Two ways to obtain the shear-wave velocity (V_S) vertical profile: (1) DownHole (DH) seismics and (2) Surface-Wave Analysis

A brief overview

Keywords: MASW, multi-component MASW, ReMi, ESAC, SPAC, ReMi, HS (*HoliSurface*), RPM, HVSR, VSP, DH, refraction, Vs30, joint inversion

Friday, 25 January 2019

This page intentionally left blank

Introduction:
shear-wave velocities (V_S) *versus* compressional waves (V_P)

The determination of the V_S values is important not only for seismic hazard studies related to the computation of the ground shaking in case of earthquakes (e.g. Seed and Idriss, 1971; Bard and Bouchon, 1980a; 1980b).

Compared to the compressional (longitudinal) waves, shear waves have a characteristic property that makes them very important also in the near-surface exploration aimed at retrieving the shallow Earth layering. Differently than the compressional waves, in the unconsolidated sediments they are in fact not markedly influenced by the presence of water.

This means that while the presence of water in unconsolidated sediments strongly influence the V_P values, it does not significantly affect the V_S.

This fact has concrete and important consequences. Let's see this point through a field dataset recorded in an area dominated by sandy sediments.

Figure 1 reports the seismic trace recorded while using a common sledgehammer as source and 23 vertical geophones. The waveforms are clearly dominated by the Rayleigh waves but some lower-amplitude early arrivals due to the P-wave refraction are also present. These low-amplitude arrivals can be emphasized by means of a simple AGC (Automatic Gain Control). **Figure 2** (upper right plot) report the first 0.15 s after the application of an AGC: the P-wave arrivals are now clearer and can be used to retrieve a simple 1D V_P profile (reported in the upper left plot).

As a matter of fact, such a V_P model is actually useful to identify the depth of the water table which is responsible of the sudden increase of the V_P value from about 600 to 1700 m/s at a depth of 3 m (the V_P value in pure water is around 1550 m/s). Such a feature actually prevents the V_P from providing any further information about the lithology/sediments beneath such a (pretty shallow) "horizon".

On the other side, if we analyze the Rayleigh-wave dispersion, we can identify the of the V_S values (clearly related to the characteristics of the sediments) even below the water table.

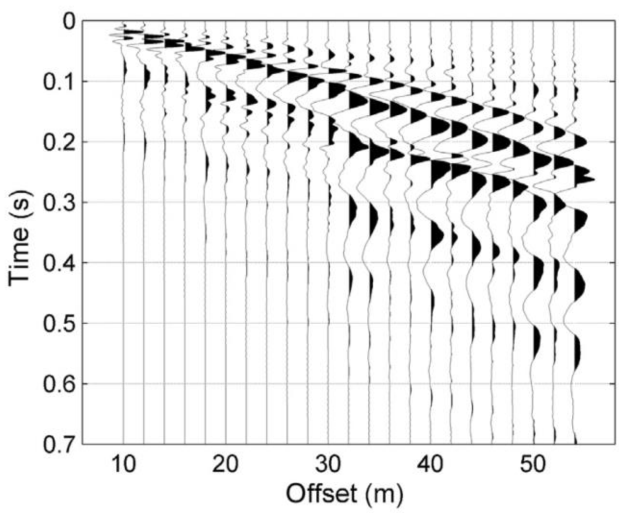

Figure 1. A field dataset: seismic traces of the ZVF component (nomenclature follows Dal Moro, 2014).

Figure 2 (lower plots) reports the phase-velocity spectra of the field dataset and of the V_S model reported (details about the data processing and this case studies are presented in Dal Moro, 2014). As can be clearly seen, **the obtained V_S profile provides information also about the sediments below the water table (that for the P waves represented a sort of physical limit/boundary)**. In very general terms it is possible to retrieve information down to a depth approximately equal to half or one third of the length of the array which, in this case, was 44 m.

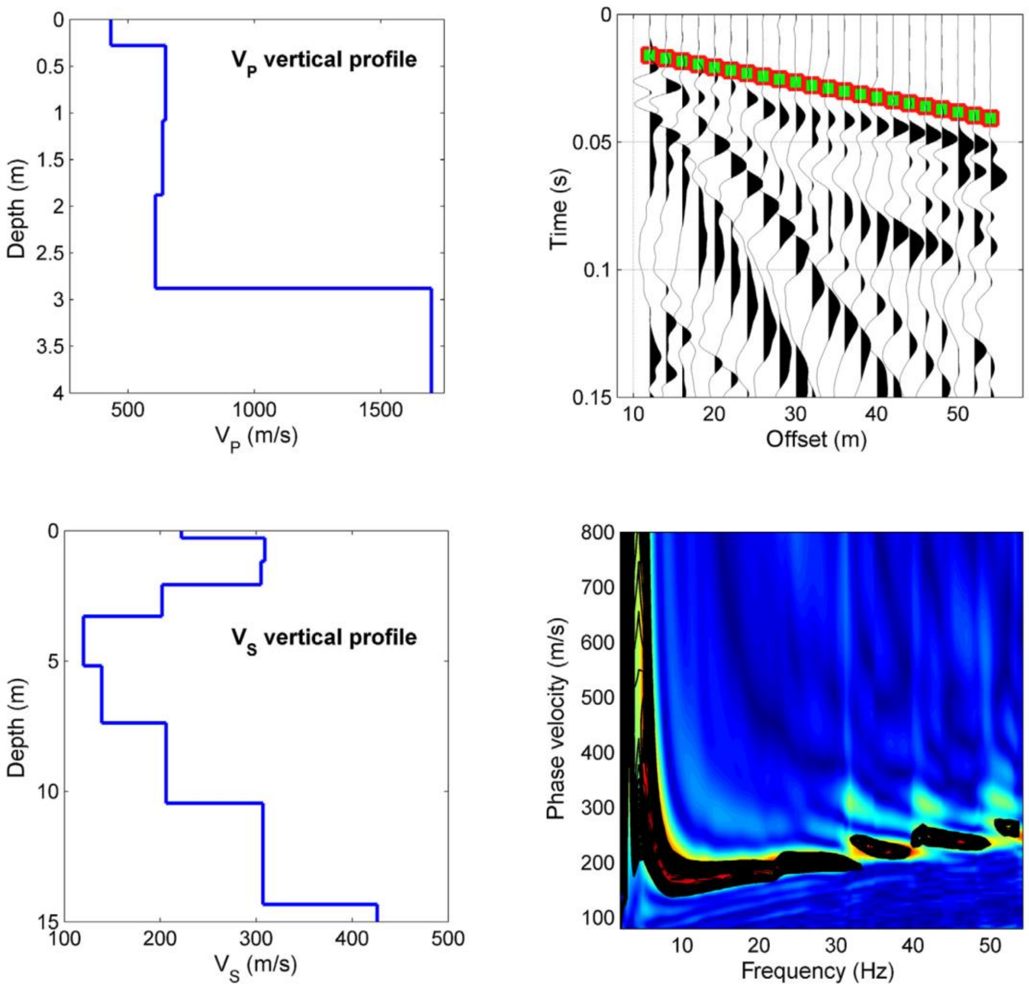

Figure 2. Results of the performed joint analysis. Upper panel: V_P profile and P-wave refraction travel times (shown only the first 0.15 s of the data – compare with Figure 1); lower panel: V_S model and observed and computed phase-velocity spectra. Background colours relate to the field data, overlaying contour lines show the synthetic velocity spectrum (FVS [*Full Velocity Spectrum*] approach). Details in Dal Moro (2014).

1. DownHole [DH] seismics
Vertical Seismic Profiling [VSP]

In order to obtain data suitable for the identification of the SH-wave arrivals, it is necessary to use a Horizontal Force (HF) source that will (mainly) produce SH waves. **Figures 3 and 4** provide the basic information about the common set up.

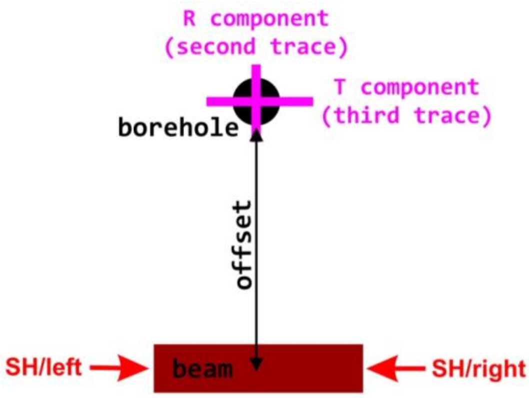

Figure 3. Map view of a classical borehole set up for the acquisition of seismic data useful for the identification of the SH-wave arrivals (see also Figure 4). In order to discriminate P-wave first arrivals, it is often useful to hit the beam both from the left and right side.
The two data/traces will be then subtracted so to cancel early P-wave (low amplitude) arrivals.

Figure 4. Field operation: a) downhole survey for the generation and acquisition of SH waves. The wooden beam is secured/coupled to the ground thanks to the weight of the car (this way it transmits most of the energy generated by the hammer impact). The survey took place in *San Severino Marche* (IT) after the 2016 central Italy seismic crisis. Courtesy ABgeo (www.abgeo.org). Data processing: a) several software applications for the processing of DH data assume a linear path but this does not represent a correct solution (see Figure 5).

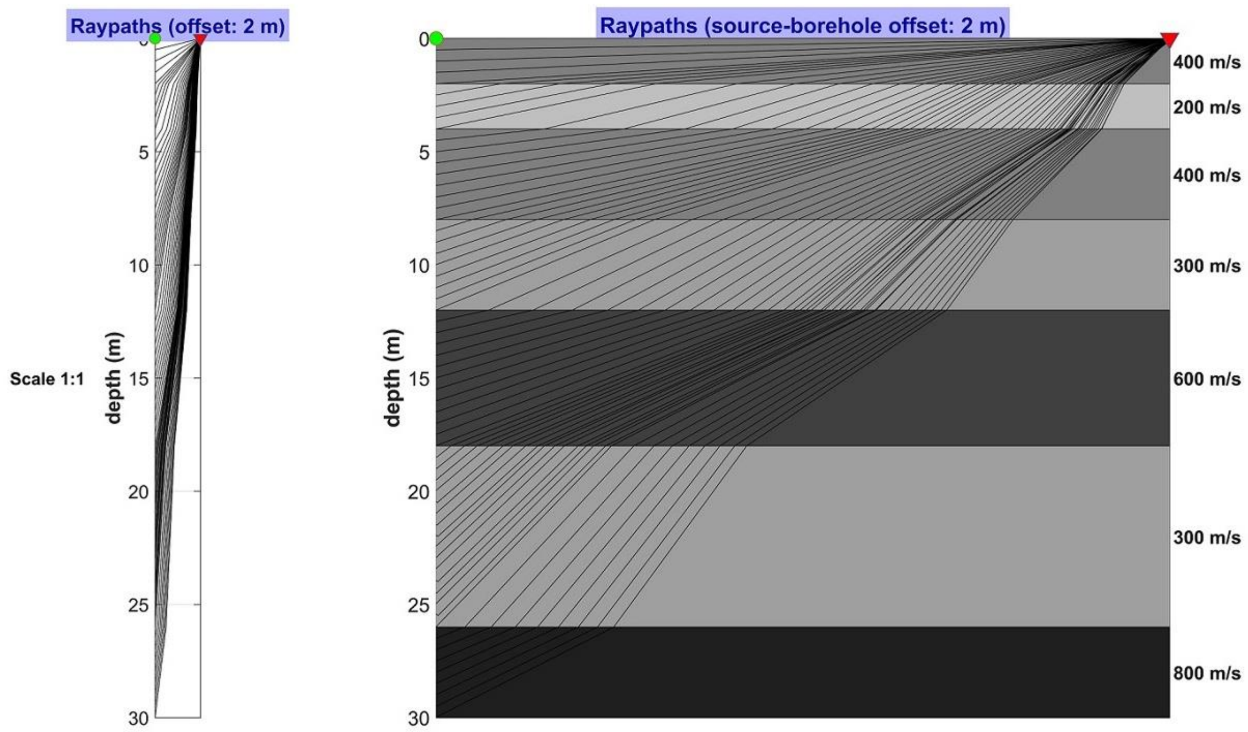

Figure 5. The actual path of the seismic wave follows a non-linear trajectory determined by the refraction of the ray itself. The definition of the correct velocities would require the correct modelling of such a "non-linear" behaviour. This becomes particularly important when abrupt variations of the velocities occur (presence of low-velocity or stiff layers). Please, also notice that if the distance between the source and the borehole (*offset*) is too small, complex wave phenomena can occur and prevent from the possibility to properly identify the transmitted waves.

Pro	Cons
✓ Detailed reconstruction of the V_S model	✓ Expensive and time consuming
✓ If a Vertical-Impact (VF) source is also applied, it is possible to determine the V_P values and, consequently, the Poisson ratio.	✓ Obtained information are very local

2. Surface-wave analysis

The surface-wave propagation (the well-known *Ground Roll*) can be used to extract information about the V_S values in the subsurface.
The first and most important point to highlight is that surface-wave analysis can be performed through a vast number of techniques and that the well-known MASW approach (with the analysis of the interpreted modal curves) represents just one of the possible approaches (and often is not the best one).
Table 1 represents a synthetic scheme with the main active and passive techniques currently available (more details in Dal Moro, 2014; 2018). An overview of the fundamentals on data acquisition is provided in Dal Moro (2014) [Chapter 2].

	Technique	Pro	Cons	Notes
active	MASW [single-component + modal dispersion curves]	Pretty popular	Velocity spectra can be highly ambiguous. Solution is non-unique.	Dispersion can be analyzed according to the FVS approach (more detailed with respect to the classical approach based on the modal dispersion curves)
active	Multi-component MASW	Requires the acquisition of at least 2 components [see Figure 6]	It solves the ambiguities of the velocity spectra. It strongly reduces the non-uniqueness of the solution.	
active	HS [*HoliSurface*]	Very simple acquisition setting (just one 3-component geophone)	Currently still not very popular	
active	SH-wave refraction	-	Complex field operations	-
passive	ReMi	-	Ambiguities in the determination of the <u>*effective*</u> dispersion curve	Dispersion must be modelled according to the <u>*effective*</u> dispersion curve and <u>**not**</u> to the fundamental modal curve. See Tokimatsu et al. (1992).
passive	ESAC / SPAC	The obtained effective dispersion curve does not suffer from the ambiguities typical of the ReMi approach	Complex field operations	
passive	MAAM [*Miniature Array Analysis of Microtremors*]	It requires just 4 or 6 (high-quality) vertical geophones and limited room [just 2-5 m]	Very sensitive to the quality of the equipment and to the precision of the acquisition procedure (see Dal Moro, 2018)	
passive	HVSR [*Horizontal-to-Vertical Spectral Ratio*]	Simple acquisition procedures	Highly non-unique. To be used only together with dispersion data (see other methods)	

Table 1. Main methodologies for the acquisition and processing of surface waves for the determination of the subsurface V_S profile (overview, details and case studies in Dal Moro, 2014; 2018).

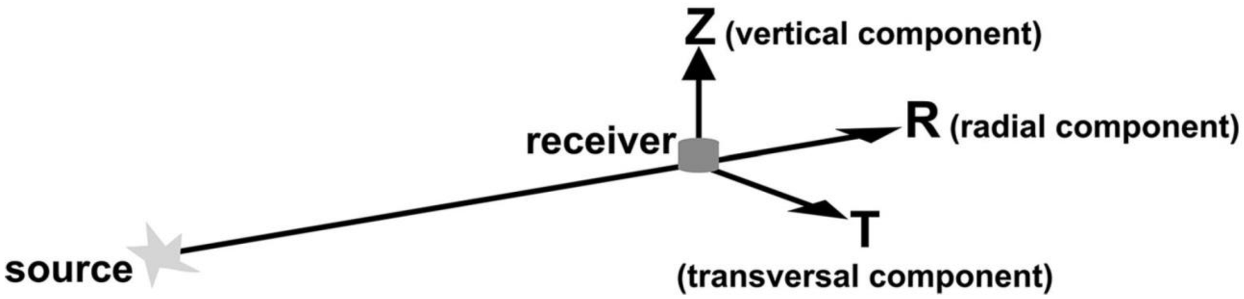

Figure 6. Seismic components: the acquisition and processing of more than one component allows the joint inversion of several "objects" and, consequently, the determination of a well-constrained subsurface model that does not suffer from significant non-uniqueness of the solution (see Figure 7 and related text).

Facing the non-uniqueness of the solution

The analysis of any kind of surface data inevitably suffers from the problem of the non-uniqueness of the solution (e.g. Scales et al., 2001).
A synthetic and conceptual representation of this well-known problem is schematized in **Figure 7**. In this representation, the method/dataset/object A (for instance the velocity spectrum of the vertical component of Rayleigh waves) can be explained by seven models (A-G) while the method/dataset/object B (for instance the Love-wave velocity spectrum) by the E-M models. Only some of them (the models G, E, and F) are in common and that means that by considering both the methods/datasets/objects we have now better constrained the solution, by excluding the models A-D (possible if we would use only the first method/dataset/object) and the models H-M (that could be used to justify the second method/dataset). This concept can be continued to include more and more "objects" thus reducing the ambiguities that would otherwise taint and jeopardize any inversion procedure based on a single method/dataset/object.
In the conceptual example of **Figure 7**, the joint analysis of the three considered objects allows to identify the model F as the only one capable of explaining all the three observations.
The classical approach (e.g. classical MASW, ReMi, ESAC/SPAC, MAAM etc) require the acquisition of data by using a set of vertical geophones but the inevitable consequence is that, this way, we will deal with just one single "object" (the dispersion of the vertical component of Rayleigh waves).
In order to obtain more "objects" to jointly invert we can use a set of horizontal geophones and follow the simple procedure necessary to acquire the radial component of Rayleigh waves (RVF) and Love waves (THF) (see Dal Moro 2014; 2019).
On the other side we can decide to deal with only Rayleigh waves and record the vertical (Z) and radial (R) components according to the acquisition procedures shown

in Figure 8 and 9 (see Dal Moro 2014 and Dal Moro et al., 2018). This way we will be able to deal with three objects: the Z and R phase-velocity spectra and the RPM (Rayleigh-wave Particle Motion) surface.
On the other side, it can be underlined that through the **HS approach** (a methodology based on the active data recorded by **a single geophone** and processed according to the group velocities and RVSR and RPM curves), it is possible to obtain the same results (Dal Moro et al, 2018).

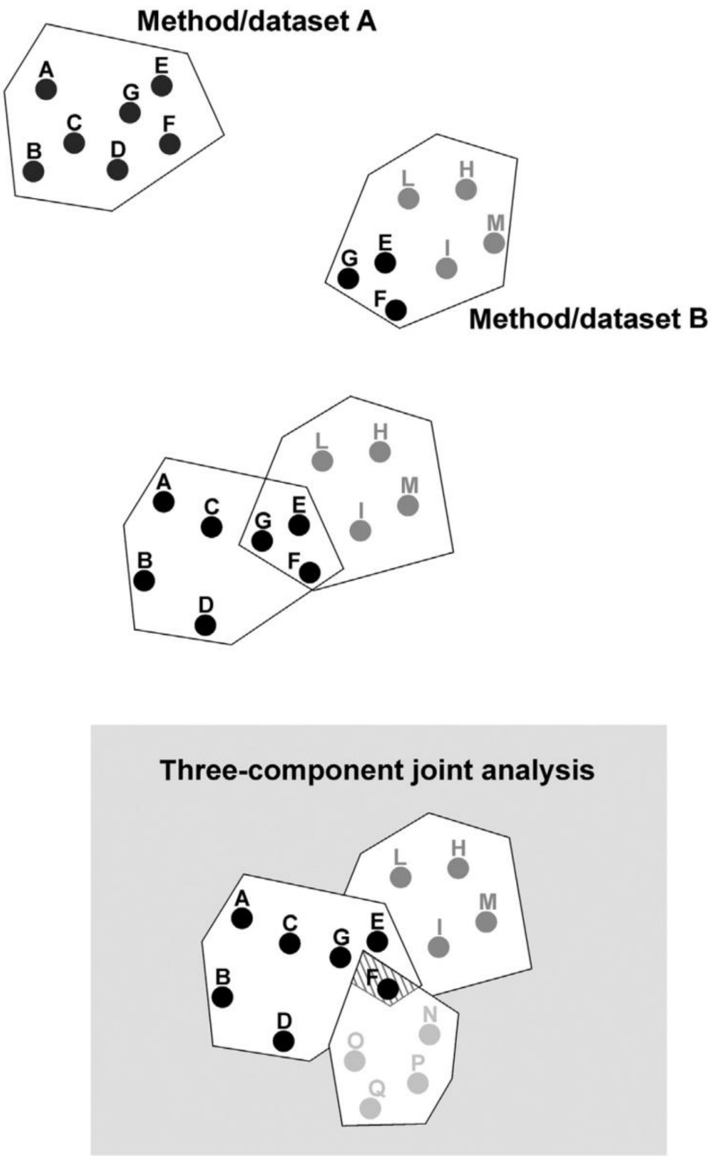

Figure 7. Conceptual scheme representing the importance of the joint analysis for reducing the ambiguity and non-uniqueness of the solution: only by using more “objects” (see Dal Moro et al., 2018 and Dal Moro, 2018) it is possible to fully constrain the solution and identify the correct subsurface model.

Rayleigh Waves

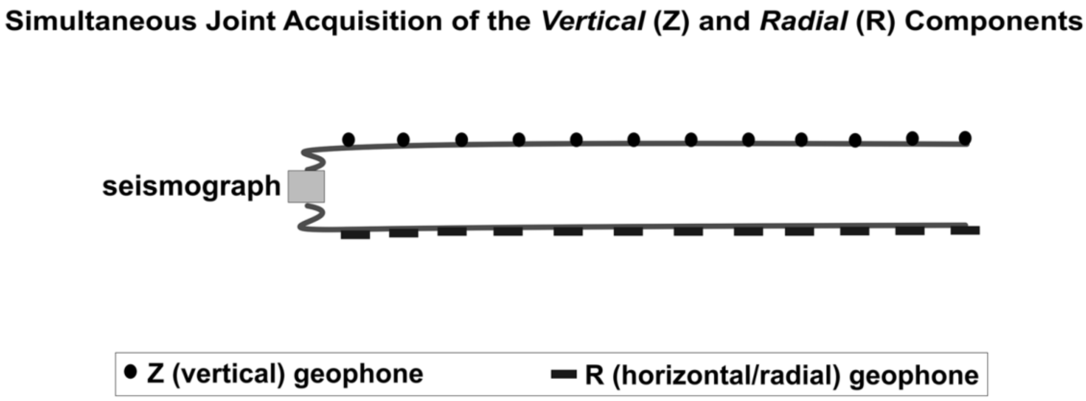

Figure 8. Joint acquisition of multi-offset data for the vertical (Z) and radial (R) components [see also Figure 9] useful for the joint analysis of the Z and R components also jointly with the frequency-offset RPM (Rayleigh-wave Particle Motion) surface [see also Figure 10] . More details in Dal Moro et al. (2018).

Figure 9. A urban multi-component surface-wave survey: Land-streamer equipped for the acquisition of both the Z (yellow vertical geophone) and R (green horizontal geophone) components (see also Figure 8). Courtesy of www.roXplore.ch.

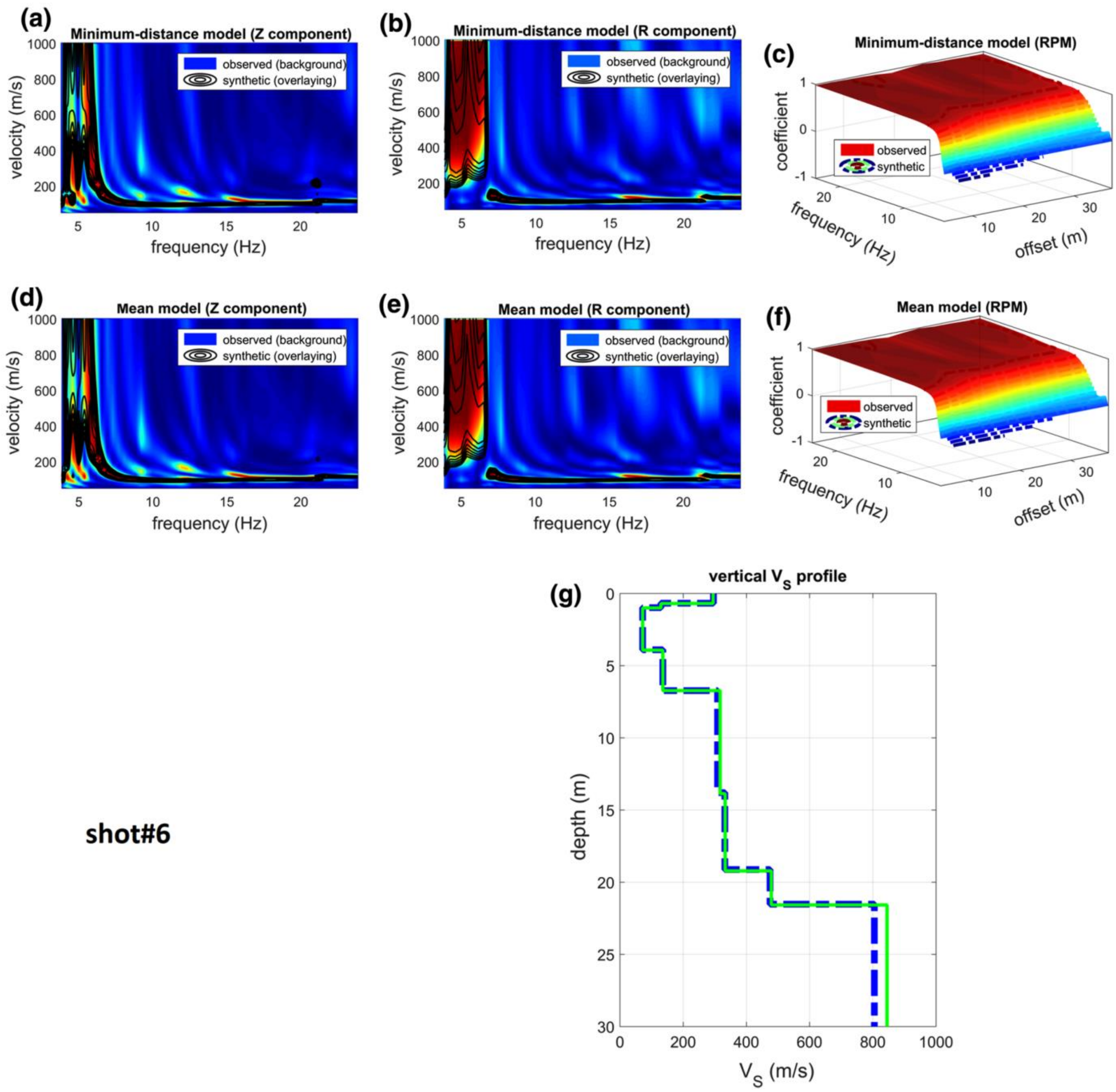

Figure 10. Joint inversion accomplished according to the MO-RPM-HS approach (see Dal Moro et al, 2018). Upper plots refer to the *minimum-distance model*: a) vertical-component phase velocity spectra; b) radial-component phase velocity spectra; c) RPM frequency-offset surfaces. Lower plots refer to the mean model (computed by considering all the Pareto front models): d) vertical-component phase velocity spectra; e) radial-component phase velocity spectra; f) RPM frequency-offset surfaces. The two Vs profiles are reported in the g) plot. For the velocity spectra, the colours in the background represent the field data, while the overlaying black contour lines reflect the synthetic data of the identified models. For the RPM data, the synthetic surface is reported by dashed contour lines with the same colour scale as the field data (since the agreement between the field and synthetic data is extremely good, the two surfaces are visually hardly separable) (from Dal Moro et al., 2018)

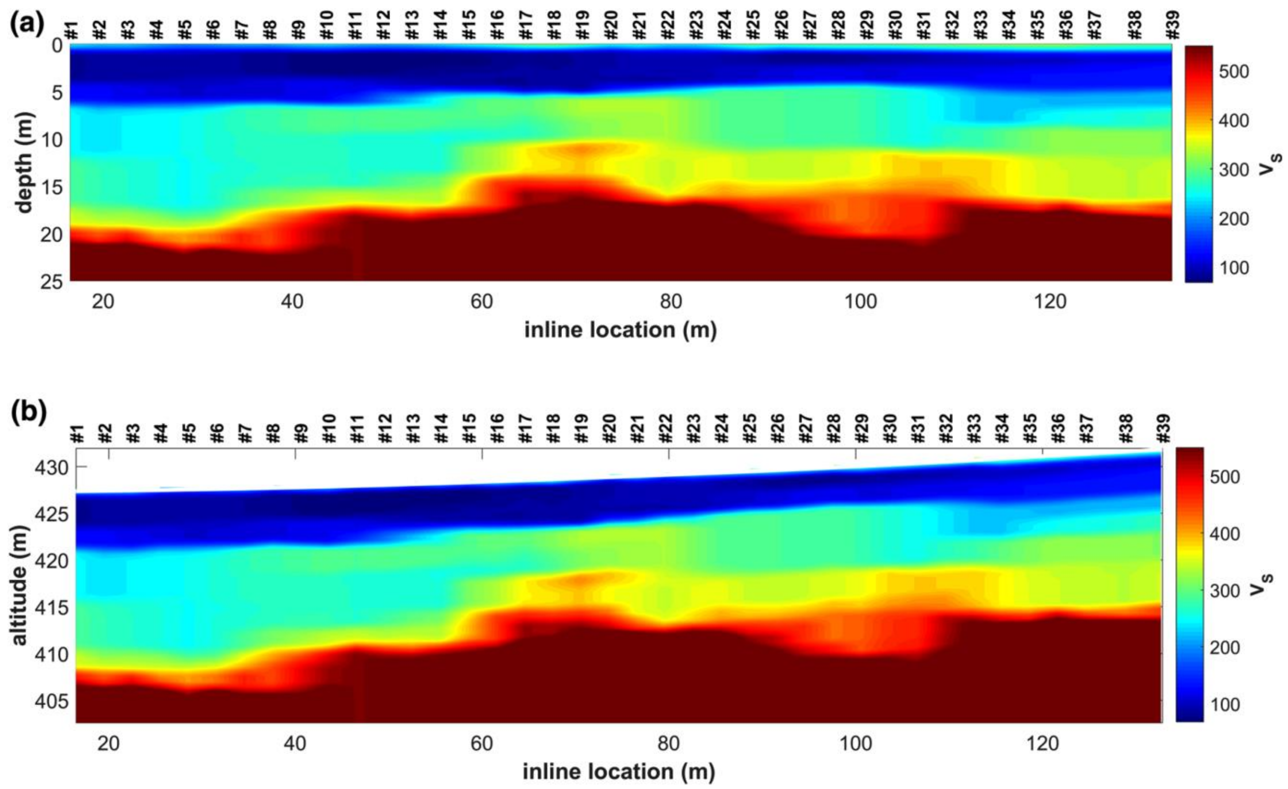

Figure 11. Example of a 2D Vs section obtained from the joint analysis of the Z+R components also jointly with the RPM surface (see Figures 9 and 10): a) Vs section as a function of the inline position and depth from the surface; b) Vs section as a function of the inline position and altitude (above sea level). Labels reported at the top of the two sections indicate the *shot number* (Figure 10 refers to the shot#6). From Dal Moro et al. (2018).

References

Bard, P.-Y. & M. Bouchon, 1980a. *The seismic response of sediment-filled valleys. Part 1. The case of incident SH waves*. Bull. Seism. Soc. Am., 70, 1263-1286.

Bard, P.-Y & M. Bouchon, 1980b. *The seismic response of sediment-filled valleys. Part 2. The case of incident P and SV waves*. Bull. Seism. Soc. Am., 70, 1921-1941

Dal Moro G., 2019. *Surface wave analysis: improving the accuracy of the shear-wave velocity profile through the efficient joint acquisition and Full Velocity Spectrum (FVS) analysis of Rayleigh and Love waves*. Exploration Geophysics, in press (http://www.publish.csiro.au/EG/justaccepted/EG17116)

Dal Moro G., 2018. *Effective Active and Passive Seismics for the Characterization of Urban and Remote Areas: Four Channels for Seven Objective Functions*. Pure and Applied Geophysics, https://doi.org/10.1007/s00024-018-2043-2

Dal Moro G., Al-Arifi N.,Moustafa S.R., 2018. *Improved holistic analysis of Rayleigh waves for single- and multi-offset data: joint inversion of Rayleigh-wave particle motion and vertical- and radial-component velocity spectra*. Pure and Applied Geophysics, 175, 67–88. https://link.springer.com/article/10.1007/s00024-017-1694-8

Dal Moro G., Keller L., Poggi V., 2015. *A comprehensive seismic characterization via multi-component analysis of active and passive data*. First Break, 33, 45-53

Dal Moro G., 2014. *Surface wave analysis for near surface applications*, ISBN 978-0-12-800770-9, Elsevier, 252pp

Scales, J.A., Smith, M.L., Treitel, S., 2001. Introductory Geophysical Inverse Theory. open file. Samizdat Press, 193 pp.

Seed, H.B. and Idriss, I.M., 1971. *Influence of soil conditions on building damage potential during earthquakes*. J. Struct. Engrg., ASCE, 97(2), 639-663.

Tokimatsu, K., Tamura, S., Kojima, H., 1992. *Effects of multiple modes on Rayleigh wave dispersion characteristics*. J. Geotech. Eng. ASCE 118 (10), 1529–1543.

Contacts

e-mail: winmasw@winmasw.com

Twitter: https://twitter.com/#!/winmasw

Skype: g_dal_moro