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RELIABILITY AND ACCURACY ASSESSMENT OF INVASIVE AND NON-INVASIVE SEISMIC METHODS FOR SITE CHARACTERIZATION: FEEDBACK FROM THE INTERPACIFIC PROJECT.

F. Garofalo[(1)], S. Foti[(2)], F. Hollender[(3)], P.-Y. Bard[(4)], C. Cornou[(5)], B.R. Cox[(6)], A. Dechamp[(7)], M. Ohrnberger[(8)], D. Sicilia[(9)] and C. Vergniault[(10)]

[(1)] *PhD, Politecnico di Torino, c.so Duca degli Abruzzi 24, 10129 Torino, Italy, flora.garofalo@polito.it*
[(2)] *PhD, Politecnico di Torino, c.so Duca degli Abruzzi 24, 10129 Torino, Italy, sebastiano.foti@polito.it*
[(3)] *PhD, CEA, DEN, F-13108 St Paul lez Durance, France, fabrice.hollender@cea.fr*
[(4)] *Scientist, ISTerre, University of Grenoble Alpes / IFSTTAR, F-38058 Grenoble, France, pierre-yves.bard@univ-grenoble-alpes.fr*
[(5)] *PhD, University of Grenoble Alpes /IRD, F-38041 Grenoble, France, cecile.cornou@ujf-grenoble.fr*
[(6)] *PhD, University of Texas, 301 E. Dean Keeton Stop C1792, Austin TX 78712, USA, brcox@utexas.edu*
[(7)] *Engineer, CEA, DAM, DIF, 91297 Arpajon, France, aline.dechamp@cea.fr*
[(8)] *University of Potsdam, Karl-Liebknecht-Str. 24, 14476 Golm, Germany, matthias.ohrnberger@geo.uni-potsdam.de*
[(9)] *EDF CEIDRE, 905, Av. du Camp de Menthe, 13097 Aix-en-Provence, France, deborah.sicilia@edf.fr*
[(10)] *EDF CEIDRE, 905, Av. du Camp de Menthe, 13097 Aix-en-Provence, France, christophe.vergniault@edf.fr*

Abstract

The InterPacific project (Intercomparison of methods for site parameter and velocity profile characterization) aims to assess the reliability of seismic site characterization methods (borehole and surface wave methods) used for estimating shear wave velocity (VS) profiles and other related parameters (e.g., VS30).

Three sites, representative of different geological conditions relevant for the evaluation of seismic site response effects, have been selected: (1) a hard rock outcrop, (2) a deep soft deposit, and (3) an intermediate case with thick stiff soils and a velocity inversion and large bedrock depth. Two to three boreholes have been drilled at these sites and various companies were invited to perform in-hole measurements (cross-hole, down-hole and PS-logging).

Both active and passive surface wave data were also collected. All of them located in the vicinity of the boreholes to facilitate the robust comparison between results from the invasive and non-invasive methods. The same experimental non-invasive datasets, without any prior information about the sites, were provided to the different teams, which were asked to retrieve the Vs profiles while working on the preferred subset of available experimental data.

For surface wave methods, results indicate that the dispersion curves provided by the participants were in very good agreement with each other. Inverted Vs profiles were also found to be very consistent with respect to the known reliable resolution depth ranges of these techniques. Results obtained from invasive methods show a variability of VS estimates on the same order as about the variability of Vs estimates obtained from non-invasive methods.

We also delivered guidelines to recommend good practices for non-expert users. These guidelines provide practical indications on the acquisition and analysis of surface wave data by reviewing basic principles and providing specific suggestions related to common situations. The guidelines are primarily targeted to non-expert users applying surface wave testing techniques, but can be useful to specialists in the field as a general reference guide. These guidelines, however, cannot be a substitute for experience in surface wave analyses; rather, they provide a common reference to establish the necessary dialogue between the service provider and the end-user of the results. The guidelines are based on the experience gained within the InterPacific project and on the expertise of the participants in acquisition and analysis of surface wave data.

Keywords: Surface wave methods, cross-hole, down-hole, velocity profile, Vs30

1. Introduction

The project InterPacific (Intercomparison of methods for site parameter and velocity profile characterization) is aiming at the comparison of the main techniques for surface wave methods (intra-methods comparison) as well as the comparison between such non-invasive techniques and the invasive ones (inter-methods comparison) in order to evaluate the reliability of the results obtained with such different techniques. These comparisons help us to improve the understanding on those theoretical and practical issues whose differences in the implementation could impact the results. As a consequence, the suggestion of guidelines for a good practice for non-expert users is another challenging task of the InterPacific project.

Other projects were carried out in the past to improve the overall practice in these methods, like the NERIES-JRA4 European project (NEtwork of Research Infrastructures for European Seismology) ([1] – [4]). In the InterPacific project, three sites were chosen in order to evaluate the performance of both invasive and non-invasive techniques in three different subsoil conditions: soft soil, stiff soil and rock. In all the sites, at least two boreholes are available to perform the in-hole measurements. Both active and passive surface wave data were collected, all of them located in the vicinity of the boreholes for a better comparison between the results from invasive and non-invasive methods. Different teams of engineers, geologists and seismologists, were invited to take part in the project in order to perform a blind test: the same experimental non-invasive datasets and very little information about the sites were provided to all of the teams and then the results were compared. As far as the invasive methods are concerned, different techniques were performed by different companies in order to assess the repeatability of this kind of measurements.

3. The Interpacific project

Boreholes and surface wave measurements have been performed at specifying testing sites by applying different methods. As far as the surface wave methods are concerned, both active and passive surface wave data were collected while different companies have been involved for a multiple acquisitions of cross-hole, down-hole and PS-suspension loggings datasets. Different participating teams have been invited for the processing and inversion of the raw experimental data. The results related to different techniques and obtained by different operators are compared in order to assess inter-method variability (difference between results from different seismic tests) and intra-method variability (repeatability of the results). These issues are of paramount importance for the assessment of uncertainty bound in seismic site response studies.

3.1 The Test Sites

Three testing sites have been chosen: Cadarache and Grenoble in France and Mirandola in Italy (Figure 1). These sites have been selected to cover a wide range of subsoil conditions, respectively: rock, stiff soil, and soft soil. For the sake of the blind test, very little information was provided to the teams that analyzed the non-invasive data. In the following, we provide the information that was available for the teams and a further more detailed description of each site.

3.2 The datasets

In all the three sites cross-hole, down-hole and PS suspension loggings were performed by at least three different companies in boreholes that were drilled within this project or within other research activities. A three-brorehole configuration for cross-hole tests has been realized in Cadarache (33 m, 33 m and 50 m) and Grenoble (all 50 m) where the borehole were specifically drilled for InterPacific project, whereas only two boreholes (both 123 m) are available in Mirandola (previously drilled in the frame work of the Italian strong-motion network). Both active and passive surface wave data have been collected at each site in the vicinity of the boreholes. In particular, ambient vibration acquisitions were performed with 16 Güralp broadband CM6TD seismometers with integrated digitizers in different configurations: concentric circle, triangle and L shape.

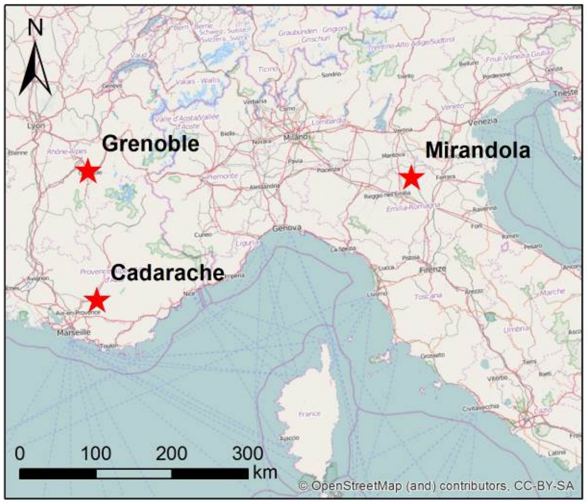

Figure 1 –Localization of the three sites: Mirandola in Italy, Grenoble and Cadarache in France (from Garofalo et al. 2016a, [5]).

The different arrays were centred in the same common point. Circular arrays are formed by 7 equally-spaced sensors on a circumference of a given radius. Acquisitions were performed with different radii (from 5 m to 405 m). In addition, 5 nested triangles were simultaneously collected with the side of triangle increasing from 12.5 m to 300 m. The L-shape geometry is implemented locating the sensors along two perpendicular lines that cross each other at the previously identified centre point. The sensors were located along the two lines with a distance that ranges from 5 to 150 m. Even if very large arrays are not common for the seismic characterization at the depth of interest in geotechnical and earthquake engineering applications, additional arrays were acquired with wide spacing for deep investigation.

As far as the active measurements are concerned, Rayleigh wave data were acquired by using a 8 kg sledgehammer and 48 vertical geophones (4.5 Hz natural frequency). Different receiver spacing was adopted in each site ranging from 0.5 m in Cadarache to 2 m in Mirandola, according to space availability and expected subsoil properties. Along the same lines, SH waves were generated by using a hammer striking on an iron beam and the data were acquired using 24 horizontal geophones (20 Hz natural frequency) to study the propagation of Love that may add further information to constrain the inversion process.

All the acquired data is distributed as possible material to benchmark further developments. All material (whole data set and detailed description of it) could be find at this address: http://interpacific.geopsy.org.

4. Comparison of non-invasive methods

The Non-Invasive methods are mainly based on surface wave analysis of both passive and active seismic data, available at each site. Fourteen teams, from several research institutes from around the world (see Table 1), were involved and each team was free to adopt the strategy and the procedure they consider to be the best to estimate the S-wave velocity (VS) profile.

Once the raw seismic data are acquired, the surface wave analysis is typically based on two main steps: the processing to retrieve the dispersion curve and then the solution of the inverse problem to estimate the shear wave velocity profile. Both the dispersion curves and the S-wave velocity profiles provided by the teams have been compared for each site.

The comparison of the dispersion curves retrieved by the teams takes into account three mainly aspects: the considered seismic dataset (active and/or passive), the kind of surface wave that was analysed (Raleigh and/or Love) and the method that was adopted for the processing. In particular, in the comparison of the seismic data, it was possible to distinguish between teams that analysed only active data (very few), only passive data and both.

Table 1 – List of participant teams.

ID	Label	Participants	Country
1	MU	Michael Asten, Monash University	Australia
2	CE	CEREMA	France
3	IST1	IST1 – Cornou, ISTerre	France
4	UT	Brady Cox, University of Texas	USA
5	INGV	Giuseppe di Giulio, INGV	Italy
6	BFO	Thomas Forbriger, Black Forest Observatory	Germany
7	Geom	Koichi Hayashi, Geometrics	USA
8	IST2	Bertrand Guiller, ISTerre	France
9	KU	Shinichi Matsushima, Kyoto University	Japan
10	TT	Hiroaki Yamanaka, Titech	Japan
11	GV	Antony Martin, Geovision	Italy
12	SED	Valerio Poggi, SED ETH	Switzerland
13	PU	Mathias Ohrnberger,Postdam University	Germany
14	PT	Politecnico di Torino	Italy

The methods of processing to retrieve the dispersion curves are based mainly on the following approaches: SPAC: Spatial autocorrelation and its variants like ESPAC, MSPAC, etc; f-k: frequency-wavenumber transformation (either with conventional 2D FFT or with a frequency domain beamformer method FDBF); PF: slowness-frequency transformation; 3 CWD: combination of three-component f-k (3C) and wavefield decomposition (WD).

While most of the teams analysed the fundamental mode of Rayleigh wave (R0), some analysed also higher modes (R1, R2, R3, R4) and effective mode (RE) of this kind of waves. Some teams also analysed both fundamental and higher modes of Love waves (L0, L1, L2). It is worth to notice that the team from Monash University (MU) adopted a method for estimating the VS profile that does not require the retrieval of the dispersion curve. For this reason, for this team the dispersion curve is not reported in the comparison.

The comparison of VS profiles took into account mainly the search/optimization method during the inversion. The most popular was the Neighbourhood-Algorithm implemented within Geopsy (Wathelet 2008), hereafter defined as “NA_geopsy”, while others adopted one or the combination of the following methods: LLS: Linearized Least-Squares; GA: Genetic Algorithm; EYE: By-Eye (manual forward modelling with a trial and error procedure); SA: Simulated Annealing; NLS: Nonlinearized Least-Squares and MC: Monte Carlo. It is worth to mention that no (or very little) a-priori information was provided to the teams.

4.1 Results: Mirandola

Figure 2 shows the dispersion curves retrieved by each team on the Mirandola site. Even if the teams adopted different approaches, the retrieved dispersion curves are in good agreement. The resulting V_S profiles are reported in Figure 3 (zoom of the shallow part, until 200-m depth). On this figure, the V_S profiles are compared also to the pseudo V_S profile obtained directly from the dispersion curve by assuming that the V_S is equal to 1.1 times phase velocity and the depth equal to half wavelength. If we analyse the results until a depth of interest for engineering applications, despite the pseudo V_S profiles are very in good agreement with each other (Figure 3, left), the V_S profiles from inversion (Figure 3, right) do not show a significant trend for depth greater than 90 m. The larger variability of the retrieved V_S profiles at greater depth does not affect the computation of the $V_{S,30}$ which most of the profiles converges on the same value equal to 210 m/s.

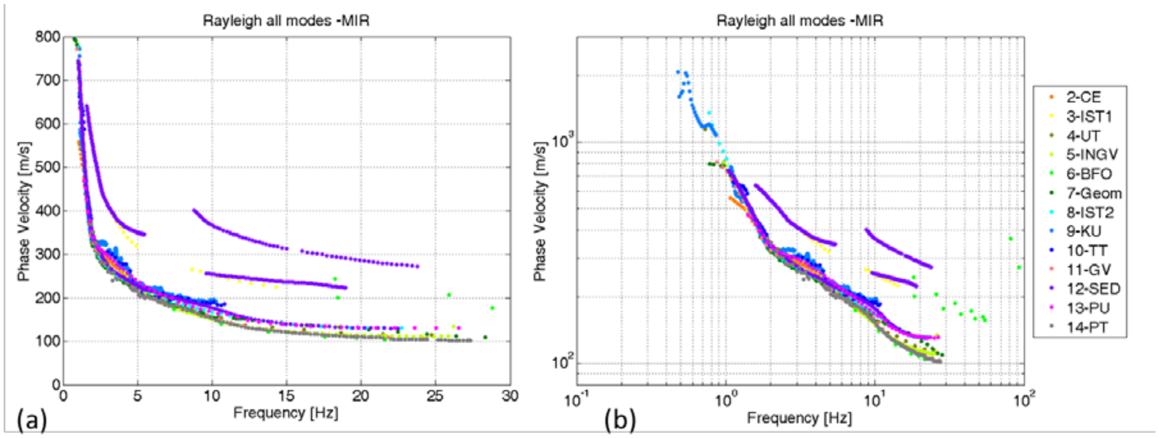

Figure 2 – Mirandola: comparison of the dispersion curves provided by the teams. Only the dispersion curves of all the modes of Rayleigh wave are shown. In a) the dispersion curves are reported in linear scale of frequency and phase velocity while in b) the dispersion curves are reported in a log scale of both frequency and phase velocity.

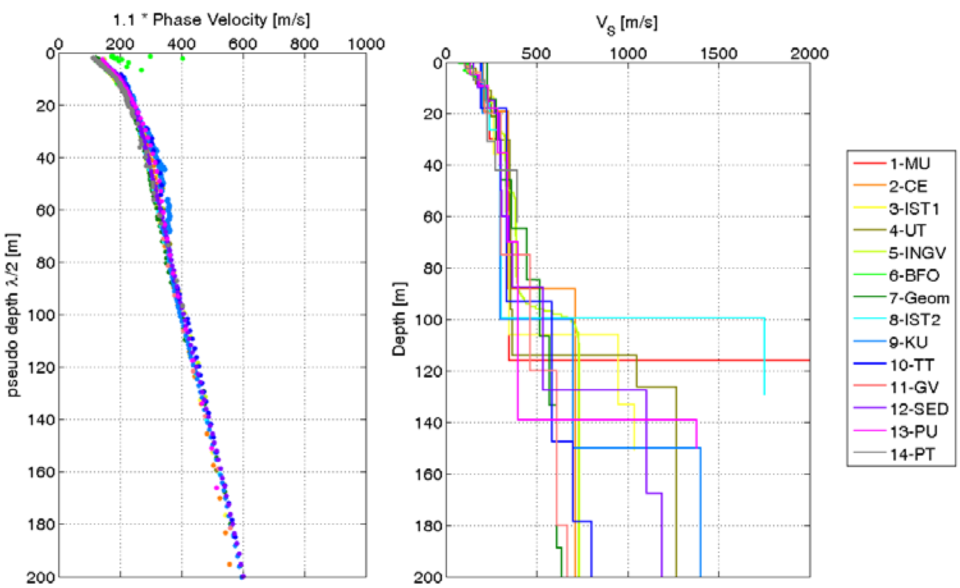

Figure 3 – Left) Dispersion curves plotted in pseudo profile: V_S equal to 1.1* Phase velocity while the pseudo depth is reported as wavelength (λ) divided by 2. Right) V_S profiles provided by teams. Zoom on the 200 top most meters.

4.2 Results: Grenoble

Figure 4 shows the dispersion curves retrieved by each team on the Grenoble site. Even if the teams adopted different approaches, the dispersion curves are in good agreement with each other for frequency lower than 20 Hz while some differences can be noticed at higher frequencies. We also note that most teams provided DC curves that were able to identify the lower velocity layer (local minimum in the 2-10 Hz frequency range) whereas none of this was not communicated to participants. The choice of analyzing both active and seismic data was the most popular, few teams only passive data and none only active data. The analysis of both active and passive data allows for a wider frequency band than the ones of those teams that analyzed just passive data focusing more on the lower frequency and hence neglect the higher ones.

The resulting V_S profiles are shown in Figure 5 (zoom of the shallow part, until 100-m depth). On this figure, the V_S profiles are compared also to the pseudo V_S profile obtained directly from the dispersion curve by assuming that the V_S is equal to 1.1 times Phase velocity and the depth equal to half wavelength.

If we analyze the results until a depth of interest for engineering applications (in this case we consider until 100-m depth), the pseudo V_S profiles are very in good agreement with each other (Figure 5, left), but the V_S profiles from inversion show marked differences. At a depth that ranges between 15 and 55 m, some teams identified a lower-velocity layer but the interfaces are not consistent with each other. Similarly the interface at around 80 m is affected by a large variability.

Some teams were able to identify a low velocity zone, even if the exact depth of this layer was not determined with accuracy with non-invasive measurements. If we restricted the analysis to the first 200 m, the overall agreement is still rather good even if the variability is now larger than for Mirandola. The variability of the retrieved V_S profiles does not affect the computation of the $V_{S,30}$ and most of the profiles converge on the same value equal to 363 m/s.

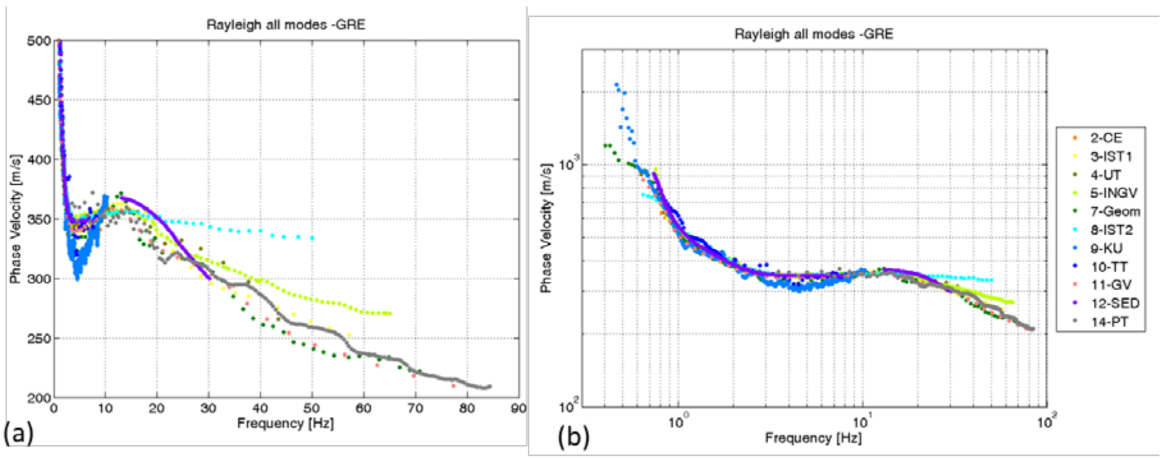

Figure 4 – Comparison of the dispersion curves provided by the team for the test-site of Mirandola. Only the dispersion curves of all the modes of Rayleigh wave are shown. In a) the dispersion curves are reported in linear scale of frequency and phase velocity while in b) the dispersion curves are reported in a log scale of both frequency and phase velocity.

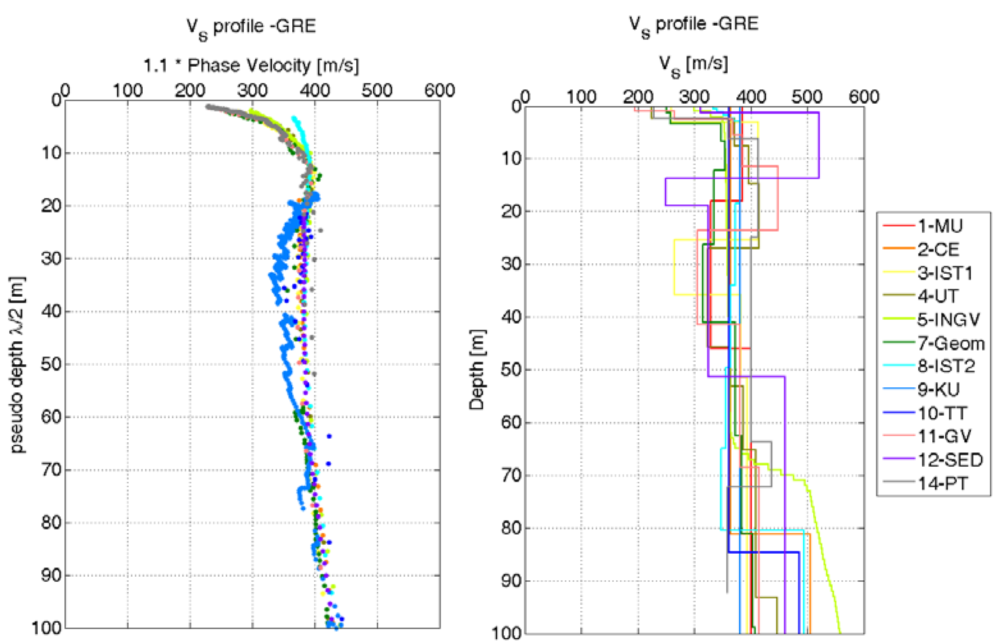

Figure 5 – Left) Dispersion curves plotted in pseudo profile: V_S equal to 1.1* Phase velocity while the pseudo depth is reported as wavelength (λ) divided by 2. Right) V_S profiles provided by teams. Zoom on the 200 top most meters.

4.3 Results: Cadarache

Figure 6 shows the dispersion curves retrieved by each team on the Cadarache site. In this case the dispersion curves are not so in good agreement as we observed for the others sites especially at higher frequencies. Some teams were able to identify higher modes, while others were not.

The resulting V_S profiles are reported in Figure 7 (zoom of the shallow part, until 50-m depth). In these figures, the V_S profiles are compared also to the pseudo V_S profiles obtained directly from the dispersion curves by assuming that the V_S is equal to 1.1 times Phase velocity and the depth equal to half wavelength. It is worth to notice how the V_S profiles show mainly two trends at very high depth one at 2500 m/s and the second around 3000 m/s.

If we analyze the results until a depth of interest for engineering applications, we observe that both the pseudo and the inverted V_S profiles are not so in agreement with each other until to 30-m depth. However, it is interesting how in the depth range between 30 and 50 m the S-wave velocity varies in a narrow band between 2500 and 2800 m/s.

The larger variability of the retrieved V_S profiles in the shallow part leads to the same variability in the $V_{S,30}$; indeed, VS,30 shows a bimodal distribution with central values 1510 and 1780 m/s.

5. Comparison between Invasive and Non-Invasive Methods

In each site also invasive measurements were performed. In particular at all the sites 3 teams performed the following invasive tests: cross hole (XH) (both in terms of S-wave and P-wave) and down Hole (DH) (both in terms of S-wave and P-wave). In addition, one team performed Suspension Logging (SL). In all the sites University of Texas (UT) provided the results of the analyses of the experimental data acquired by one of the previous teams. In Mirandola additional invasive measurements are available.

We will not discuss in depth the invasive measurement here, more information can be found in Garofalo et al. (2016b, [6]). In this section we will focus on the comparison between the V_S profiles from invasive (and hence hereafter called invasive V_S) and non-invasive methods. In particular for the non-invasive V_S profiles, we also distinguish between those profiles that were estimated analyzing both active and seismic data (and hence hereafter called active+passive V_S) and the ones obtained from only passive seismic data (and hence hereafter called passive V_S).

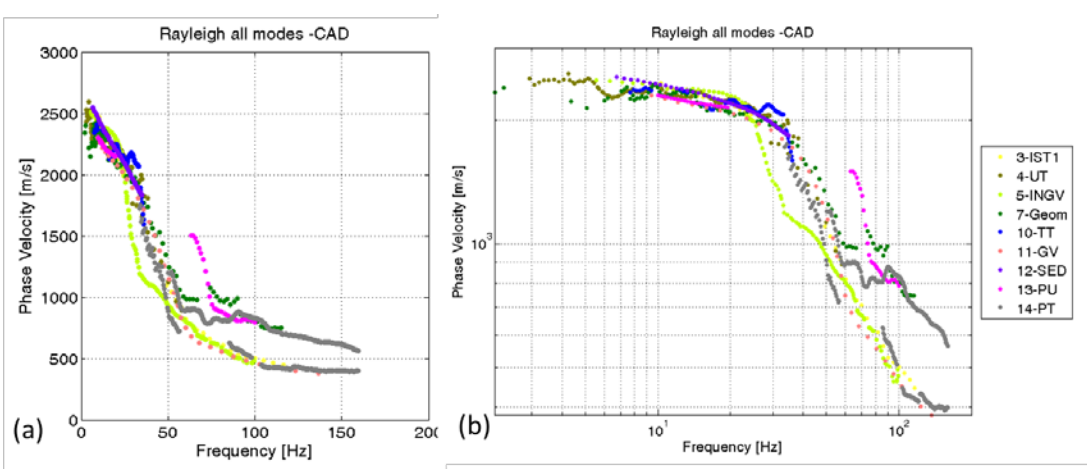

Figure 6 – Cadarache: comparison of the dispersion curves provided by the teams. Only the dispersion curves of all the modes of Rayleigh wave are shown. In a) the dispersion curves are reported in linear scale of frequency and phase velocity while in b) the dispersion curves are reported in a log scale of both frequency and phase velocity.

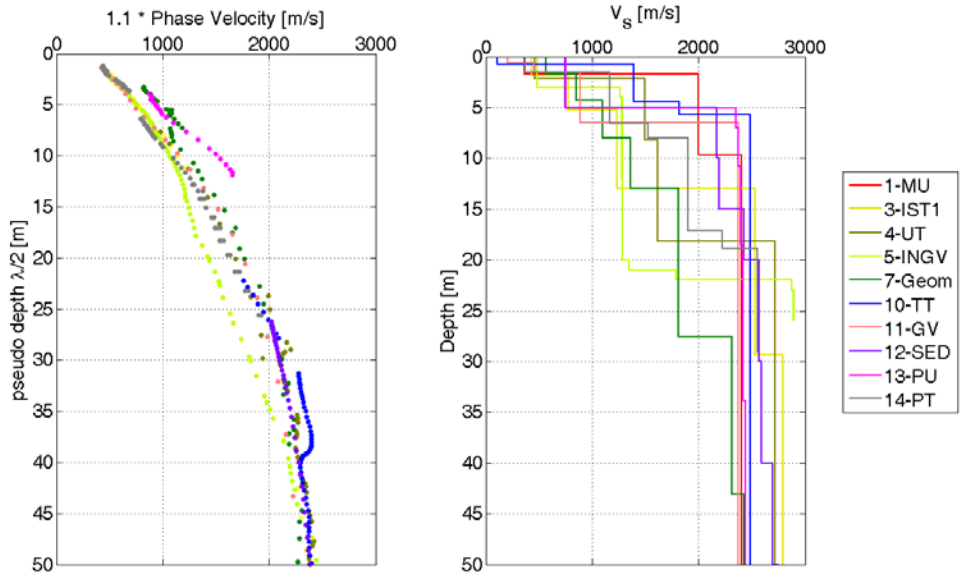

Figure 7 – Left) Dispersion curves plotted in pseudo profile: V_S equal to 1.1* Phase velocity while the pseudo depth is reported as wavelength (λ) divided by 2. Right) V_S profiles provided by teams. Zoom on the 50 top most meters.

Figure 8 shows the aforementioned comparison and the profiles until the depth equal to 50 m (on this figure, on can see an DH V_S profile on each site that produced clearly wrong values: we will exclude it from the further discussion).

In Mirandola, for depth greater than 100 m, some passive profiles overestimate the V_S and identify an interface between 90- and 120-m while invasive methods identify such interface around 115 m, and most active+passive profiles show an interface more in agreement with the invasive results. In addition, in the shallow part of Mirandola profiles (Figure 8, right panel), some passive profiles do not describe in details the trend of the V_S but they show a single layer until roughly 15 m. On the contrary, both invasive and active+passive profiles describe adequately the behavior in the shallow part. Such behavior is recognized also in Grenoble (Figure 8, central panel) where most of the passive results show a constant value until 50-m depth and they do not recognize some details as the other methods do. For example, both invasive and active+passive profiles better describe the low S-wave velocity field in the shallow part (few meters from the ground). At around 17-m depth all the invasive results show a lower velocity layer that is not fully recognized by all the non-invasive results. A second lower velocity layer is well identified between 25- and 37-m and such thick layer is identified also by some active+passive profiles. As far as the site of Cadarache is concerned (Figure 8, right panel), the non-invasive methods identify two main trends: the only passive profiles shows higher velocity in the very shallow part than the others while most of the active+passive results overestimate the velocity in the same depth range. The invasive results lie in the middle of the two trends identified by the non-invasive ones.

The mean profiles of each group of results were compared to each other (Figure 9). It is interesting how the combination of the information from both active and passive seismic data provides more reliable results both in the shallow and in the deep sections of the profile. As a matter of fact, it is worth to highlight the agreement between the mean of active+passive and invasive results in the shallow parts in Grenoble and Cadarache (Figure 9, central and right panels, respectively) and the bedrock at 115-m depth in Mirandola (Figure 9, left panel).

From all the results obtained for each kind of method (Invasive or Non-Invasive) we computed the statistics of the value of $V_{S,30}$ (Table 2) in term of: mean, standard deviation (std) and coefficient of variation (CoV), estimated as the ratio between the mean and standard deviation. The latter value is a dimensionless normalized measure of the variability of the results for a better comparison of different sites. In the estimation of these statistic values for the invasive results, the outlier previously discussed was excluded.

From an analysis of the CoV, it is interesting to highlight that such value is quite similar between invasive and non-invasive for Mirandola and Grenoble while in Cadarache the CoV of Invasive results is slightly higher than the non-invasive one. It is important to highlight that Cadarache was a very difficult site to study for both invasive and non-invasive methods and for this reason the higher values of CoV for this site with respect to the other two sites.

The values of $V_{S,30}$ obtained from both invasive and non-invasive results for the three sites were compared to other studies reported in the literature ([7], [8], [9] and [10]). Such results are reported in figure 10. It is important to mention than within the InterPacific project, we are able to propose error bars for both invasive and non-invasive methods. The comparison shows that in terms of the $V_{S,30}$, the estimate is robust and can be considered accurate as both class of method provide similar values.

Table 2 – Statistic values of $V_{S,30}$ (mean, Standard deviation and Coefficient of Variation) computed for each site

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

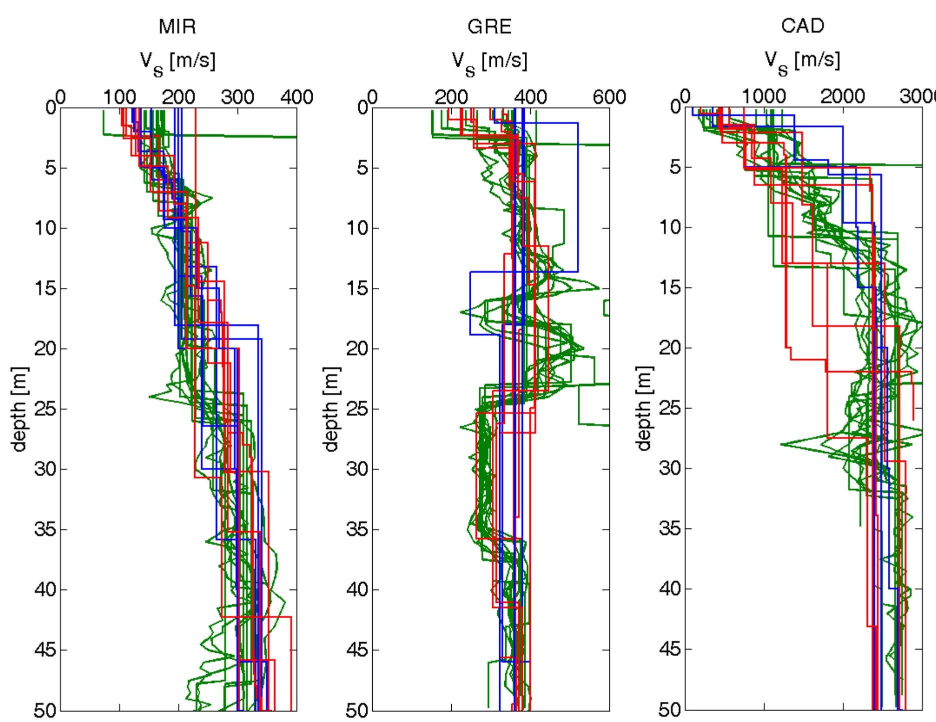

Figure 8 – Comparison of V_S profiles. Zoom of Figure 6.1. V_S profiles obtained with invasive methods (in green) and non-invasive methods, distinguishing between those profiles related to the analysis of active and passive seismic data (in red) and only passive seismic data (in blue). The comparison is performed for each site: Mirandola (MIR, in the left panel), Grenoble (GRE, in the central panel) and Cadarache (CAD, in the right panel).

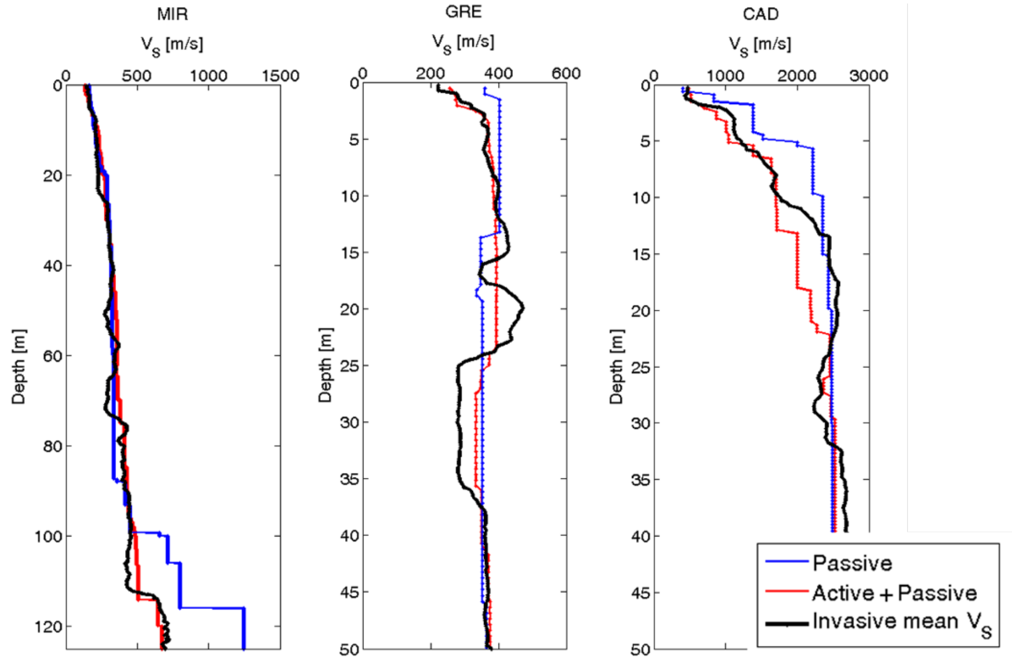

Figure 9 – Comparison between the mean profiles for each group of results (passive, active+passive and invasive) for each site (MIR in the left panel, GRE in the central panel, CAD in the right panel).

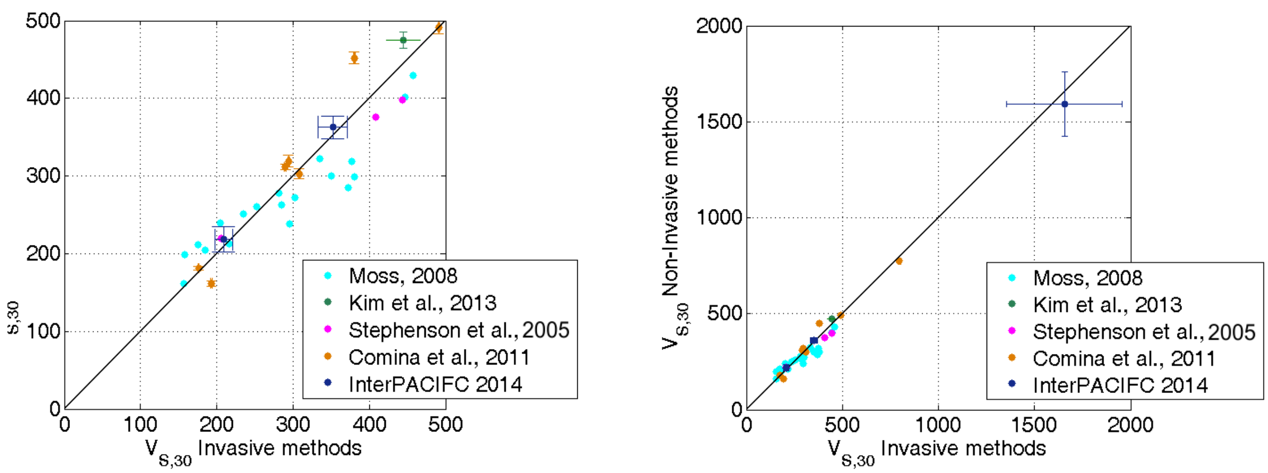

Figure 10 - Relation between $V_{S,30}$ estimated with invasive and non-invasive methods

6. Conclusions

As far as the surface wave methods are concerned, the determination of the dispersion curve is much less critical than the inversion process. The dispersion curves provided by the participants were in very good agreement with each other in all the three sites that means in three very different subsoil conditions. Nevertheless, the V_S profiles obtained by the inversion of those curves, show a quite high variability and some features, like the bedrock interfaces in Mirandola and Grenoble, are not uniquely identified or not identified at all like for example the lower velocity layer in Grenoble. This is a further demonstration of how much the non-uniqueness of the solution affects the reliability of the method. However, it is important to remark that, since it was a blind test, no a-priori information was provided to the teams. Nevertheless, some teams constrained the inversions by exploiting as much as possible the information contained in the experimental data. Some teams estimated the P-wave velocity distribution by analyzing the seismic refraction information contained in the active seismic datasets and from this result, it was possible to deduce the water table position and it helped to make more proper assumptions on the Poisson's ratio while other people performed H/V analysis to retrieve the depth of the bedrock. Nevertheless, if we restricted the depth of analysis, the accordance between results is still much better than what we expected and overall, much better than some people in the community expect from non-invasive methods.

The combination of the information from both active and passive data allows retrieving a dispersion curve in a wider frequency band and hence it is possible to better define the model both in the shallow and in the deeper parts. Discussing about the limits of the model definition, it is interesting how the analysis of the wavelength could help in the choice of the parameterization of the model. We observed that some teams defined the model in those areas, like very thin shallow layers and very high investigation depth, even if the dispersion curve was not sensitive to such part of the model as one can deduct from the analysis of the retrieved wavelength. Maybe it could be better to define the resolution of the model in agreement with the retrieved wavelength.

As far the $V_{S,30}$ is concerned, it is interesting to note that even if the variability of velocity profiles for non-invasive methods is higher than for invasive methods, the standard deviation in $V_{S,30}$ is comparable between both methods (and even lower for non-invasive methods for Cadarache site). This is surely due by the fact that if the inversion process overestimates (resp. undersestimates) the velocity at shallow depth, it will compensate by an underestimation (rep overestimation) at higher depth in order to produce whole velocity profile that fits the dispersion curve.

The invasive methods are traditionally considered more reliable than the non-invasive methods. Within this project, the same in-hole measurements were performed by different companies in an effort to assess the repeatability of such methods. The results show a surprising dispersion, even if they remain less dispersed than the non-invasive method results when velocity profiles are considered at a given depth. However, the invasive methods induce a standard deviation in $V_{S,30}$ that is of the same order of the one computed taking into account only the non-invasive results.

In closing, the non-invasive methods provide reliable results, as the invasive ones, if some precautions are adopted as we will report in the guidelines. In addition, they are ready to use: in the meaning that no additional boreholes must be drilled.

More information on the InterPacific project results can be found in [5] and [6].

7. Acknowledgments

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8. Copyrights

9. References

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