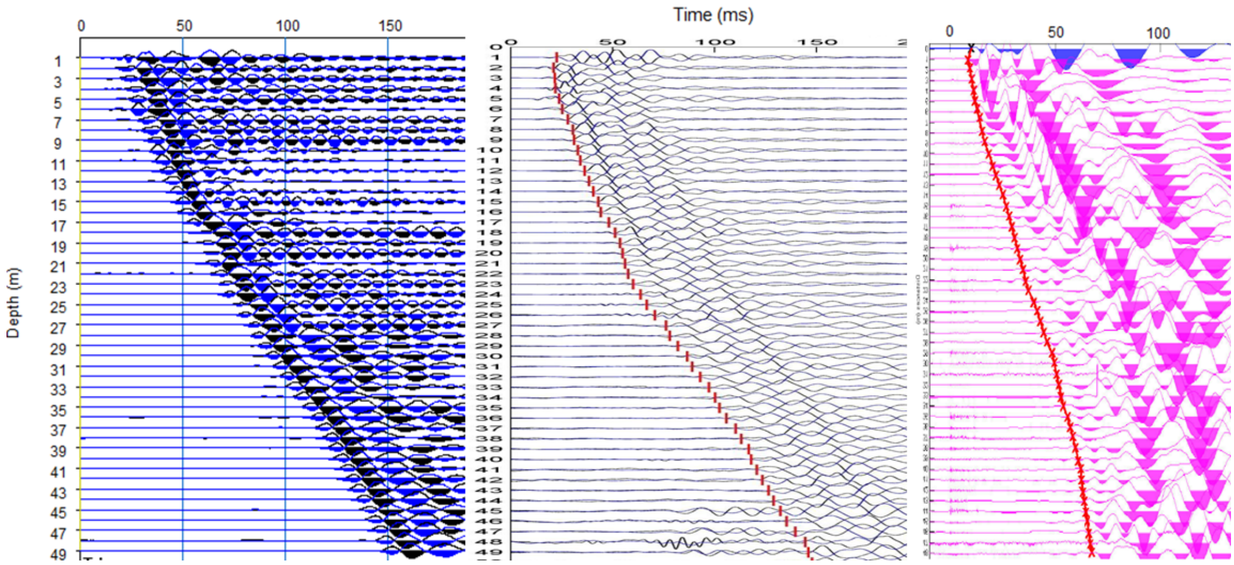

Figure 7 – Grenoble Site downhole data: raw data and first arrival picks. Each panel corresponds to one team.

3.2.2 Inter-method comparison

XH and DH are the most popular invasive methods in practice. This section considers the intra-method variability between these two methods.

The Vs results obtained from DH and XH tests at Mirandola are presented in Figure 8. The absolute Vs values are in very good agreement over the entire investigation depth (Figure 8a), neglecting the DH Vs profile that was mistakenly obtained from tube waves, as discussed above. The variability in Vs results was quantified using the coefficient of variation (COV) (Figure 8c). It should be noted that the COV values are limited by relatively small sample sizes, as shown in Figure 8d by the number of profiles as a function of depth. Nonetheless, the COV values are still a valuable indicator of intra-method variability even though the absolute values may not be completely accurate because of the small sample size used to calculate the statistics. While the COV values are slightly higher for the DH results, both DH and CH results generally have COV values less than 0.1 over the top 50 m and less than 0.2 down to approximately 100 m. Considering that low energy sources were used for the DH excitation (i.e., the horizontal strike of a sledgehammer on a beam), the results show that DH tests can provide reliable results up to large depths with minimal loss of precision.

Specific features of the V_S profiles were well detected by both DH and XH methods (see for example the interfaces at 8 and 25 m and the slight velocity increase at 40 m depth). Two velocity reversals in V_S distribution (slow layers) were identified by all the XH and most of the DH results at 48- and 65-m depth. The Pleistocene bedrock was consistently identified by DH methods at 112-m depth, while the XH profiles show a gradually increasing S-wave velocity, between 112 and 120 m. The $V_{S,z}$ values (Figure 8b) for all profiles are very similar, excluding the XH results obtained by Team 1, which have significantly lower $V_{S,z}$ values due to a much softer surface layer that is approximately 3-m thick. This relatively thin, soft layer right at the surface has a very strong impact on the Vs,z results. The $V_{S,z}$ results at 30 m (i.e., $V_{S,30}$) range from approximately 185 to 230 m/s. $V_{S,30}$ values are discussed in more detail later in the paper.

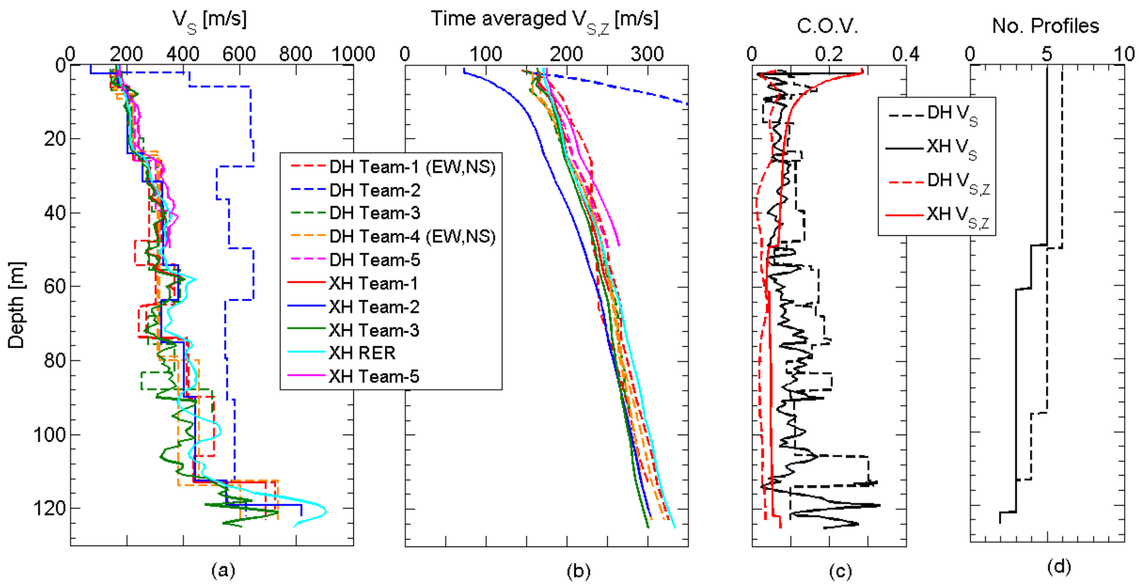

Figure 8 - Mirandola: comparison between XH (solid lines) and DH (dashed lines) results. (a) V_S profiles, (b) time-averaged Vs profiles, (c) variability within each method expressed as COV values and (d) number of profiles.

At Grenoble, almost all DH results (Figure 99a) identify a soft layer at the surface that increases from roughly 200 to 400 m/s at 2-3 m. However, the XH methods do not identify this soft surface layer. In the authors' experience, DH tests are often less accurate in the top 2-4 m due to unknown wave propagation paths from the surface source to the borehole receiver. As the receiver is advanced deeper in the borehole, the fastest wave travel path is less uncertain (i.e., approximately vertical). In this depth range, the COV reaches roughly 0.35 for the DH results and 0.2 for the XH results (Figure 9c). At a 17m depth some of XH results show a thin low-velocity layer (about 3 m thick). This layer is also identified by 3 of 5 DH results. At 25m depth a thicker lower-velocity layer is identified by both XH and DH methods. This layer is roughly 11m thick and both methods provide very high precision in the estimate of the location and velocity of this layer, with COV. values below 0.05. The decrease of the variability is clearly associated with the transition from coarse-grained soils to fine-grained soils (see Figure 2). Considering that as depth increases, the error associated with the verticality survey is expected to increase (see [20] for an example), the improvement in precision is very likely associated with better quality signals.

Below the low-velocity layer the results are still in good agreement and the COV is generally below 0.10. It is interesting to note that the variability of the XH results is greater than or equal to that of the DH results over the majority of the exploration depth. Also, a larger variability was observed in the top part of the profile (top 25 m). This is likely due to the significant level of background noise at the site, which strongly affects the determination of first breaks in the signals both for XH and DH tests. Indeed, the site is very close to a main motorway and several pieces of heavy equipment in the research facilities induce high levels of background noise, especially in the high frequency range. These vibrations are particularly significant close to the ground surface as they are mainly associated with surface-wave propagation.

The $V_{S,Z}$ values (Figure 9b) for all profiles at Grenoble show significantly more scatter than those for Mirandola (refer to Figure 8b). Much of this variability is caused by differences in Vs over the top 5 m. While the Vs profiles are very similar below 5 m, the impact of these differences on $V_{S,Z}$ is observed significantly deeper. The $V_{S,Z}$ results at 30 m (i.e., $V_{S,30}$) range from approximately 325 to 450 m/s. $V_{S,30}$ values are discussed in more detail later in the paper.

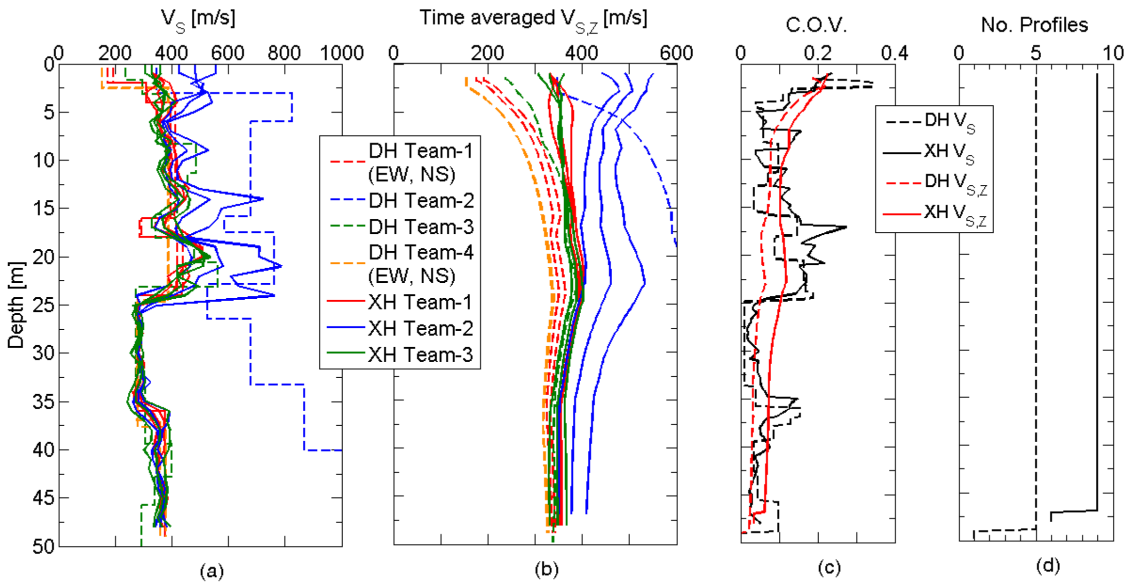

Figure 9 - Grenoble: comparison between XH (solid lines) and DH (dashed lines) results. (a) V_S profiles, (b) time averaged Vs profiles, (c) variability within each method expressed as COV values and (d) number of profiles.

At Cadarache, most XH results (

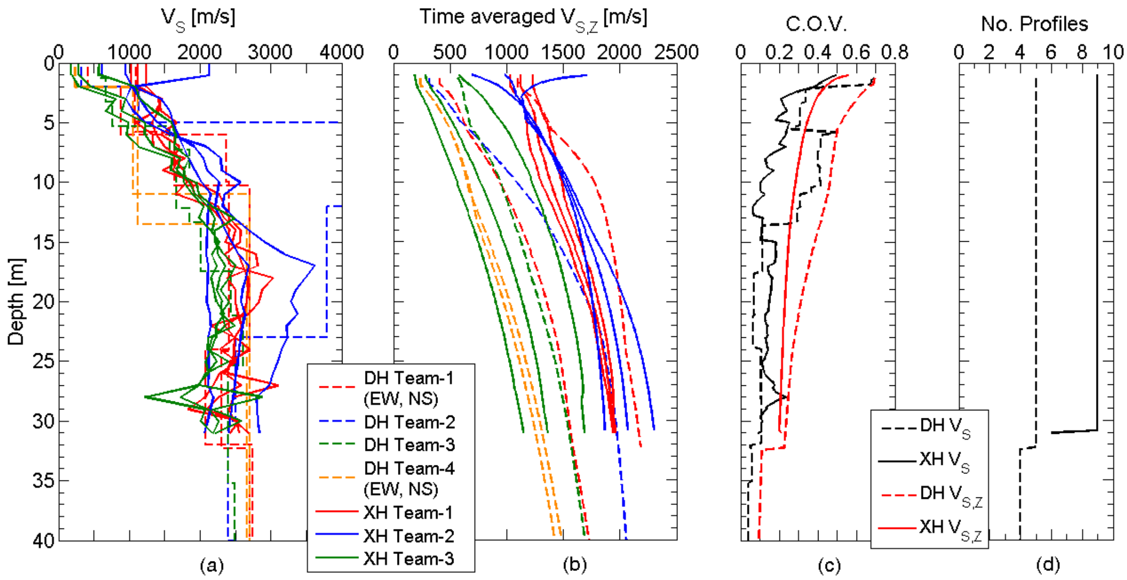

Figure 10a) show a gradual increase in Vs until 13-m depth. The DH results, which are based on the assumption of a layered model, exhibit significant variability over this depth range. This could be due to complicated wave propagation paths in the near-surface caused by fracturing/weathering of the limestone, which presumably reduces with depth. As noted above, DH tests in the near-surface may be less reliable due to complicated wave paths that are difficult to predict/account for during analysis. The COV values for both XH and DH (Figure 9c) are very high at the surface, approaching 0.5. However, the COV values for the XH results fall below 0.2 at depths greater than about 7 m, while the DH COV values do not fall below 0.2 until approximately 13 m. In general, the near-surface COV values at Cadarache are significantly greater than those at the two soil sites discussed previously. And, all analysts who processed the borehole and surface wave data noted how much more complicated the data analysis was at the rock site versus the two soil sites. These observations underscore the difficulties associated with high-quality site characterization of rock sites, particularly over the top 10 m of the subsurface, where weathering effects are greatest. For depths greater than 13 m, both methods detect an S-wave velocity that predominantly varies between 2000 and 2800 m/s. Over this depth range, the COV is higher for the XH results than for the DH results, which is due in large part to the presence of a single outlier in the XH results (recalling that the DH results by Team 1 were omitted from the COV calculations). .

The $V_{S,z}$ values (Figure 10b) for all profiles at Cadarache show significant scatter due to the differences in Vs over the top several meters. Again, these differences in the near surface Vs have a significant impact on the $V_{S,z}$ values due to the depth-averaging effect of the $V_{S,z}$ calculation. The $V_{S,z}$ results at 30 m (i.e., $V_{S,30}$) range from approximately 1,100 to 2,300 m/s. $V_{S,30}$ values are discussed in more detail later in the paper.

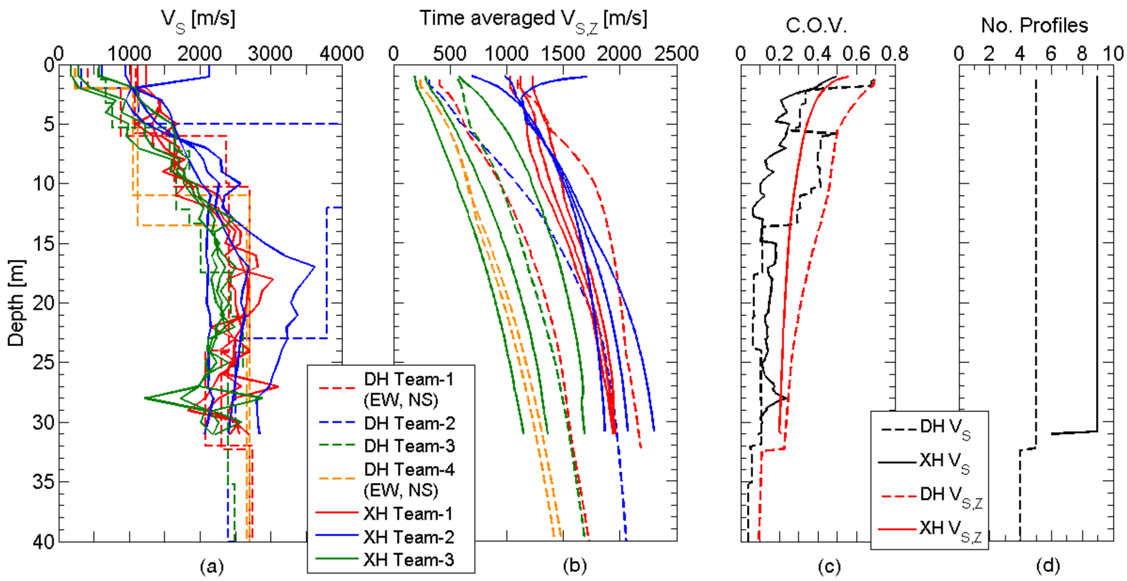

Figure 10 - Cadarache: comparison between XH (solid lines) and DH (dashed lines) results. (a) V_S profiles, (b) time averaged Vs profiles, (c) variability within each method expressed as COV values and (d) number of profiles.

For SL, only a single realization and interpretation of the tests are available at each site, preventing an assessment of intra-method variability and, hence, precision of the method. In order to assess the accuracy, we compare the SL results with the mean V_S profiles of the populations of XH and DH results in Figure 11. For the SL, both estimates (source to first receiver, S-R1, and receiver-to-receiver, R1-R2) provide V_S profiles very similar to those from the XH and DH methods. In particular, at Mirandola the SL was able to detect the interfaces at 25-m (Figure 11b) and at 112 m (Figure 11a) detected by the XH and DH. However, the most significant contrast in the SL Vs profiles at Mirandola is a high-velocity layer at 73 m, which was detected only by the SL. From a lithological point of view, this stiff anomaly is apparently at odds with the stratigraphic log for the site, which does not indicated any type of material that would be expected to have a Vs of 600-700 m/s (Figure 1). At Grenoble (Figure 11c), the two low-velocity layers at 15 and 25 m were detected with the SL. However, the SL Vs profiles have lower Vs values than the XH and DH results from about 3-7 m. At Cadarache, the SL results are in quite good agreement with the XH and DH Vs at most depths, with slightly higher values between 12-22 m (Figure 11d). Interestingly, the SL and XH tests reveal a lower-velocity layer starting at about 24 m, where a more fractured limestone and clay layer was observed in the stratigraphy (Figure 3).

The SDMT was performed only at Mirandola and was located in the vicinity of the boreholes. Only the topmost 18 m were characterized (Figure 11b) and the obtained V_S profile is in very good agreement with the other invasive results.

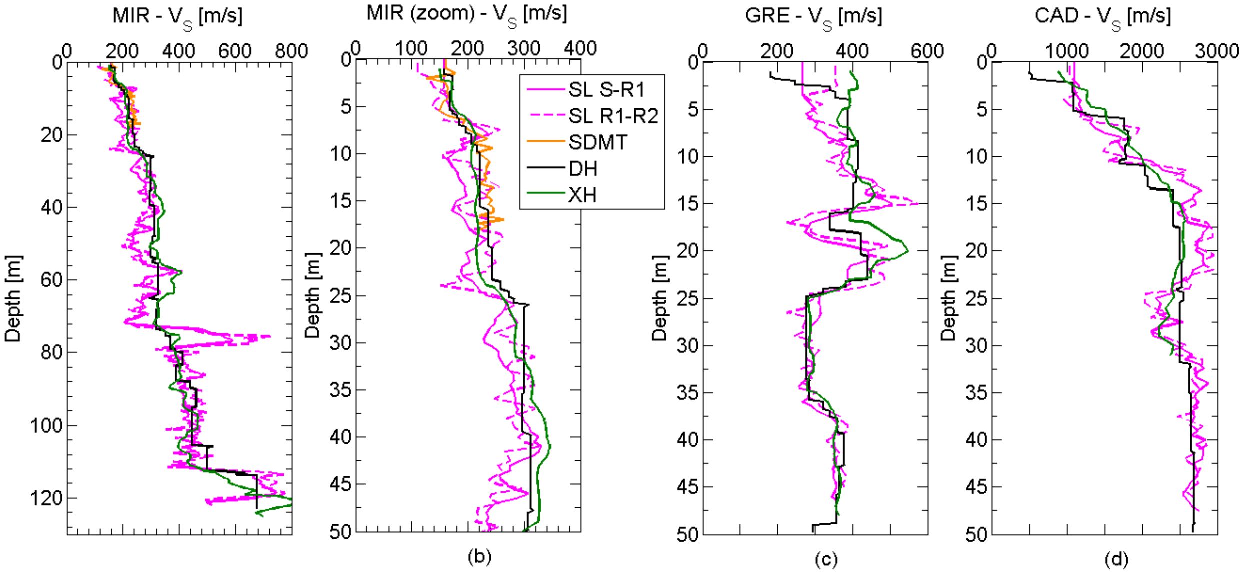

Figure 11 - Comparison of mean V_S profiles from XH and DH results with Vs profiles obtained using SL and SDMT at Mirandola (MIR; a,b), Grenoble (GRE; c), and Cadarache (CAD; d).

Figure 12 shows the comparison of $V_{S,30}$ estimated from the population of results from XH, DH and SL. At Mirandola, the $V_{S,30}$ estimated with the three methods are quite similar to each other. At Grenoble, similar results are obtained with SL and DH (Figure 12b), however, the $V_{S,30}$ estimated with XH is, on average, slightly higher than the other methods (Figure 12a and c). At Cadarache, the SL $V_{S,30}$ is quite similar to the XH, but both SL and XH Vs,30 values are higher than the DH result. In Figure 12 the results of Jung et al. [1] are also reported. The authors conducted a comparative study of invasive methods in two different environments: a natural soil deposit and a shallow embankment. With the exception of the Cadarache site, the Vs,30 results between invasive methods from this project are generally in better agreement than those presented by Jung et al (2012).

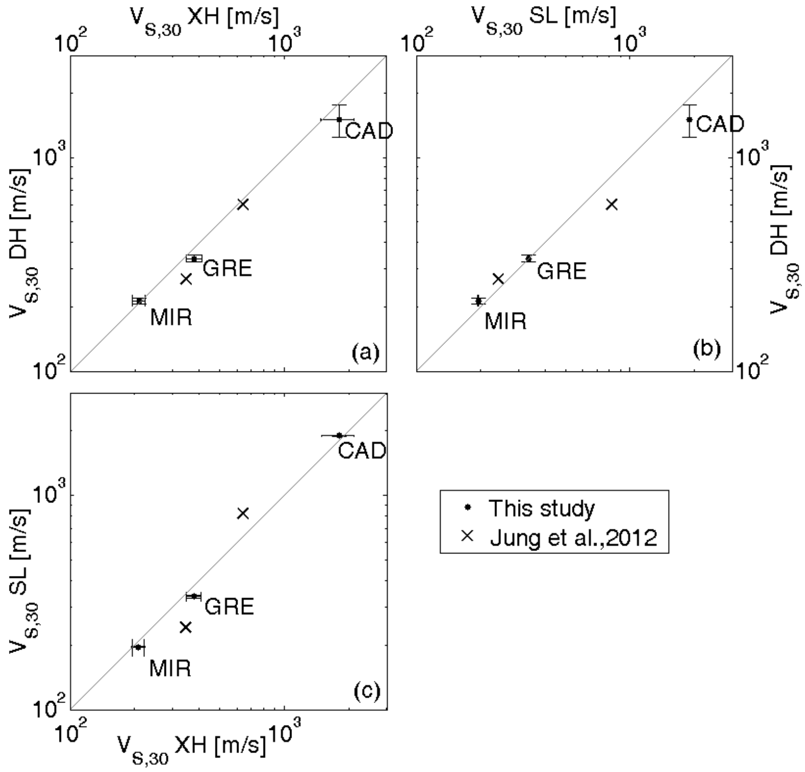

Figure 12 - Comparison between $V_{S,30}$ estimated with Cross-Hole ($V_{S,30}$ XH), Down-Hole ($V_{S,30}$ DH) and suspension logging ($V_{S,30}$ SL) methods: a) XH-DH; b) SL-DH; c) XH-SL.

3.3 Discussion of invasive results

Invasive tests were performed by a limited number of teams at a limited number of sites. Thus, the information presented below must be viewed in that light. Moreover, each team performed the measurements with their own equipment; hence, the observed trends are a combination of instrumental precision and analyst ability.

As depth of investigation increases, the DH method is sometimes considered to be less reliable (because the wave travels from the surface) than the XH method (because the wave consistently travels for only a few meters from one borehole to another). However, in general, this study demonstrates similar variability, as estimated using COV values, for XH and DH Vs profiles. Even at Mirandola, where COV values for DH were slightly higher than those for XH at depths greater than 30 m, it was possible to identify the deep interface at 112m via DH and the Vs were in very good agreement with the XH and SL, whose measurements are based on a very local wave travel path. Moreover, at Grenoble and Cadarache, the intra-method COV of XH results actually exceeds the COV from the DH results over the majority of the investigation depth. This means, on the basis of a limited sample, that the DH results are equally, and sometimes more, precise than XH results. The exception to this broad statement is for the top few meters of the subsurface, where the DH results can sometimes suffer from assumptions made about the wave propagation path, as discussed above.

An interesting trend in terms of precision is observed at Grenoble (Figure 9), where the transition from coarse-grained soils to fine-grained soil is clearly associated with a significant improvement in precision for both the cross-hole and down-hole tests. The improvement is particularly marked for the soft clay (low-velocity layer), for which the agreement between different results is remarkable, with COV values lower than 0.05. Moreover, for the same layer, the very good agreement between XH and DH results suggests that the estimates are very accurate.

4 Comparison between surface-wave and borehole methods

In this section we compare the V_S profiles at each site obtained from invasive and non-invasive methods. In particular, the non-invasive results were obtained from the analysis of surface-waves. The details on the adopted surface wave methods, the participating teams and the results are discussed in Garofalo et al. [14]. While some of the variability in Vs profiles derived from surface wave testing at these three sites is caused by dispersion/data processing, it is primarily due to choices made during parameterization and the non-uniqueness of the solution of the surface-wave inverse problem [14].

4.1 Results

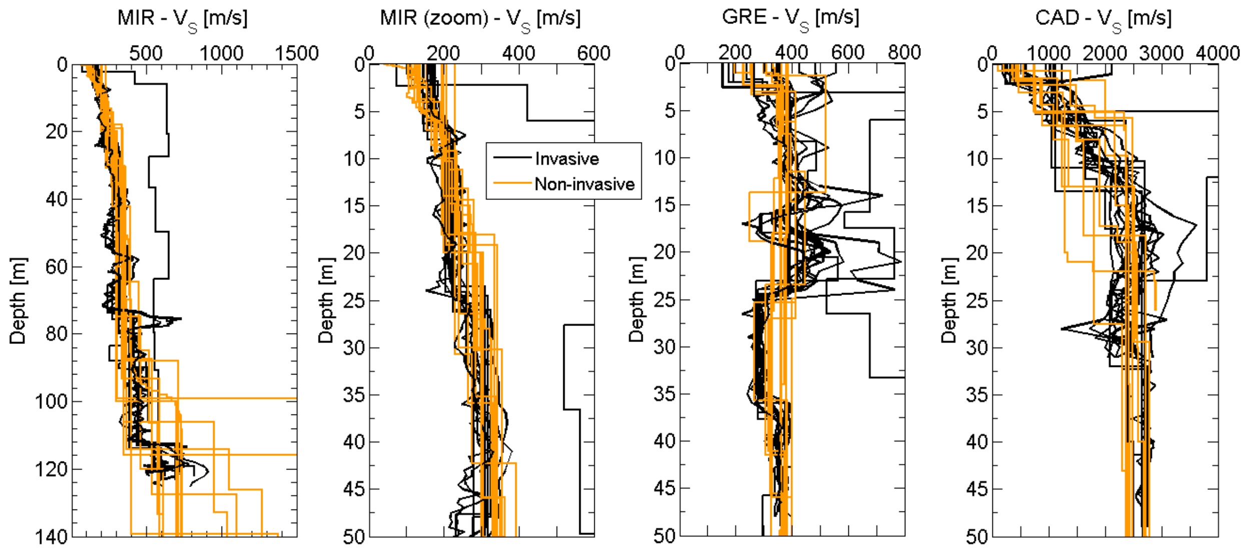

Figure compares the invasive and non-invasive Vs profiles for all the three sites. Figure distinguishes the non-invasive profiles obtained using only passive surface wave data (i.e., more band-limited) from those obtained using a combination of both active and passive data.

At Mirandola, the Vs profiles obtained from invasive and non-invasive methods agree remarkably well clear down to 90-100 m (Figure 13a and 13b). Nevertheless, there are a few differences. For example, at shallow depths some profiles developed solely from passive data do not capture the increasing trend in S-wave velocity as a function of depth and only show a single layer of uniform velocity until roughly a depth of 15 m (Figure b). This at odds with most of the non-invasive results obtained by those who used both active and passive surface wave data and all of the invasive methods, which indicate thinner layers and more gradually increasing Vs as a function of depth. Additionally, some invasive methods were able to identify two slightly lower-velocity layers at depths of approximately 48 and 65 m, while most of the surface-wave Vs profiles show a constant layer in that portion of subsoil. Another interesting feature of the S-wave velocity profiles is an interface that was detected between 20 and 26 m by invasive methods, and between 13 and 30 m by surface-wave methods. The interface of the bedrock at Mirandola, which is expected at approximately a 112 m depth, is well detected by invasive methods, but not so well

by non-invasive methods (

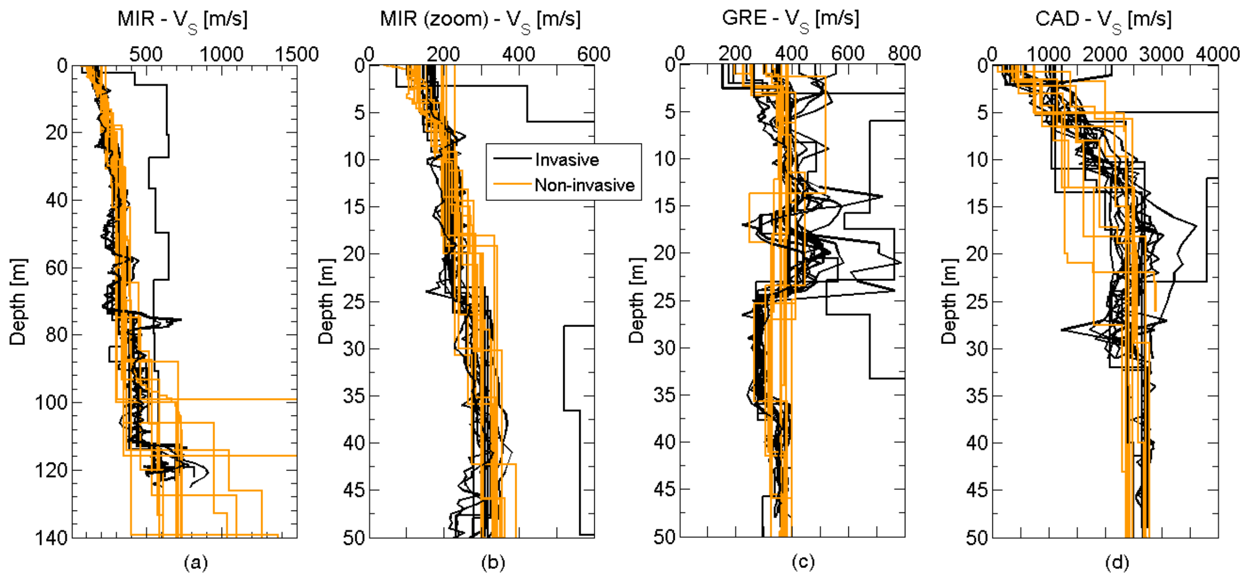

Figure a). The non-invasive profiles show a high velocity contrast, but the depth of this interface ranges from 90 to 120 m, while the variability of this contact based on invasive results is between 110 and 115 m. The estimation of the S-wave velocity of the bedrock is 780 +/- 370 m/s and 690 +/- 210 m/s for non-invasive and invasive methods, respectively. If one considers which experimental surface-wave data was analysed (Figure a), it becomes clear that most profiles derived from a combination of active and passive data show an interface that is in better agreement with the invasive results. On the other hand, some profiles developed using only passive data overestimate V_S, with some values exceeding the upper bound in Figure a.

At Grenoble (

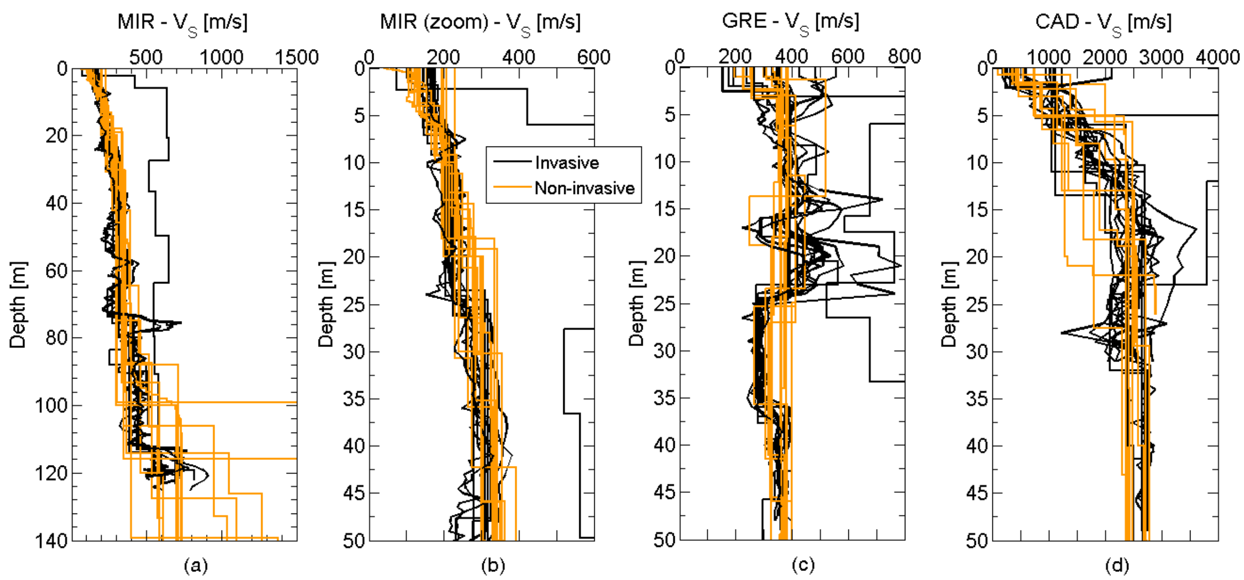

Figure c) three distinct features were detected by the invasive methods: a very shallow interface at around 2 m and two low-velocity layers at depths of 17 and 25 m. These details are not identified by most of the purely passive results (Figure c), which show nearly constant values until 50 m depth. On the other hand, the shallow interface was better described by both invasive and combined active and passive profiles. At roughly 17 m, all invasive profiles exhibit a low-velocity layer, while only one of the non-invasive profiles shows this layer. The second low-velocity layer is identified to be between 25 and 37m by all invasive profiles. Five non-invasive profiles derived from a combination of active and passive data detect this low-velocity layer, although the velocity and depth ranges vary more significantly (Figure c).

At Cadarache (13d) a very shallow bedrock was expected, but the interface was not clearly identified by any method. Both surface-wave analyses and DH tests, which are interpreted on the assumption of a layered model, show high variability with the interface depth ranging from from 2-21 m. Again, the non-invasive results were grouped by those who analysed only passive data and those who analysed both active and passive data (14c). The purely passive profiles show higher velocities over the top 15 m, while most of the combined active and passive profiles exhibit lower velocity values in the same depth range. The invasive results lie in the middle of the two trends identified by the non-invasive profiles. A few of the combined active and passive Vs profiles significantly underestimate the Vs between 15-25 m. The invasive and non-invasive results generally agree quite well below about 25 m.

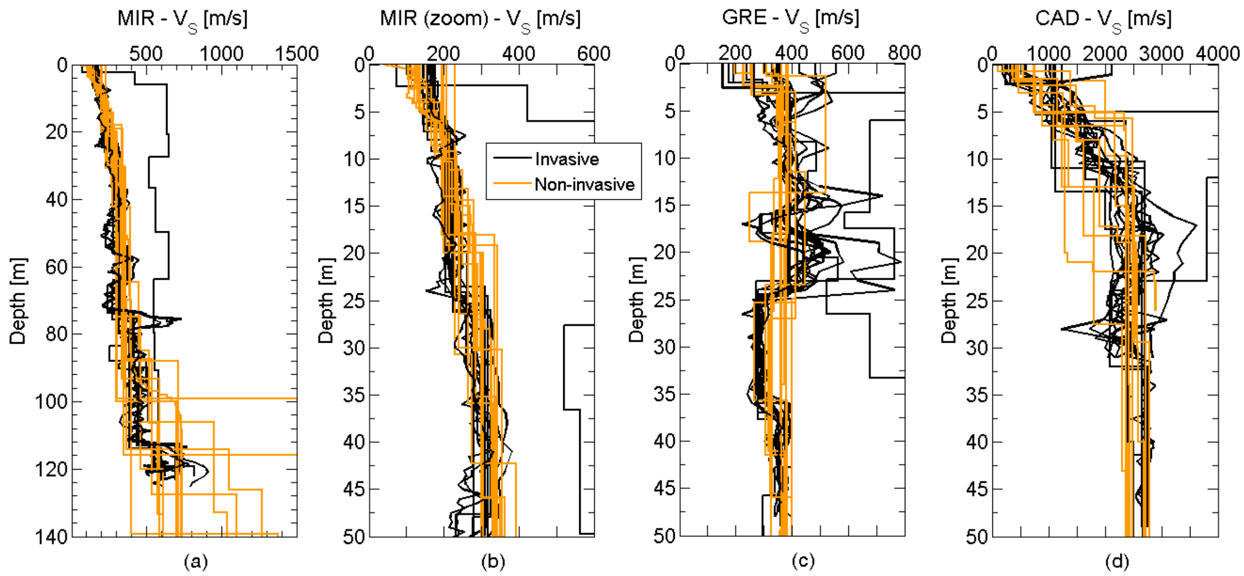

Figure 13 - Comparison of Non-Invasive methods and Invasive methods including XH, DH and SL for all the three sites: Mirandola (MIR; a and b), Grenoble (GRE; c), and Cadarache (CAD; d).

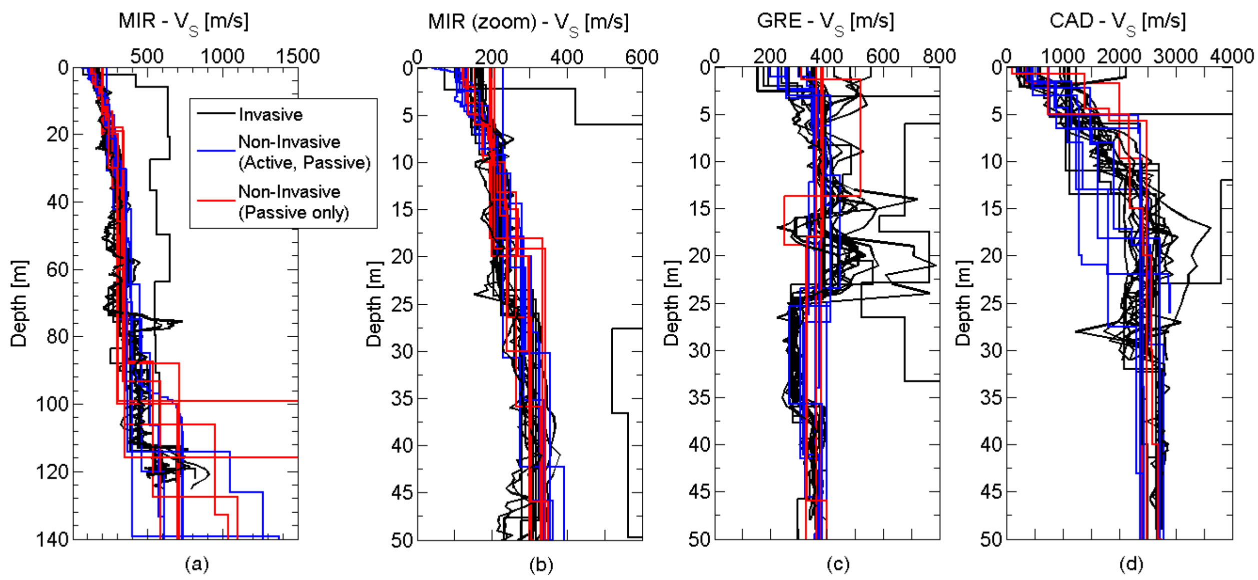

Figure 14 – Discrimination in the non-invasive results between those profiles estimated by analysing only passive data and those utilizing the combination of active and passive data for Mirandola (MIR; a,b), Grenoble (GRE; c) and Cadarache (CAD; d).

The remainder of the paper only considers two distributions of results: invasive and non-invasive. The populations are insufficient to perform a rigorous statistical analysis, however, the COV was computed as function of depth for each population of data and plotted in Figure 15. At all three sites, the variability of the invasive and non-invasive profiles is quite similar and is generally less than or equal to a COV of 0.20 over most depth ranges. Furthermore, over certain depth ranges at each site, the COV of the non-invasive results is actually less than the COV of the invasive results. However, significant differences in COV can be observed below approximately 80 m at Mirandola (Figure a). While the COV of the invasive results is relatively constant below 80 m, with values between 0.10 to 0.25, the COV associated with the non-invasive results continuously increases with depth and reaches values greater than 0.8. This results from the challenge of accurately resolving the depth and velocity of the bedrock when using surface wave methods. While some surface wave analysts resolved the depth and velocity quite well (Figure 14a), many did not. At Cadarache the variability associated with both invasive and non-invasive profiles is highest in the shallow part of the subsurface where the bedrock is highly weathered (Figure 15d).

It is also interesting to assess the variability of the different results as function of depth as the ratio between the maximum and the minimum (max/min ratio) V_S values of each population of results (Figure 16). This ratio can indeed be considered a more significant parameter than the standard deviation of the results for two reasons: for one, because the population is not statistically significant; then also because each profile is potentially the outcome of a site investigation, hence the distance between minimum and maximum is a clear representation of the possible range of values. For the three sites the variability is quite similar between invasive and non-invasive tests and it is lower or equal to 1.5 almost everywhere, except close to the ground surface. In Mirandola the variability for non-invasive results reaches values greater than 3 at high depth, whereas the one for invasive results is quite constant around 1.5 up to 125 m depth. In Cadarache the variability of both invasive and non-invasive results is quite high at shallow depth.

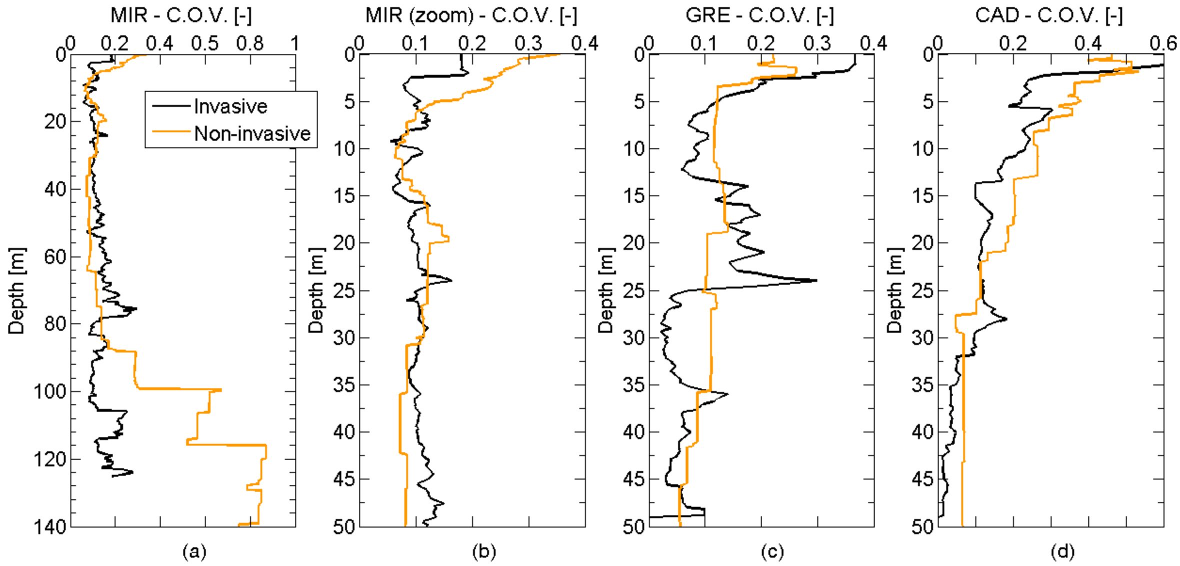

Figure 15 – Comparison of invasive and non-invasive Vs COV values as a function of depth at Mirandola (MIR; a,b), Grenoble (GRE; c) and Cadarache (CAD;d).

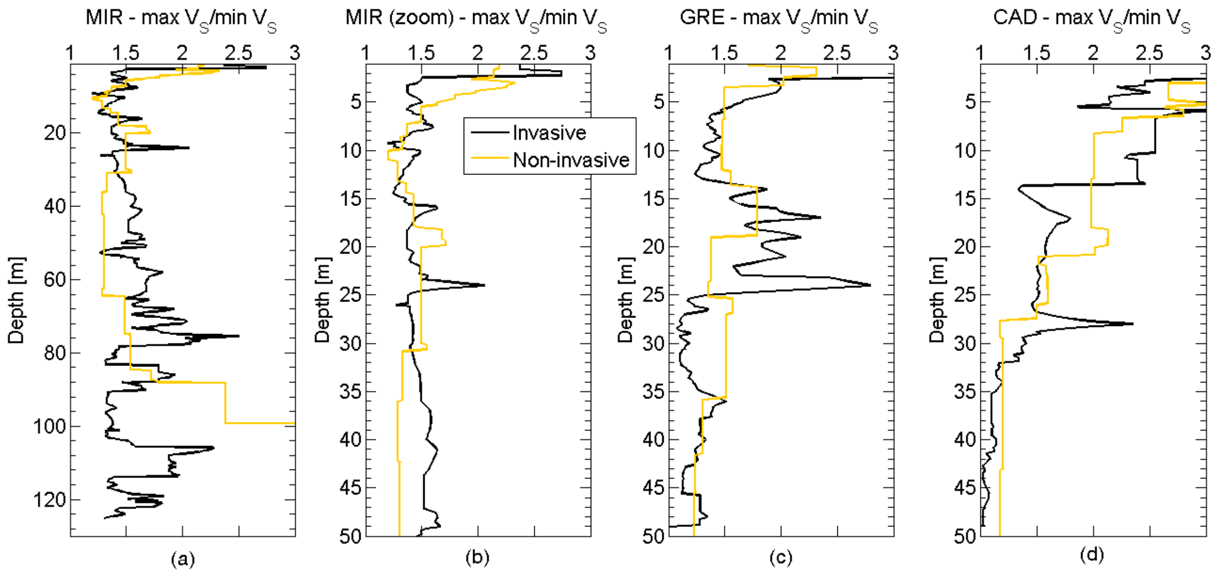

Figure 16 – Comparison of invasive and non-invasive Vs variability as a function of depth at Mirandola (MIR; a,b), Grenoble (GRE; c) and Cadarache (CAD;d).

A similar comparison of invasive and non-invasive results is reported in terms of Vs,z in Figure 17, with corresponding Vs,z COV values in Figure 18. At all the three sites, despite the large variability of Vs,z at shallow depths, at the reference depth (*z* = 30 m), the Vs,30 values are, on average, quite similar to each other. For example, consider the simple statistics detailed in Table 1. For each class of methods (invasive and non-invasive) the mean, standard deviation (std) and coefficient of variation (COV) of $V_{S,30}$ are provided. At all three sites, the mean values of Vs,30 for invasive and non-invasive methods are within 4% of one another. Furthermore, the COV of $V_{S,30}$ is quite small and similar for the invasive and non-invasive results at Mirandola and Grenoble. Conversely, the COV of the invasive results at Cadarache is nearly twice the non-invasive COV and both values are larger than those for the soil sites. As mentioned above, it is important to emphasize that rock sites like Cadarache can be very difficult to characterize for both invasive and non-invasive methods.

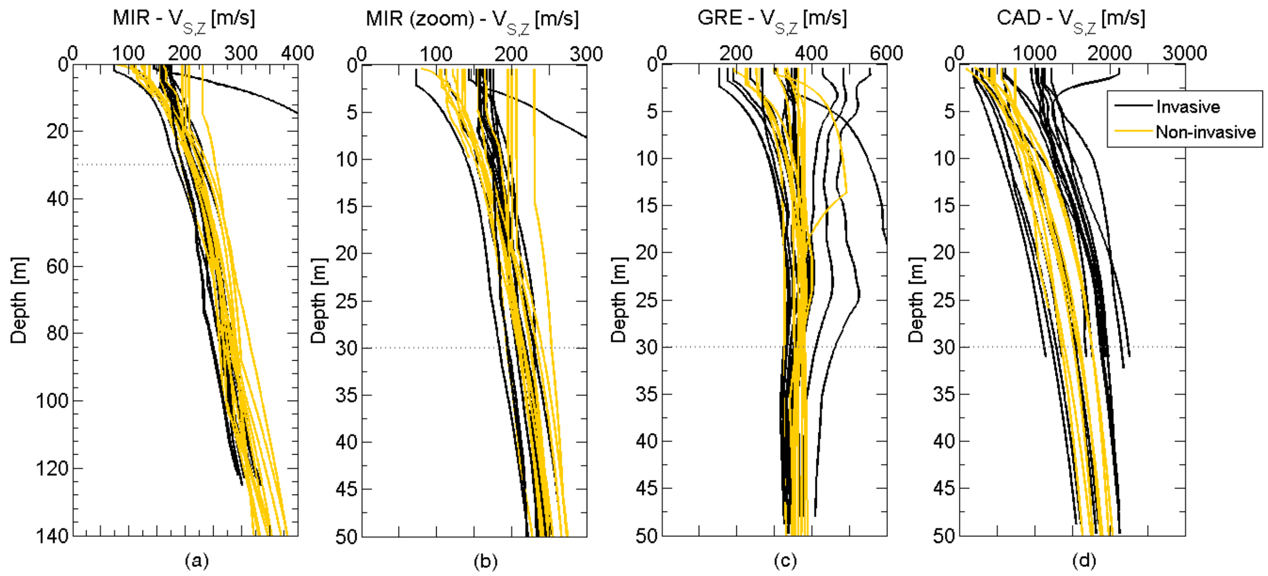

Figure 17 - Time-averaged S-wave velocity in Mirandola (a,b), Grenoble (c) and Cadarache (d).

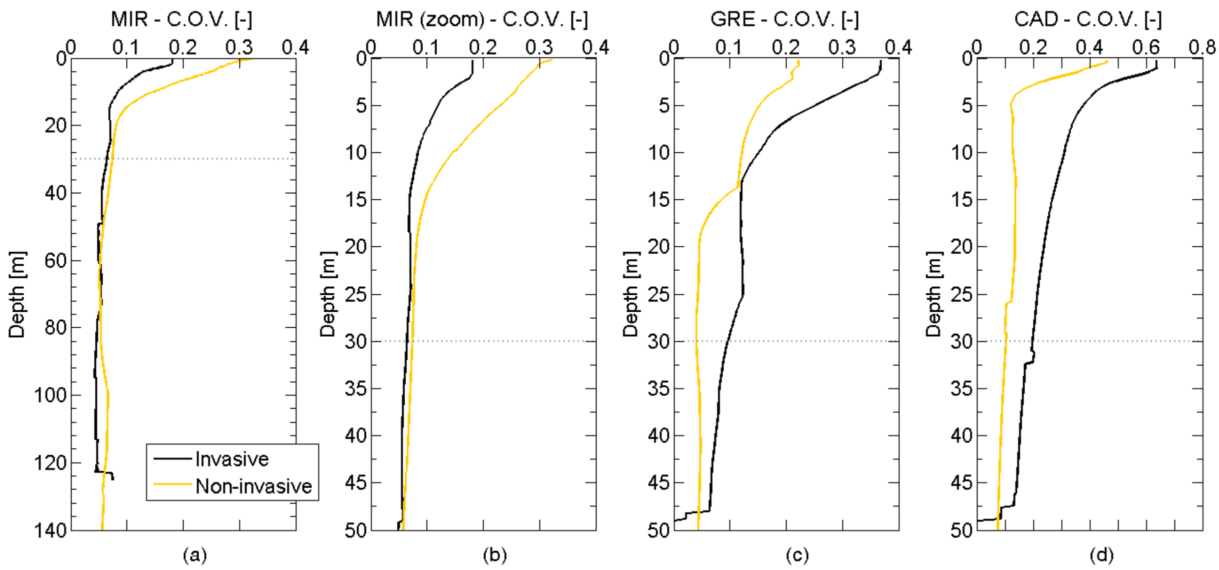

Figure 18 - Inter-method variability of the results: C.O.V. of the time-averaged S-wave velocity distribution. Mirandola (a,b), Grenoble (c) and Cadarache (d).

Table 1 – Statistics of $V_{S,30}$ estimated with different methods.

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	361	32.0	0.089
	Non-Invasive	363	14.6	0.040
Cadarache	Invasive	1656	301	0.182
	Non-Invasive	1591	168	0.106

The $V_{S,30}$ values obtained from both invasive and non-invasive results for the three sites are compared to other results from the literature [9, 27, 10, 24] in Figure 19. Within the InterPACIFIC project, we are able to propose error bars for both invasive and non-invasive methods. The comparison shows that $V_{S,30}$, estimates are robust and can be considered accurate since both classes of methods provide similar values.

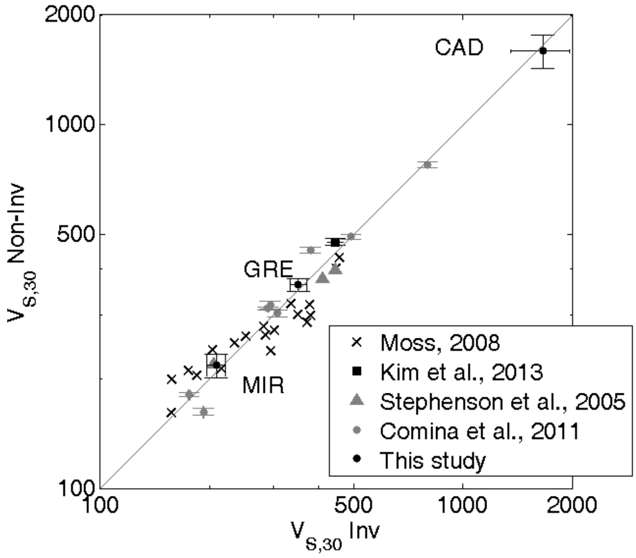

Figure 19– Comparison of $V_{S,30}$ values from invasive and non-invasive methods in this study (InterPACIFIC) and others found in the literature.

4.2 Discussion

In the shallow subsurface (i.e., depths < 30 m) investigated by both invasive and non-invasive methods, the agreement between Vs profiles is generally very good. Despite the ability to detect subtle stratigraphic details, a relatively large, and perhaps surprising, variability in the invasive results was observed. The variability is more significant for the Grenoble and Cadarache sites. This may be explained by the noisy environment at Grenoble and the challenging wave propagation conditions at Cadarache due to the presence of weathered rock. . Furthermore, at rock sites such as Cadarache, uncertainties in time estimates are in principle expected to be more significant as the measured wave propagation travel-times are much smaller. Both sites represent critical conditions in which the choice of appropriate equipment and experimental protocols are absolutely necessary to get reliable results. On the other hand, the different invasive methods were generally able to detect specific features, such as low-velocity layers and gradually increasing velocity, at all three sites.

The Vs profiles derived from surface wave methods can show a higher variability than the invasive results, but they can also show less variability, depending on the depth and site conditions. Moreover, some features like the bedrock interface at Mirandola and the low-velocity layers at Grenoble, may not be uniquely identified or may be missed completely. The most expert surface wave analysts can resolve these features better than others. However, it should be noted that all participants in the InterPACIFIC project would be considered as highly-experienced “experts”. Thus, the results presented herein are likely a best case scenario and standard analysts may be expected to produce more variable results. This is a consequence of the limited resolution achieved with non-invasive methods and the non-uniqueness of the inverse problem. However, the combination of the information from both active and passive surface-wave data allows for a better identification of the subsurface conditions in the shallow parts and thus results in better agreement with invasive results.

It is important to note that this was a fully blind test and no a-priori information was provided to the invasive or non-invasive teams. The introduction of a-priori information (e.g. stratigraphic logs and water table position) can constrain the inversion of non-invasive results and would certainly reduce the variability of surface-wave analysis results. It would have also been a benefit to the invasive methods.

Despite the differences in volume of material sampled and depth resolution, both invasive and non-invasive methods resulted in average $V_{S,30}$ values that were within 4% of one another with relatively low COV. As shown in previous studies (e.g. [10]), this is due to the fact that $V_{S,30}$ is an averaged parameter and in its estimation the issue of non-uniqueness of the solution is mitigated.

5 Conclusions

In the InterPACIFIC project we compared both invasive and non-invasive techniques to evaluate their reliability and variability in the estimation of the S-wave velocity profile. All results have been obtained with a fully-blind approach. This is particularly penalizing for non-invasive methods, which require the solution of an inverse problem and a much more complex interpretation than invasive methods.

For invasive techniques, the same in-hole measurements were performed by different companies in an effort to assess the repeatability of such methods in three different subsoil conditions. From the comparison of invasive methods, we observed that the downhole method, sometimes considered less reliable than the crosshole method, provided very similar results and exhibited similar precision (repeatability) even at large depths. . However, it should be noted that the downhole results in the top 2-4 m were somewhat less reliable and more variable.

Despite the fact that non-invasive methods are traditionally considered less reliable than invasive methods, the variability of the results for both classes of methods were generally comparable. Considering that typically a single realization of a given test is available for the characterization of a site, this uncertainty has to be considered unavoidable and it affects any deterministic site response analysis. Invasive methods provide a higher resolution, as confirmed by the differences in detecting specific features such as low-velocity layers. This implies that higher accuracy is achieved by invasive methods, but the results show that despite the problem of solution non-uniqueness, non-invasive methods provide a precision that is comparable to the one of invasive methods. In terms of averaged parameters for the subsoil (e. g., $V_{S,30}$) both accuracy and reliability are comparable, confirming that the higher resolution provided by invasive methods is irrelevant for this scope.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the on line version at http://dx.doi.org/10.1016/j.soildyn.2015.12.010. These data include Google maps of the most important areas described in this article.

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