The magnifying effect of a thin shallow stiff layer on Love waves as revealed by multi-component analysis of surface waves

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In the last decades, surface wave analysis has become a standard tool for an increasingly large number of geotechnical applications that require the determination of the subsurface shear-wave velocity ($V_S$) profile. In the present paper, we investigate the role of a shallow stiff layer on Rayleigh and Love wave propagation. Multi-component synthetic and field data are considered to analyse the vertical (Z) and radial (R) components of Rayleigh waves as well as Love waves (T component). Velocity spectra are analysed according to the Full Velocity Spectrum (FVS) approach together with the Rayleigh-wave Particle Motion (RPM) frequency-offset surface that reveals the actual prograde-retrograde motion of Rayleigh waves. The FVS approach to surface wave analysis reveals particularly powerful in case we intend to reproduce the actual modal energy and when, because of complex mode excitation, the velocity spectra cannot be easily interpreted in terms of modal dispersion curves. The analysis of both synthetic and field data highlights two major facts. On one side, along the T component (Love waves) the presence of a thin shallow stiff layer excites higher modes whose top velocity is controlled by the shear-wave velocity of the deeper layers. On the other side, such a stiff layer does not massively influence the velocity spectra of the Z and R components (Rayleigh waves) and the related RPM: irrespective of the presence of the superficial stiff layer, RPM clearly shows the change from retrograde to prograde due to the $V_S$ increase in the deep layers. In case a superficial stiff layer is present (this condition is quite common in urbanized areas such as the one of the field dataset here considered), Love waves can then be an interesting tool for an expeditious estimation of the $V_S$ of the deep layers.
For instance, while considering Rayleigh waves, the acquisition of both the vertical (Z) and radial (R) components allows also the computation and analysis of the Radial-to-Vertical Spectral Ratio (RVSR) and the Rayleigh-wave Particle Motion (RPM) data which can be jointly inversed with the Z and R velocity spectra. Joint inversion can be accomplished considering the single objective function defined as the summation of the misfits obtained from the considered observables or through a multi-objective inversion scheme.

Several recent studies have pointed out the utility of Love waves in near-surface applications. It was shown that while Rayleigh waves can be extremely complex to interpret in terms of modal dispersion curves, Love-wave velocity spectra are usually much simpler and therefore represent an important tool to avoid pitfalls in the interpretation of the Rayleigh-wave velocity spectra.

Furthermore, in some previous studies about Love waves, it was observed that a superficial stiff layer may excite higher modes and give rise to peculiar phase-velocity spectra. A stiff layer can be considered as the opposite of a Low-Velocity Layer (LVL), i.e. as a layer whose velocity is higher than the velocities of the layers above and below it (the case of a superficial layer is just a special case).

In the present paper, the effect of a shallow stiff layer is investigated in detail through the analysis of the behaviour of Rayleigh and Love waves for a series of synthetic and field datasets.

In general terms, it must be underlined that higher modes do not represent a problem but rather a source of valuable information that, if properly handled, significantly helps in better constraining the inversion process, thus retrieving the subsurface model.

Data and analyses presented in this paper refer to multi-channel, multi-offset and multi-component data that can be generically referred to as MASW (Multichannel Analysis of Surface Waves), although the presented analyses go beyond the classical inversion of the modal dispersion curve(s) interpreted from the phase-velocity spectrum obtained from a single-component dataset and attempt to describe and analyse the propagation of surface waves in a more comprehensive (holistic) perspective.

Surface-wave dispersion is here analysed according to the Full Velocity Spectrum (FVS) approach, thus without interpreting the velocity spectra in terms of dispersion curves. Furthermore, Rayleigh waves are analysed not only with respect to the velocity spectra of the vertical and radial components, but also considering the actual particle motion.

The Rayleigh-wave Particle Motion (RPM) frequency-offset surface was recently introduced in order to provide a quantitative description of the actual Rayleigh-wave motion, which is often far from being retrograde (as often erroneously believed). Such a surface represents the correlation values between the radial component and the Hilbert transform of the vertical component as a function of both the frequency and offset: +1 indicates a pure retrograde motion, while -1 a pure prograde motion. Since the actual particle motion is a complex mix, the correlation values range between +1 and -1 as a function of both the frequency and offset.

In order to better constrain the subsurface Vp model, field data are therefore analysed by considering the RPM frequency-offset surface jointly with the phase velocity spectra of all the three considered components (Z, R and T). The nomenclature adopted is described in details in several papers: ZVF and RVF refer to the vertical (Z) and radial (R) components while considering a Vertical Force (VF) source (e.g. a common sledgehammer or weight drop), while THF is the transversal (T) component when a Horizontal Force (HF) is applied.

**Synthetic data: the phase-velocity spectra**

In order to investigate the role of a surficial stiff layer on surface-wave propagation, we computed a series of synthetic seismograms based on the modal summation approach [we considered the first 10 modes]. The four considered models (Fig. 1) differ because of the presence of a superficial layer (models #2, 3 and 4), the depth of the “deep” (gravel-like) layer (for the models#1, 2 and 3 is slightly more than 10 m while for the model#4 slightly more than 7 m) and for the Vp value of the deep stiff material (350 m/s for the models#1 and 2 and 600 m/s for the models#3 and 4).

The effect of a thin superficial stiff layer can be highlighted through the comparison of the seismic traces and phase-velocity spectra of the four considered models.

While Rayleigh-wave velocity spectra show minor differences and just in the very high frequency range (compare for instance the Z component in Figs. 2a and 3a), the effect of the shallow stiff layer on Love waves is definitely more significant. In fact, when a shallow stiff layer is present, large-amplitude higher modes appear (compare Figs. 2c and 3c) and their top velocities closely relate to the Vp value of the deep (gravel-like) layer.

This is apparent also by comparing the theoretical power spectra of the transversal component (Love waves) for the four considered models. The computed power spectra express the amount of energy of each mode and are reported in Fig. 4 together with the respective modal dispersion curves. By comparing the power spectra of the four models it is clear that the presence of a shallow stiff layer excites the higher modes that have otherwise a lower energy compared to the fundamental mode (Fig. 4a). For the model#2, on the other hand, the top velocity of the higher modes is larger than 9 Hz (associated to the deep layer).

It is once again clear that the top velocities of the Love- higher modes are closely related to the shear-wave velocity of the deep layer even at very high frequencies while Rayleigh waves provide information about the deep layers just in the low-frequency range.
The power spectra of the model#3 (Fig. 4c) show, for instance, that in the 21–31 Hz frequency range the most energetic mode is the second higher mode that reaches a “top velocity” of about 600 m/s (see the phase-velocity spectrum in Fig. 5c).

Is it clear that the top velocities observed in the phase-velocity spectra (computed from the seismic traces according to the phase-shift method 14) correspond to the area (velocities) where Love-wave modal dispersion curves reach a plateau value of about 350 m/s for the models #1 and 2 and 600 m/s for the models #3 and 4 (see modal dispersion curves in the upper plots of Fig. 4).

We can also point out that the presence of a shallow stiff layer is responsible for a peculiar feature of the seismic traces of the transversal component (Love waves), which assume a hyperbola-like characteristic trend (see Fig. 6 and compare with Fig. 2c).

By comparing the data reported in Figs. 5c and 7c (models #3 and 4), it is also clear that the number of higher modes in a fixed frequency range depends on the depth of the deep stiff layer (the shallower the contact, the lower the number of higher modes) but the top velocity of the higher modes does not significantly change.

Further insights from synthetic data. Data and analyses presented in the previous section demonstrate the effect of a superficial stiff layer on the phase-velocity spectra of Love and Rayleigh waves. While Love waves reveal the deep VS values through their massive higher modes (even at high frequencies), the phase-velocity spectra of Rayleigh waves do not appear dramatically influenced by such a superficial stratigraphic feature.

We might anyway wonder whether the particle motion induced by the Rayleigh waves is or not influenced by the presence of such a shallow stiff layer.

In order to address this point, we can compare the RPM frequency-offset surfaces for model#3 and model#1, i.e. for two models that differ for the presence of a superficial stiff layer.

From the comparison of the RPM surfaces shown in Fig. 8a,b, it is clear that in the frequency range of primary interest in common near-surface applications (about 4–30 Hz) the presence of a surficial stiff layer does not significantly affect the prograde-retrograde motion of Rayleigh waves (between 4 and 5 Hz Rayleigh waves change their motion from retrograde to prograde because of the large VS increase at about 10 m of depth).

As shown in the previous section, Love waves can be quite effective for the characterization of even relatively-deep features but a further question arises: what is the influence of the array length?

In order to briefly investigate this point, two final synthetic datasets were computed considering the model#3 (Fig. 1). The synthetic traces and velocity spectra obtained while considering two different arrays are reported in Fig. 9. The comparison of the computed phase-velocity spectra shows that, in a given frequency range, the number of excited higher modes is the same. On the other side, because of simple mathematical facts (the velocity spectra shown in this work were computed according to the phase-shift method 14), in case of very short arrays the velocity spectrum is less focused.

Surface-wave dispersion analysis: the FVS approach in brief. In order to clarify the analysis of the field dataset presented in the next section, we here briefly summarize the Full Velocity Spectrum (FVS) approach to dispersion analysis 13,18,23,26,28. In fact, the analysis of interpreted modal dispersion curves 14,27,31 is not the only way to analyse surface wave propagation and the FVS technique represents a possible improved approach.

The FVS approach is based on the computation of the synthetic traces hereby accomplished via modal summation 14,26,28. Considering the simple single-component case, once the velocity spectrum of the field traces is computed, the FVS inversion consists of three main steps:
Figure 2. Synthetic seismograms and phase-velocity spectra for the model#1 (no superficial stiff layer): (a) ZVF (vertical component of Rayleigh waves considering a Vertical Force source); (b) RVF (radial component of Rayleigh waves); (c) THF (Transversal component obtained considering a Horizontal Force source - Love waves).

Figure 3. Effect of a superficial stiff layer: synthetic seismograms and phase velocity spectra for the model#2 (which differs from model#1 only because of a thin surficial stiff layer): (a) ZVF (vertical component of Rayleigh waves); (b) RVF (radial component of Rayleigh waves); (c) THF (Love waves). The top velocity of the THF higher modes is closely related to the $V_s$ of the deep layer (see model#2 in Fig. 1).
(1) computation of the synthetic trace(s) of a tentative model;
(2) computation of the velocity spectra of the synthetic traces;
(3) computation of the misfit between the velocity spectra of the field and synthetic traces.

Figure 4. Transversal (T) component (Love waves): phase-velocity modal dispersion curves (upper panel) and power spectra (lower panel) for the four considered models (model#1 is the one without the surficial stiff layer). Shown the curves for the first six modes. The power spectra shown in the lower panel provide the evidence of the reason why, in case a shallow stiff layer is present, higher modes dominate over the fundamental one. Further comments in the text.

Figure 5. Effect of a superficial stiff layer: synthetic seismograms and phase velocity spectra for the model#3: (a) ZVF (vertical component of Rayleigh waves); (b) RVF (radial component of Rayleigh waves); (c) THF (Love waves). The top velocity of the THF higher modes is closely related to the VS of the deep layer (see model#3 in Fig. 1).
These three steps are implemented within a heuristic optimization algorithm that minimizes the misfit, thus eventually providing a subsurface model that has a velocity spectrum as close as possible to the velocity spectrum of the field data. It is important to understand that this way we deal with the entire velocity spectrum (i.e., the frequency-velocity matrix) and not with a dispersion curve (i.e., a frequency-velocity curve that represents a personal - i.e. subjective - interpretation of the velocity spectrum in terms of modal dispersion curves). Figure 10 reports an example of single-component FVS analysis and intends to briefly and visually express how, during a FVS inversion process, we aim at identifying a subsurface model whose velocity spectrum is as close as possible.
to the one of the field traces. In fact, as Fig. 10b clearly shows, the phase-velocity spectrum (black contour lines) of the synthetic traces of the subsurface model identified by means of the above-mentioned inversion scheme matches quite well with the velocity spectrum of the field data (background colours and Fig. 10a).

We should highlight that the classical analysis of the modal dispersion curves do not demonstrate that a certain mode is (or not) excited. On the other side, the FVS approach provides the evidence that a certain mode is actually excited and we can therefore better constrain the inversion process. The analyses reported in Fig. 11 can help to further clarify this point. In the upper plot (Fig. 11a) we show an example of standard modelling based on the modal dispersion curves. The velocity spectrum of the field data (background colours) is interpreted so that the energy below 7 and above 15 Hz pertains to the fundamental mode while in between to higher modes.
Figure 10. Example of single-component FVS analysis: (a) phase-velocity spectrum of a field dataset (THF component – i.e. Love waves); (b) phase-velocity spectra for the field data (background colours) and for the model obtained through the FVS inversion (overlaying black contour lines - the agreement between the two velocity spectra is apparent); (c) identified V₃ model; (d) qd values (dynamic point resistance) from a DPSH (Dynamic Probing Super Heavy) penetrometer test performed down to 9.8 m. The shallow stiff layer at a depth of about 2 m is responsible for the higher modes that largely dominate the THF velocity spectrum.

Figure 11. Upper plot: standard surface-wave analysis via modal dispersion curves (background colours represent the phase-velocity spectrum of a field dataset while the three overlying dispersion curves refer to the first three modes of a tentative subsurface model); lower plot: FVS analysis of surface-wave dispersion: the overlaying black contour lines refer to the phase-velocity spectrum of the model identified via FVS inversion. The field and synthetic velocity spectra are in apparent good agreement. See text for comments.
Anyway, this standard approach to surface-wave analysis via modal dispersion curves presents a clear problem: modal curves do not show which modes are actually exited. In fact, considering the data reported in Fig. 11a we might ask: how can we provide the proof that between 7 and 15 Hz higher modes are actually excited? Or, similarly: why below 6 Hz and between 15 and 30 Hz the data are dominated by the fundamental mode and not by higher overtones? How can we demonstrate that, in a given frequency range, the considered subsurface model actually excites certain modes?

The FVS approach provides the evidence (i.e. the proof) that, frequency by frequency, certain modes are (or not) excited.

In fact, if we consider the data reported in Fig. 11b, we can see that the velocity spectrum of the identified model (overlying black contour lines) excellently reproduces the velocity spectrum of the field data. In other terms, the identified model is associated to a velocity spectrum that, in the 7–15 Hz frequency range, is actually dominated by higher modes while outside that frequency range the fundamental one dominates.

Furthermore, the FVS approach goes beyond the subjectivity of the classical modal dispersion curves which are picked based on the personal understating of the experimental velocity spectra and can therefore be wrong18,24.

For the analysis of the field dataset presented in the next section, we considered multi-component data that enable us to better constrain the inversion procedure and overcome the non-uniqueness of the solution13,18,19,25,26,30.

A **field dataset.** The considered site is located in a NW-Italy urban area (La Spezia) characterized by about 15 m of soft sediments covering a thick sequence of gravel-like materials13. Multi-component (Z, R and T) multi-offset data were acquired along the pathway (covered with a stiff layer of crushed gravel - Fig. 12) of a city park. The acquisition parameters are reported in Table 1 and the data are available for download (see Data availability statement).

| parameter         | value                              |
|-------------------|------------------------------------|
| sampling rate     | 1 ms (1000 Hz)                     |
| acquisition length| 1 s                                |
| minimum offset    | 5 m                                |
| geophone spacing  | 1 m                                |
| number of channels| 48                                 |
| source            | 8 kg sledgehammer                   |
| stack             | 10                                 |

Table 1. Acquisition parameters.

Rayleigh-wave data (phase-velocity spectra of the Z and R components and RPM frequency-offset surface) are shown in Fig. 13. Although at high frequencies (above about 24 Hz) some energy related to higher mode(s) is apparent (see Fig. 13c,d), the overall energy distribution does not show any peculiar characteristic. On the other side, the RPM frequency-offset surface (Fig. 13b) puts in evidence a very distinctive feature: between about 4 and 6 Hz, the particle motion changes from retrograde (correlation value equal to about +1) to prograde (correlation value equal to about −1).

Although the actual Rayleigh wave particle motion is the result of several parameters and it is actually impossible to predict its behaviour (even very simple subsurface models can excite prograde motion) in some cases it was observed that prograde motion is the result of an abrupt increase of the $V_s$.13,25,30,41.
Figure 14 reports the field traces and phase-velocity spectrum of the recorded Love waves (THF component). Similarly to the synthetic data presented in the previous sections for the models #2–3 and #4, higher modes appear strongly excited and their top velocities is around 350–400 m/s.

The four computed observables (the phase-velocity spectra of the Z, R and T components and the RPM frequency-offset surface) were jointly analysed according to the multi-objective approach based on the Pareto optimality. The results of the accomplished joint inversion are presented in Figs. 15 and 16 (the shown Vs model is the one having the minimum geometrical distance from the utopia point, often referred to as the minimum-distance model).
The effect of the thin superficial stiff layer (the crushed-gravel park pathway) on Love waves is apparent (Fig. 15d): higher modes are excited in the peculiar way already described in the previous sections and their top velocity relates to the shear-wave velocity of the gravels present at a depth of about 15–17m (Fig. 16).

Conclusions
Through both synthetic and field data, we showed the effect induced by a shallow stiff layer on surface wave propagation. Main facts can be summarized in four points:

1. a shallow stiff layer excites large-amplitude THF (Love waves) higher modes;
2. the top velocity of such Love-wave higher modes is strictly related to the shear-wave velocity of the deeper layer even at very high frequencies and this allows the estimation of the deep $V_s$ values even by considering just the high frequencies (these two facts can be summarized with the expression “magnifying effect”);
3. by moving upwards the deep stiff layer, the number of higher modes decreases but the top velocity does not significantly change;
4. the Rayleigh-wave velocity spectra of the Z and R components and the RPM frequency-offset surface (i.e. the particle motion induced by the Rayleigh-wave propagation) are not massively influenced by the presence of a thin shallow stiff layer.
One of the consequences is that, through the Full Velocity Spectrum analysis of Love waves, we can define the $V_s$ values of the deep layers by considering even just the high frequencies. The FVS approach provides in fact the evidence that a certain mode is actually excited and, consequently, represents a powerful tool that, compared to the standard modal dispersion analysis (which does not provide the proof that a certain mode is actually excited), is capable of better constraining the inversion process.

Needless to say that while the analysis of a single component cannot fully solve possible ambiguities (non-uniqueness of the solution), the joint inversion of the velocity spectra of the $Z$, $R$ and $T$ components together with the RPM frequency-offset surface is capable of providing an highly-constrained (i.e. robust) sub-surface model.

Data availability

The field data presented in the "5. A field dataset" section are available from the corresponding author on reasonable request or can be download from the following link: https://doi.org/10.6084/m9.figshare.11913750.

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**Competing interests**

The author declares no competing interests.

**Additional information**

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