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Determination of the V_S profile in a noisy industrial site: further evidences about the importance of Love waves and the opportunities of the group velocity analysis

Giancarlo Dal Moro
Institute of Rock Structure and Mechanics - Academy of Sciences of the Czech Republic
Prague, Czech Republic

dalmoro@irsm.cas.cz / gdm@winmasw.com

***keywords*:** Surface waves; Rayleigh waves; Love waves; ESAC (*Extended Spatial AutoCorrelation*); MAAM (*Miniature Array Analysis of Microtremors*) ; FVS (*Full Velocity Spectrum*); joint analysis; phase velocity; group velocity, surface waves; HVSR; HS (*Holistic analysis of Surface waves*); RPM (*Rayleigh-wave Particle Motion*)

Introduction

In the last decade, the analysis of surface-wave propagation has become extremely popular especially in the framework of seismic-hazard studies although, as a matter of fact, the determination of the shear-wave velocity (V_S) profile is useful for any geotechnical or geological application that requires the knowledge of the subsurface conditions.
In it well known that the accuracy of the V_S profile depends on the number of observables considered in the inversion process and on the kind of analyses actually put in place. In fact, in spite of the popularity of the approach based on the interpretation of the modal dispersion curves of the vertical component of Rayleigh waves (MASW – Multichannel Analysis of Surface Waves), a wide range of further options are possible and capable of providing better results, free from major ambiguities and pitfalls that characterize the standard MASW approach.
For the present illustrative study, we considered a set of multi-component active and passive data gathered in a NE-Italy heavily-industrialised area home to many industries related to metalworking and therefore characterized by an extremely-high level of microtremors.

Data and analyses

With the goal of defining the best procedures necessary to unambiguously define the subsurface model in a very noisy industrial area in NE Italy, we collected a comprehensive series of active and passive seismic data. Active data were recorded by means of a single 3-component sensor in order to work with the Holistic analysis of Surface waves (HS) (Dal Moro et al., 2019; Dal Moro, 2018; 2020) while passive data were recorded so to define the HVSR (Horizontal-to-Vertical Spectral Ratio), the dispersion curve of the vertical (Z) component of Rayleigh waves via Miniature Array Analysis of Microtremors (MAAM - Cho et al., 2006a; 2006b; 2013; Tada et al., 2007; Dal Moro et al., 2015a; 2018) and the Love-wave dispersion curve via ESAC (Extended Spatial AutoCorrelation - Ohori et al., 2002). MAAM was accomplished considering a triangular geometry with a radius of 1.7 m while data for the ESAC were collected considering various multi-offset linear arrays with total lengths ranging from 44 to 60 m and with different orientations (for a series of clarifications about the performances of the MAAM and ESAC techniques see Dal Moro, 2020).
Since it was systematically observed that Rayleigh-wave phenomenology is extremely complex and therefore prone to significant ambiguities and pitfalls (Safani et al., 2005; Dal Moro et al., 2015b; Dal Moro, 2020), first of all we accomplished the joint inversion of the HVSR together with the effective dispersion curves of the Z and T components (i.e. the vertical component of Rayleigh waves and Love waves) as obtained from MAAM and ESAC, respectively (see data and results shown in Fig. 1).

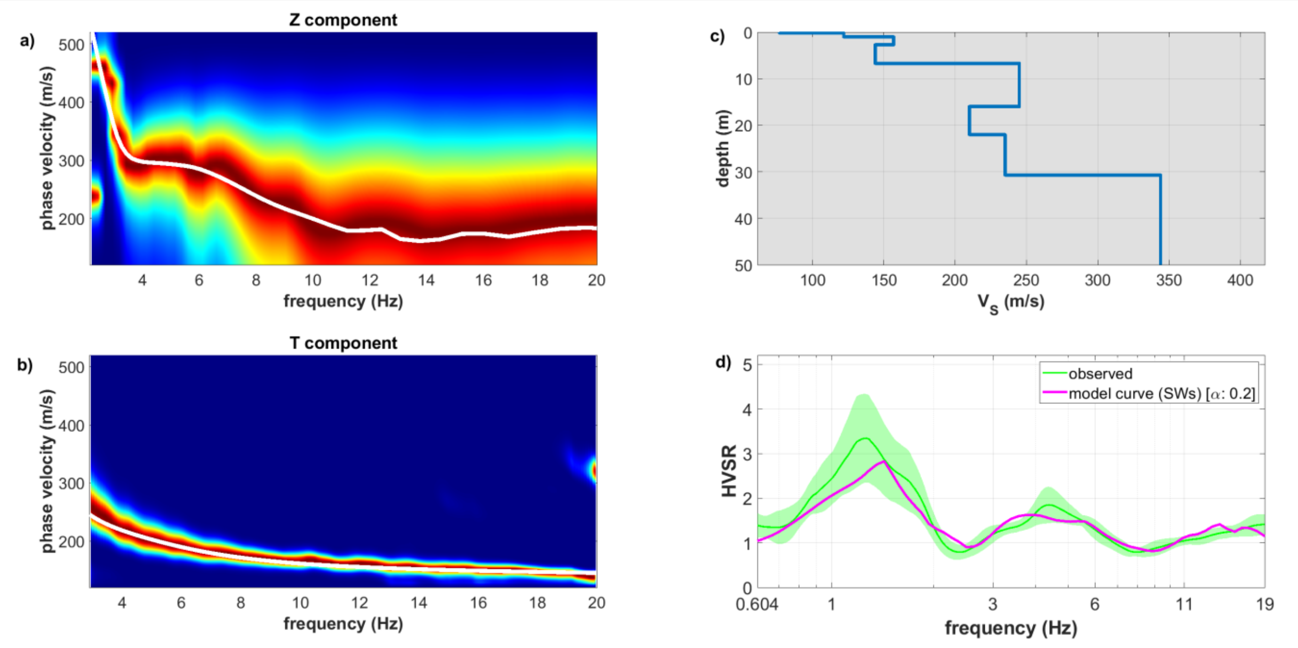

Figure 1. Purely passive data: shear-wave velocity profile (*c* plot) obtained through the joint analysis of the phase-velocity effective dispersion curves of the Z (*a* plot) and T (*b* plot) components together with the HVSR curve (*d* plot). In the *a* and *b* plots, the background colours represent the field data while the overlaying white curves are the effective dispersion curves of the identified subsurface model. In the *d* plot, the α value (0.2) in the legend represents the amount of Love waves in the microtremor field (Arai and Tokimatsu, 2004; Dal Moro, 2020).

Since a more common approach is based on the joint analysis of Rayleigh-wave dispersion and HVSR (e.g. Arai and Tokimatsu, 2005), in order to compare the outcomes we also accomplished this kind of simpler approach (in other words, unlike before, now we are not considering the Love-wave dispersion). Fig. 2 shows the obtained results. Although the overall misfits appear quite good and would inevitably represent a very satisfactory result, the comparison with the solution obtained while considering both Rayleigh and Love waves (see Fig. 1 and related text) demonstrates that the use of Rayleigh waves alone can lead to erroneous solution which are necessarily associated to higher V_S values. This is easily and plainly demonstrated if we compute the Love-wave dispersion from the V_S profile shown in Fig. 2c and compare it with the field data (i.e. the velocity spectrum shown in Fig. 1b): the Love-wave phase velocities of the model are significantly higher than the observed ones.
This is a very common problem (mistake) due to the intrinsic ambiguity of the Rayleigh-wave effective curve which, whether considering active or passive data, can be explained by a large variety of energy distribution and therefore models (Dal Moro, 2020) which cannot be solved by the HVSR (which, in turn, suffers from major non-uniqueness issues). In this case, as in other previously-published (e.g. Dal Moro, 2019; 2020), only the presence of Love waves can properly channel the inversion procedure towards the correct solution.

It should be clearly underlined that in both the accomplished procedures reported in Fig. 1 and 2, the observed dispersion curves were not interpreted in terms of modal curves but modelled according to the mathematics of the effective curve (Tokimatsu et al., 1992; Ikeda et al., 2012).

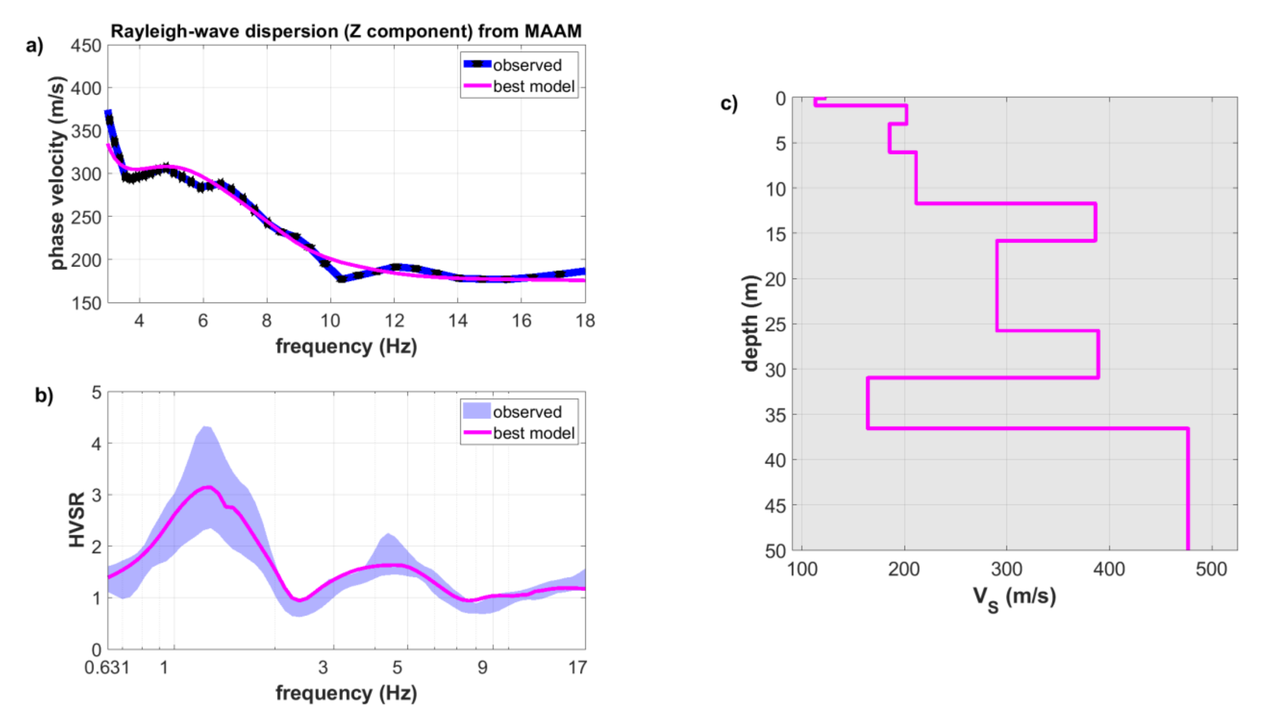

Figure 2. Result of the joint analysis of the phase-velocity effective dispersion curve of the Z component (*a* plot) and the HVSR (*b* plot). The ambiguities of the Rayleigh-wave effective dispersion curve (and HVSR) are such that the obtained shear-wave velocities (V_S profile shown in the *c* plot) overestimate the actual values. Compare with the result presented in Fig. 1 and see text for comments.

A different approach to surface-wave analysis is possible through the computation of the group velocities and their holistic analysis jointly with the Rayleigh-wave Particle Motion (RPM) curve (describing the actual particle motion due to the Rayleigh-wave propagation and quite useful in further constraining the subsurface model) and, in case we intend to investigate deeper strata, the HVSR (Dal Moro et al., 2017; 2019; Dal Moro, 2018; 2020). Group velocities are computed via frequency-time analysis (Levshin et al., 1972) and can be obtained both from passive (e.g. Fang et al., 2010) and active data (Ritzwoller and Levshin, 1998; 2002; Dal Moro et al., 2019). Differently than phase velocities, group velocities can be obtained considering a very limited field equipment which is fundamentally based on just one or two 3-component geophones, depending on whether we are considering passive or active data.
Data considered in the present study were recorded by means of a 3-component geophone deployed at a distance of 44 m from the source (a 10-kg sledgehammer). Due to the high

noise level, stack was fixed to 25. Fig. 3 shows both the extracted data (group velocity spectra of the Z and R components as well as the RPM curve) and the solution of the holistic analysis of surface waves (HS), i.e. the joint analysis of multi-component group velocities together with the RPM and the HVSR (this latter is useful to extend the investigated profile in depth). It should be underlined that in the HS approach, dispersion data (group-velocity spectra) are not analysed through the interpretation of the dispersion curves but through the multi-component Full-Velocity Spectrum (FVS) approach (Dal Moro et al., 2015a; 2015b; 2019; Dal Moro, 2019; 2020).

The result (V_S profile shown in Fig. 3e) is apparently very similar to the one obtained by considering the joint analysis of the phase velocities of the Z and T components together with the HVSR (see Fig. 1).

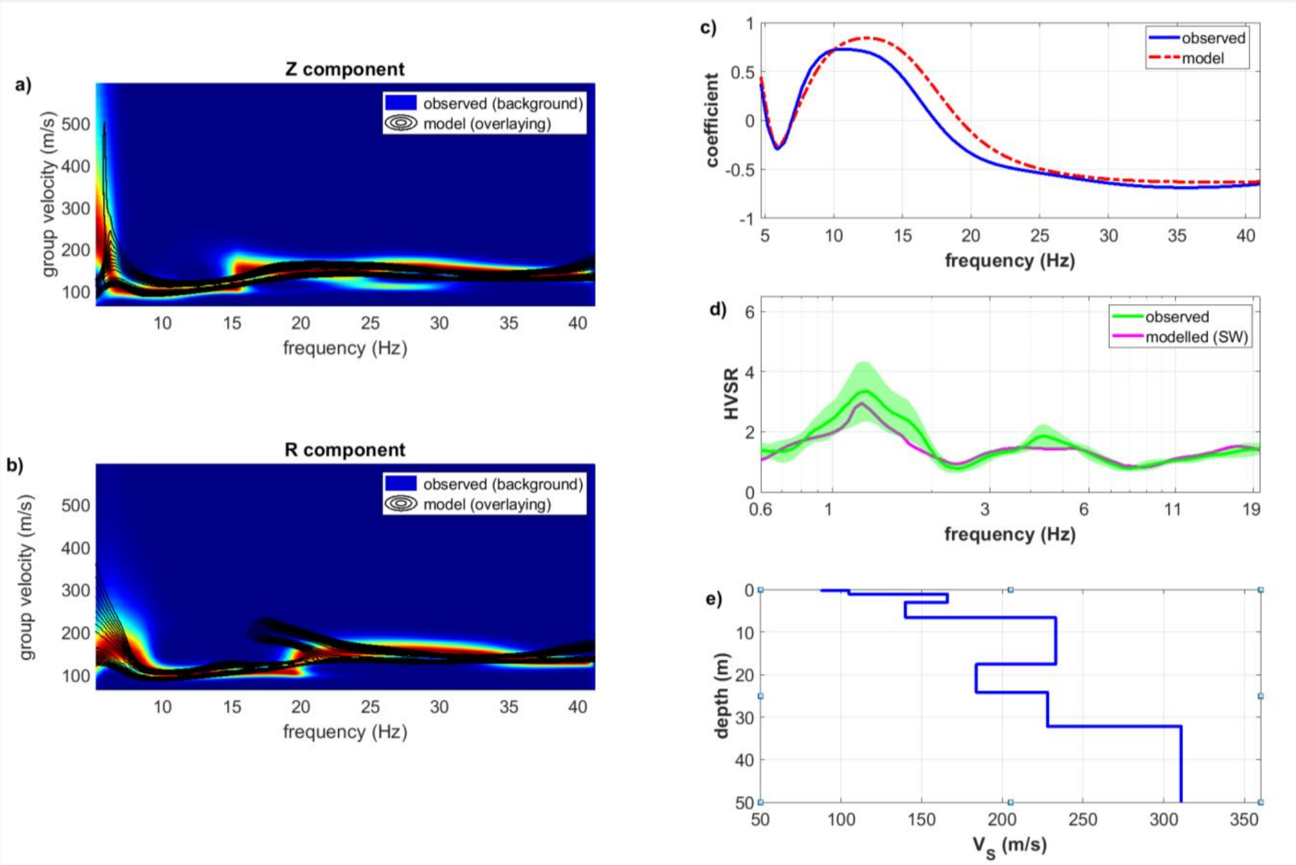

Figure 3. Holistic analysis of the group velocities of the vertical (Z) (*a* plot) and radial (R) (*b* plot) components (FVS approach – background colours represent the field data while the overlying black contour lines the obtained model) jointly with the RPM (*c* plot) and HVSR (*d* plot) curves. The obtained V_S profile (*e* plot) is entirely similar to the one obtained while considering the joint analysis of the phase velocities of the Z and T components (see Fig. 1).

Conclusions

Accomplished analyses allow to highlight the following evidences:

1) Rayleigh-wave modelling cannot be performed considering an approach based on the modal dispersion curves and the use of the effective curves (for passive data) or the FVS (for active data) is crucial;
2) Because of the intrinsic (i.e. inevitable) ambiguity of the dispersion curve, Rayleigh-wave modelling based on the effective curve does not ensure the correctness of the obtained V_S profile even when performed jointly with the HVSR;
3) Especially when analysing phase velocities, the acquisition and analysis of Love waves reveal decisive to constrain an inversion procedure capable of providing a robust solution free from significant ambiguities;
4) Love-wave dispersion can be effectively obtained from passive data via ESAC even while considering linear arrays (data and analyses are not affected by significant directivity issues);
5) The holistic analysis of multi-component group velocities and RPM curves based on the FVS approach reveals an effective way to obtain robust shear-wave velocity profiles.

Since a solution needs to be of general validity, it is therefore clear that phase velocity analyses based just on Rayleigh waves are not recommended because, due to the complex contribution of different modes, they can lead to overestimated Vs values even if the analyses are accomplished jointly with the HVSR. Due to their simpler phenomenology, Love waves represent an essential tool to properly constrain an inversion procedure.
On the other side, the holistic analysis of multi-component group velocities and RPM data appear an extremely efficient alternative both because it requires a simpler acquisition setting, both because, thanks to the possibility to deal with a large number of observables, it leads to a V_S profile free from major ambiguities.

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