Shear-Wave Velocity Reconstruction via Unconventional Joint Analysis of Surface Waves: A Case Study in the Light of Some Theoretical Aspects

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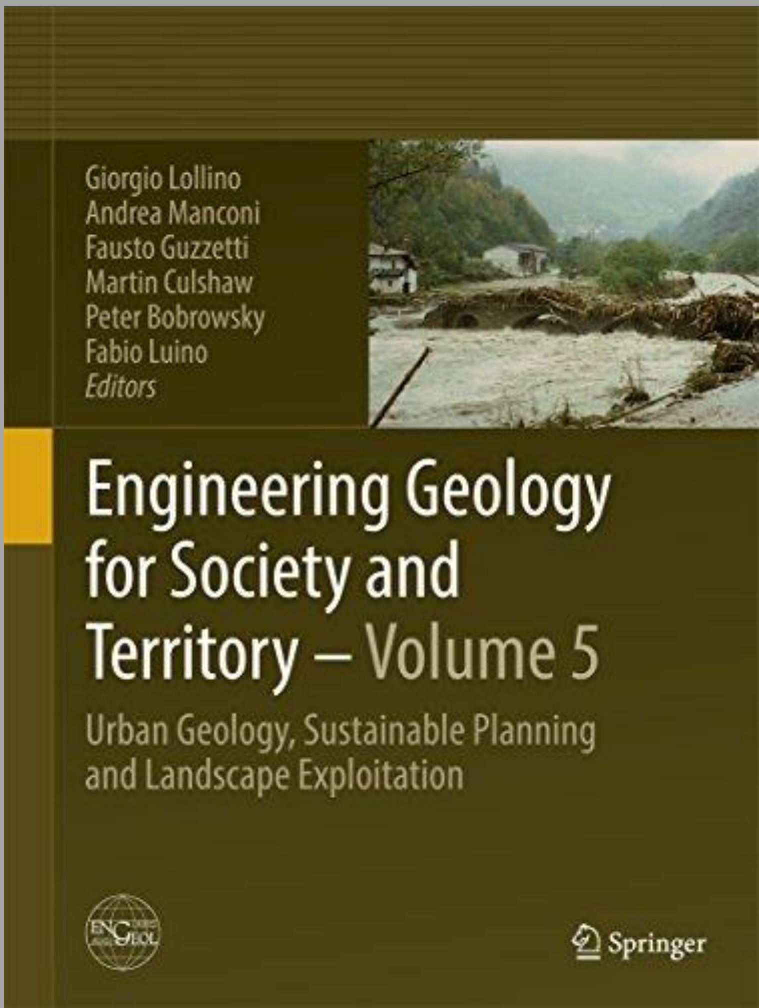

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Giancarlo Dal Moro, Velio Coviello, and Gabriele Del Carlo

Abstract

In site characterisation studies, the unambiguous determination of the shear-wave velocity (V_S) vertical profile is a crucial point often accomplished via surface-wave analysis. The determination of the dispersive properties eventually inverted for the determination of the V_S vertical profile, can be performed both via active and passive methodologies and, for land data, while considering both Rayleigh and/or Love waves. Because of its constitutive equations, Rayleigh-wave propagation is often characterized by a complex phenomenology determining non-trivial mode excitement (thus complex velocity spectra), while Love waves typically result so-to-speak simpler. These aspects logically suggest the use of a joint approach capable of reducing the non-uniqueness of the solution and solving possible interpretative issues particularly problematic when the inversion is performed according to the classical approach (picking of interpreted dispersion curves and successive inversion). After the presentation of a synthetic dataset shown to put in evidence the above-mentioned problematic aspects, a case study solved while adopting a non-ordinary approach (the joint inversion of the whole Rayleigh- and Love-wave velocity spectra accomplished by considering the *Full Velocity Spectrum* approach) is presented.

Keywords

MASW • Rayleigh waves • Love waves • Joint inversion • Full Velocity Spectrum (FVS) analysis

225.1 Introduction

Exploitation of Surface Wave (SW) propagation for retrieving V_S profiles is a technique widely used for a number of applications (e.g. Foti et al. 2000; Luo et al. 2007). Because of some so-to-say *historical* reasons (vertical-component geophones are commonly used for P-wave refraction/reflection studies), Rayleigh waves are often considered as *the* surface waves to consider for MASW (Multi-channel Analysis of Surface Waves) studies while, as a matter of fact, Love waves result often extremely important for properly interpreting complex Rayleigh-wave velocity spectra (e.g. Safani et al. 2005; Dal Moro and Ferigo 2011).

The velocity spectrum presented in Fig. 225.1 shows that a Rayleigh-wave velocity spectrum (the so-to-speak classical MASW) can be quite complex and that the continuity of a

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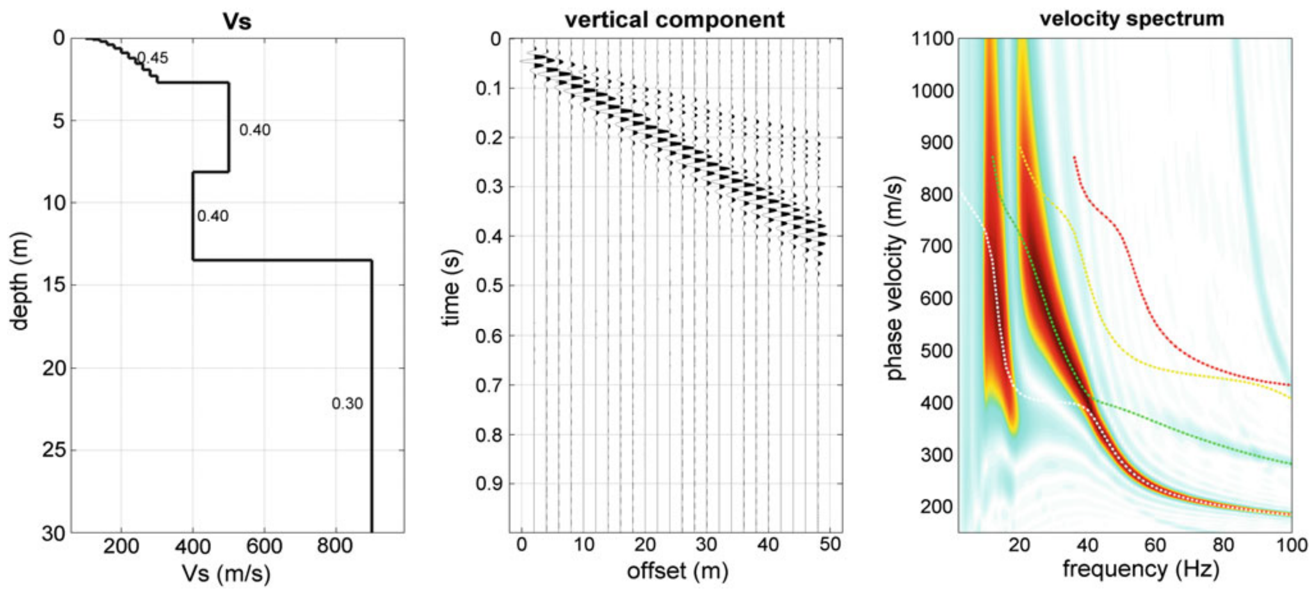

Fig. 225.1 A synthetic dataset: vertical component of Rayleigh waves. From *left* to *right*: V_S model (reported numbers are the adopted Poisson ratios), synthetic traces and velocity spectrum with, overlain, the modal dispersion curves

signal does not necessarily mean that that signal pertains to a single mode. In fact, by comparing the velocity spectrum and the overlain modal dispersion curves it should be apparent that the identification of the modal dispersion curves can be quite tricky: the continous signal at frequencies higher than 20 Hz is in fact related to two modes (the first higher overtone in the 20–40 Hz range, while the fundamental one for frequencies higher than 40 Hz and lower than 20 Hz). In short, sometimes the way SW energy unfolds cannot easily be interpreted in terms of modal dispersion curves since the effective dispersion curve does not follow a trend trivially related to single specific modes (the relation between modal and effective dispersion curves is described in Tokimatsu et al. 1992).

The importance of a joint analysis of different datasets or components of the wavefield such as Rayleigh and Love waves, refraction and/or reflection events and Horizontal to Vertical Spectral Ratio (HVSR) can be a solution both to non-uniqueness and interpretative issues. More specifically, the importance of analyses based (also) on Love waves has been treated for instance by Safani et al. (2005) and Dal Moro and Ferigo (2011).

In the present paper a case study is presented in order to illustrate a non-ordinary approach to SW analysis. The joint analysis of Rayleigh and Love waves (both quickly acquired by using horizontal geophones only) is in fact performed while adopting the *Full Velocity Spectra* (FVS) technique, an approach that considers the entire observed velocity

Table 225.1 The five components that can be considered for SW analysis: first letter indicates the geophones type and orientation (Z, R or T), while the second and third letters relate to the source (VF, EX or HF)—see also Herrmann (2003)

Component	Geophone	Source	Use
ZVF	Vertical (Z) (Fig. 225.2a)	Vertical force (e.g. sledgehammer or weight drop)	Vertical component of Rayleigh waves
ZEX	Vertical (Z) (Fig. 225.2a)	Explosive	Vertical component of Rayleigh waves
RVF	Radial (R)—axis parallel to the array (Fig. 225.2b)	Vertical force (e.g. sledgehammer or weight drop)	Radial component of Rayleigh waves
REX	Radial (R)—axis parallel to the array (Fig. 225.2b)	Explosive	Radial component of Rayleigh waves
THF	Transversal (T)—axis perpendicular to the array (Fig. 225.2c)	Horizontal force (shear source)	Love waves

spectrum without any dispersion-curve picking (i.e. interpretation) (which, as seen in the synthetic case reported in Fig. 225.1, can result quite problematic).

The Herrmann's nomenclature for the different possible source-receiver combinations (see Fig. 225.2) is adopted (Herrmann 2003). Such a nomenclature is summarized in Table 225.1 and it results particularly useful for naming the data files already on the field (during the acquisition) especially when multi-component data are collected (e.g. Dal Moro and Keller 2013).

225.2 The Full Velocity Spectrum Approach

In order to possibly overcome the interpretative issues briefly reported in the introductory paragraph (see Fig. 225.1 and related text), an inversion scheme based on the computation of the synthetic traces and the consequent optimization of the misfit of the whole velocity spectrum was implemented (see schematic representation reported in Fig. 225.3 and compare with O'Neill et al. 2003). As previously reported, for instance the sake of brevity we will refer to this approach as FVS analysis. This approach can be proficiently used both while considering a single component (for instance only the vertical component of Rayleigh waves), both considering more components in a joint manner (for instance the joint analysis of Love and Rayleigh waves).

While in the first case (single-component analysis) the optimization can be performed by adopting a standard heuristic approach based on a single objective function, for properly analyzing two or more components a multi-objective approach such as the one presented in Van Veldhuizen and Lamont (1998) and Dal Moro and Ferigo (2011) can be proficiently adopted.

The computation of the synthetic traces can be efficiently performed via modal summation (e.g. Aki and Richards 2002; Herrmann 2003) and, although the process described in Fig. 225.3 will necessarily result in higher computational load (which would clearly benefit from the parallelized procedures allowed by up-to-date multi-core CPUs), its peculiarities and results allow to properly simulate the whole observed velocity spectrum/a.

Furthermore, this procedure also allows to solve the problem to face while adopting the simpler "effective curve" approach (e.g. Tokimatsu et al. 1992). In fact, the effective curve is actually offset dependent (e.g. Foti et al. 2000) and, consequently, while considering a multi-channel acquisition its computation would result ambiguous if only one offset would be considered.

Being based on all the acquired traces/offsets, the above-described FVS approach overcomes this problem and the "object" considered during the inversion procedure is not any longer a picked dispersion curve but the whole velocity spectrum matrix (i.e. the matrix representing the data correlation as a function of frequency and velocity).

225.3 FVS Joint Analysis of Rayleigh- and Love-Wave Dispersion: A Case Study

The considered dataset was acquired for geotechnical purposes at the foothill of a limestone relief in Central Italy. Rayleigh and Love waves were acquired by adopting the appropriate source and using horizontal geophones only (radial orientation for recording Rayleigh waves and transversal for detecting Love waves—see Fig. 225.2).

Rayleigh waves were produced through a vertical-impact force (a common 8-Kg sledgehammer) while for exciting Love waves we used a simple wooden beam and a horizontal-impact force provided by the same sledgehammer.

From the practical point of view, this approach results in very simple field procedures: Love waves (THF component) are acquired while the horizontal-geophone axis is set

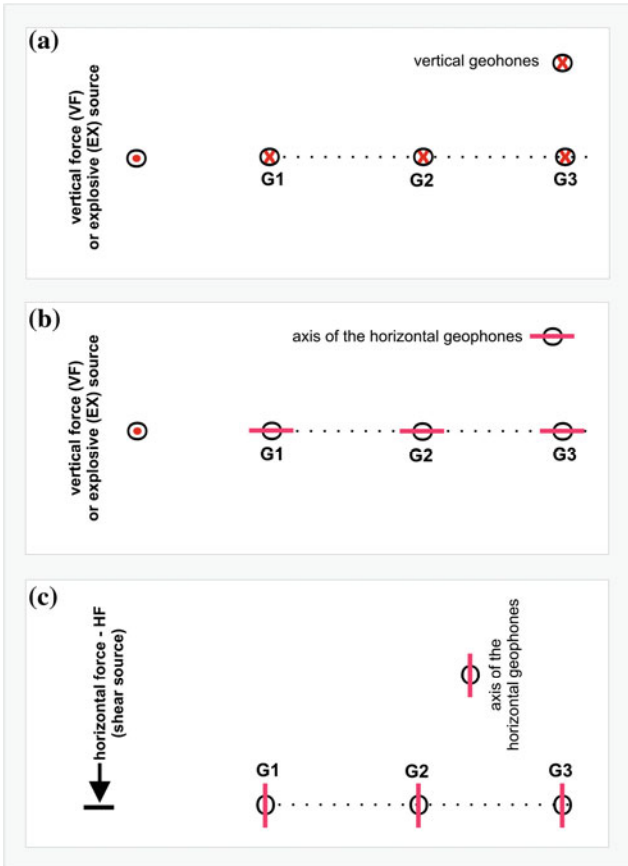

Fig. 225.2 Source and geophone orientation to adopt to obtain the five components useful for SW analysis (see Table 225.1): **a** vertical component of Rayleigh waves; **b** radial component of Rayleigh waves; **c** Love waves

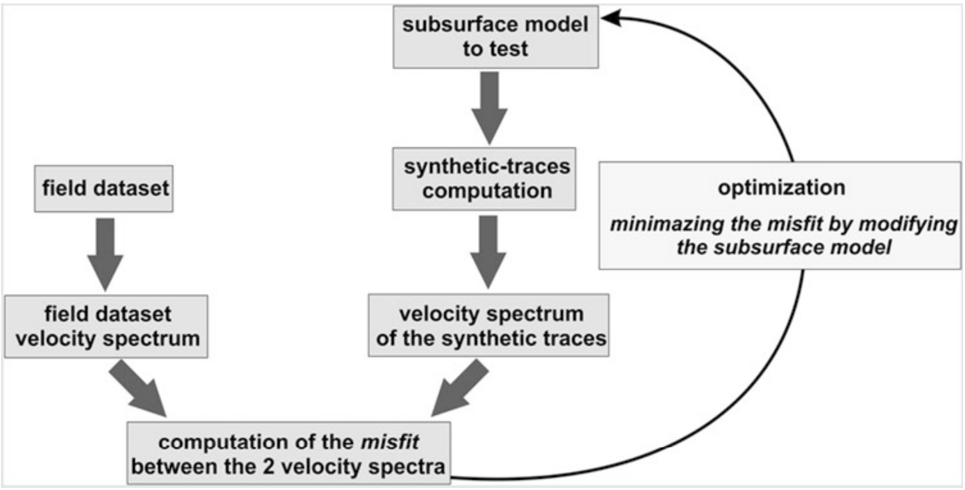

Fig. 225.3 *Full velocity-spectrum* (FSV) inversion: schematic representation of its implementation

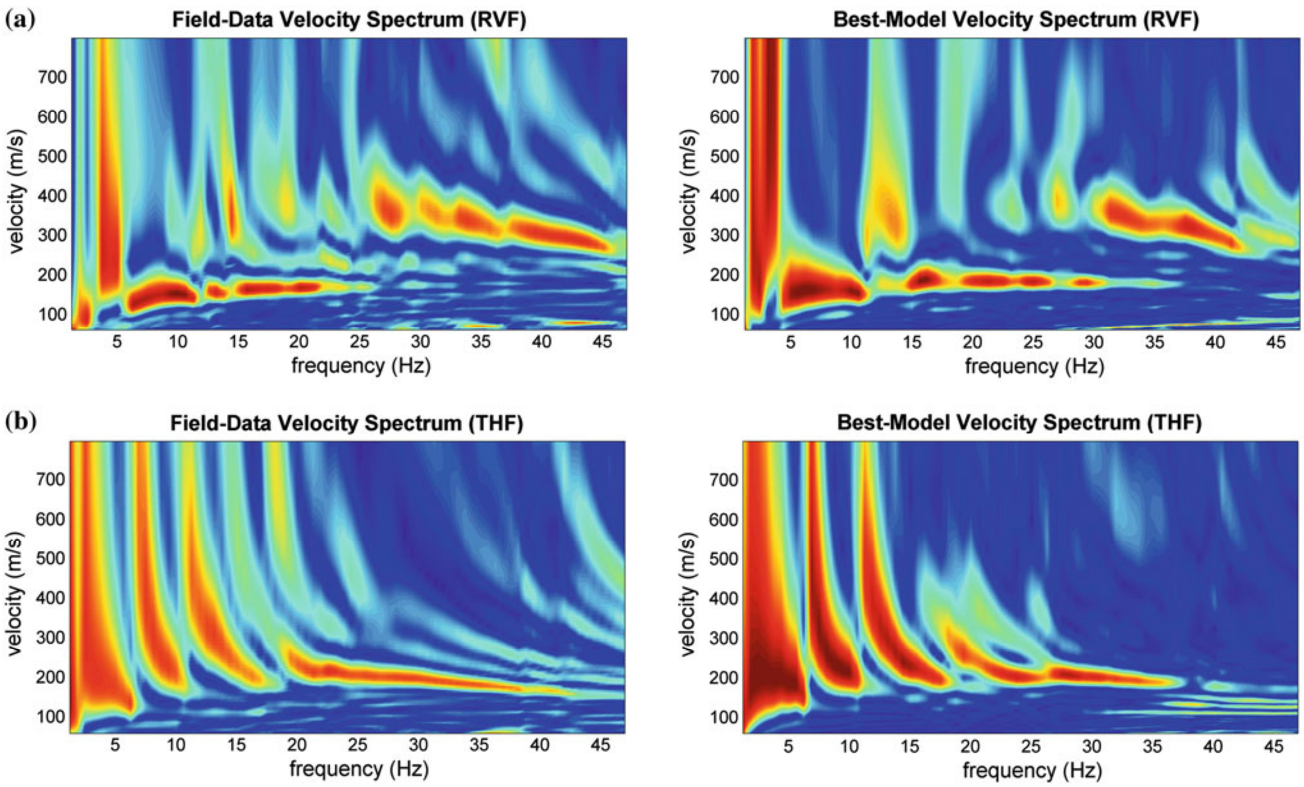

Fig. 225.4 Velocity spectra: on the left column the observed data and, on the right one, the velocity spectra of the best model identified through the FVS inversion procedure. Upper and lower panels report data related to Rayleigh (radial component) and Love waves, respectively. See also Fig. 225.5

perpendicular (transversal) with the respect the array (Fig. 225.2c), while by a simple and quick 90° rotation (aimed at setting the geophone axis parallel to the array) we are then capable of recording the radial component of Rayleigh waves (RVF) (Fig. 225.2b).

Observed velocity spectra are presented in Fig. 225.4 (left column) and show quite peculiar energy distribution among different modes. Velocity spectra were thus jointly inverted following the previously-described FVS approach with the results summarized in Fig. 225.4 (right column): the overall

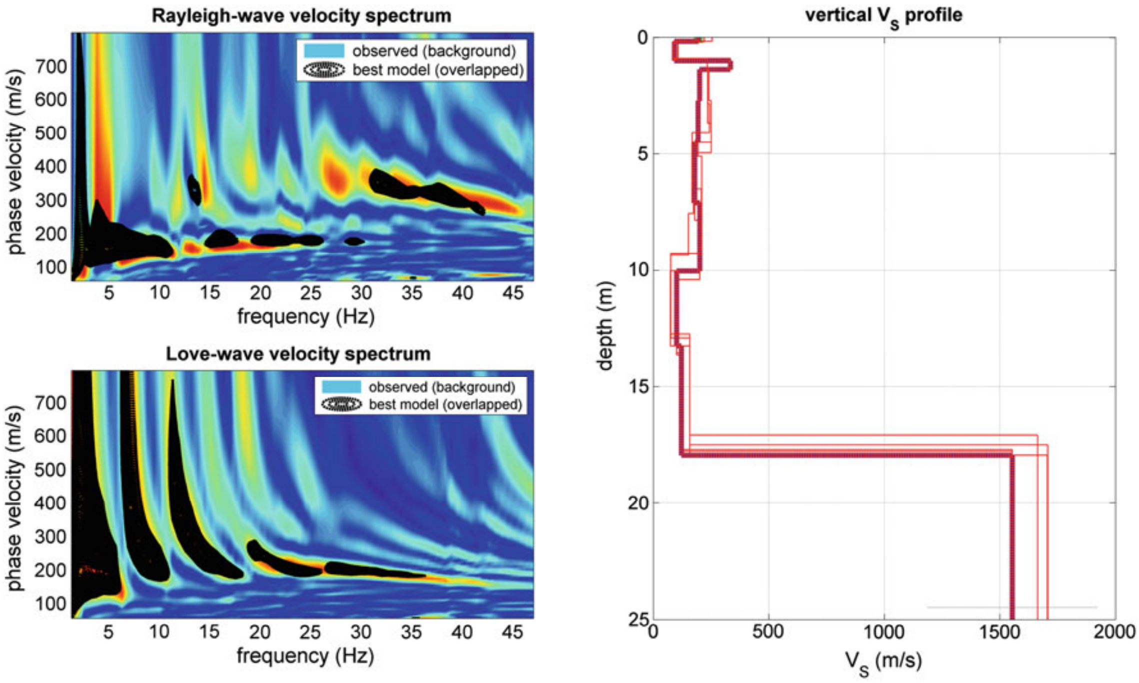

Fig. 225.5 Results of the FVS inversion reported while adopting a more compact graphical representation: the background colours represent the field velocity spectra (see Fig. 225.4, left column) while the overlaying black contour lines report the velocity spectra of the identified V_S model (Fig. 225.4, right column)

very good agreement between the field and the inverted velocity spectra is quite apparent.

In order to further synthesise these results, in Fig. 225.5 are reported the field velocity spectra as colour background and, overlain to them, the contour lines of the same synthetic velocity spectra reported in Fig. 225.4 (right columns) and pertaining to the identified V_S model. It is noteworthy to point out the effect of the small stiff superficial layer (at a depth of about 1.5 m) which is responsible for the peculiar distribution of energy among the different modes evident especially in the Love-wave velocity spectrum where higher modes are particularly energetic.

225.4 Conclusions

Because of its constitutive equations, Rayleigh-wave propagation is often characterized by a complex phenomenology expressed by non-trivial mode excitement, while Love waves result often simpler. As a result, Love-wave velocity spectra typically appear easier to interpret and can be proficiently adopted as a valuable support capable of solving possible interpretative issues resulting from complex Rayleigh-wave velocity spectra.

In the present paper, a non-ordinary approach was used to jointly invert the entire Rayleigh- and Love-wave velocity spectra without any preliminary dispersion curve picking (i.e. interpretation).

Data were quickly acquired by using horizontal geophones only, by rotating them by 90° (Fig. 225.2) and considering the appropriate source (vertical force to produce Rayleigh waves and horizontal force for Love waves).

It must be underlined that the presence of higher modes (particularly prominent in the presented case study) does not have to be considered as a problem: the problem is their correct interpretation (i.e. the correct interpretation of the velocity spectra). Actually, when properly interpreted, higher modes are extremely useful for better constraining the model.

It is also important to point out that, although the proposed FVS approach does not require any interpretation of the modal dispersion curves, the required computational load requires the use of multi-core computers and parallelized procedures.

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