

## Determination of Rayleigh wave dispersion curves for near surface applications in unconsolidated sediments

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### Summary

Multi-channel Analysis of Surface Waves (MASW) is a suitable technique for vertical shear-wave velocity profile determination whose efficiency and effectiveness depends on data acquisition parameters and processing procedures. In the present paper we compare the performances of three different methods to determine Rayleigh wave dispersion curves. Such curves are successively exploited for the inversion process, which eventually provides subsurface information of use in geological or geotechnical applications. We investigate the role of some processing procedures, with a special emphasis on the number of traces able to optimise the ratio between information content and acquisition and processing costs. We show that phase shift method is able to produce the best results in terms of accuracy and computation efficiency for the unconsolidated sediments considered in our work. Phase shift shows extremely stable results also when a reduced number of traces is considered and other methods fail due to spatial aliasing or severe noise content that prevents from unambiguous interpretation.

### Introduction

Fast, robust and cost-effective non-invasive techniques represent a highly desirable instrument in many geotechnical applications. Environmental and geotechnical studies often require the definition of volumes and lateral continuity that cannot be achieved through borehole sampling due to the high costs and the localized nature of the collected information.

Potential methods (as for instance magnetic gradiometry), resistivity as well as GPR (Ground-Penetrating Radar) and seismic surveys are commonly and proficiently used in a wide range of environmental issues.

In seismic surveys, two third of the energy involved in the acoustic-wave propagation is actually associated with surface wave generation. During their propagation surface waves suffer from an amplitude decrease much smaller than that of body waves and strongly affect the multi-channel seismograms recorded by the vertical-component geophones. They are usually considered as a primary coherent-noise factor and referred to as "ground roll". They indeed hold a great amount of information that can be usefully extracted to infer the vertical shear-wave velocity profile connected to the stiffness properties of the investigated soils (e.g. Park et al., 1999; Xia et al., 1999). In order to describe subsurface features

in terms of  $V_s$  distribution, shear-wave seismic sources and receivers can also be adopted but severe problems and limitations can arise thus leading to time-consuming procedures and ambiguous results (e.g. Xia et al., 2002).

In order to optimise acquisition and processing costs with respect to the information content of the results we investigated the effects of few basic processing techniques and the role of the survey geometry. Acquisition and processing procedures can be optimally designed in order to minimize costs while keeping all the actually necessary information content. In fact, data redundancy can lead to time-consuming procedures without actual advantages in terms of information content.

Data collection was performed in a waste disposal site characterized by 18m-thick unconsolidated sediments laying on limestone bedrock in NE Italy.

### Methods

The efficiency of algorithms for phase velocity determination can be evaluated in terms of resolution, noise content and computation times. We tested three algorithms based on the F-K and Tau-p transforms and phase shift, respectively, in order to analyse their performances in Multi-channel Analysis of Surface Waves (MASW). F-K transform is a well-known tool often employed in 2D data processing (e.g. Yilmaz, 1987). Conversion of x-t data into the F-K domain allows trivial phase velocity identification through the relation  $v=f/k$ , with  $v$  phase velocity associated to the frequency  $f$  and wavenumber  $k$ .

Velocity spectrum determination can be performed via Tau-p transform (e.g. McMechan & Yedlin, 1981). Data are first converted into the Tau-p domain and a Fourier transform is then computed along the fast dimension (time) thus leading to the velocity spectrum representation. Phase shift represents the third method we tested. As reported by Park et al. (1998), a phase shift is applied to data according to an adopted velocity and a sum is then performed for each considered frequency. The authors took into consideration the results of this method in terms of resolution then assessing its performances with respect to the velocity spectra calculated via Tau-p transform. Their test site was characterized by a vertical shear-wave velocity distribution typical of coherent rocky materials for which higher mode identification and discrimination is possible also with relatively short offsets. This cannot be easily achieved when the survey is performed on

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unconsolidated sediments, for which wider arrays should be designed (e.g. Gabriels et al., 1987; McMechan and Yedlin, 1981).

Application of band-pass filtering and amplitude correction was considered with the goal of identifying the effects on the dispersion curve determination. Zero padding was operated in order to increase horizontal resolution in the F-K domain. Special attention was paid to the analysis of the number of traces actually needed for the determination of sufficiently accurate velocity spectra.

### Data analysis

We applied a 0-2-20-30Hz bandpass filter on our original 24-trace common-shot gather and calculated the F-K transform, velocity spectra via Tau-p domain and phase shift (Fig. 1). We then compare such results with those obtained from amplitude corrected data and wider bandpass filtering that maintains higher frequency content.

Fig.2 shows the application of amplitude correction through single-trace normalisation and effects on the three computational schemes. F-K amplitude distribution appears better focused with respect to non-corrected data then allowing a more precise signal identification and phase velocity estimation. No major effect is identifiable in the velocity spectrum determined by phase shift (Fig. 2d).

In Fig.3, we present the results of the analyses performed on a 0-3-50-70Hz bandpass-filtered and amplitude corrected dataset. No fundamental-mode related signal is easily identifiable at higher frequencies (> 20 Hz) and high frequency content basically amplifies the noise that affects the F-K domain and the velocity spectrum determined via Tau-p transform. On the other hand we notice that the velocity spectrum calculated via phase shift is still well defined and noise free.

Special emphasis was dedicated to the analysis of the minimum number of traces actually needed to preserve the information content. Optimum values of such parameter minimize acquisition and processing costs. Analyses were performed progressively reducing the number of traces considered. We re-sampled the original dataset into subsets of regularly spaced traces in order to preserve the low-frequency content critical in surface wave analysis.

Results presented in Fig.4 refer to a 4-trace gather. Due to the low velocities typical of unconsolidated sediments, the loss in the high-frequency/small-wavelength region does not result in a serious information decline. F-K spectrum is definitely corrupted due to the dramatic spatial aliasing occurred as consequence of the increased geophone spacing (Fig. 4a). In spite of the extremely reduced number of traces velocity spectrum determined via Tau-p is still

interpretable even if seriously affected by noise, while the phase shift procedure still provides definitely satisfying and noise free results (compare Figs.2d and 4d).

A further reduction in number of traces showed a dramatic quality decrease also for the Tau-p and phase-shift algorithms.

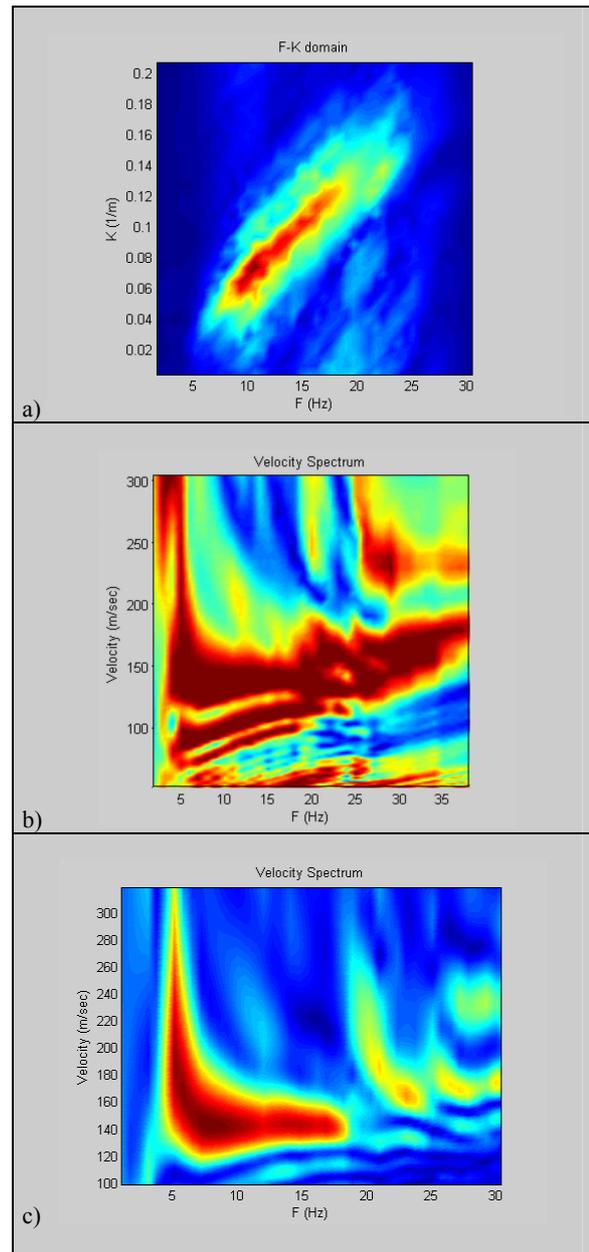


Fig. 1. Original 24 traces bandpass filtered (0-2-20-30) (see text). a) F-K transform; b) velocity spectrum via Tau-p; c) velocity spectrum via phase shift.

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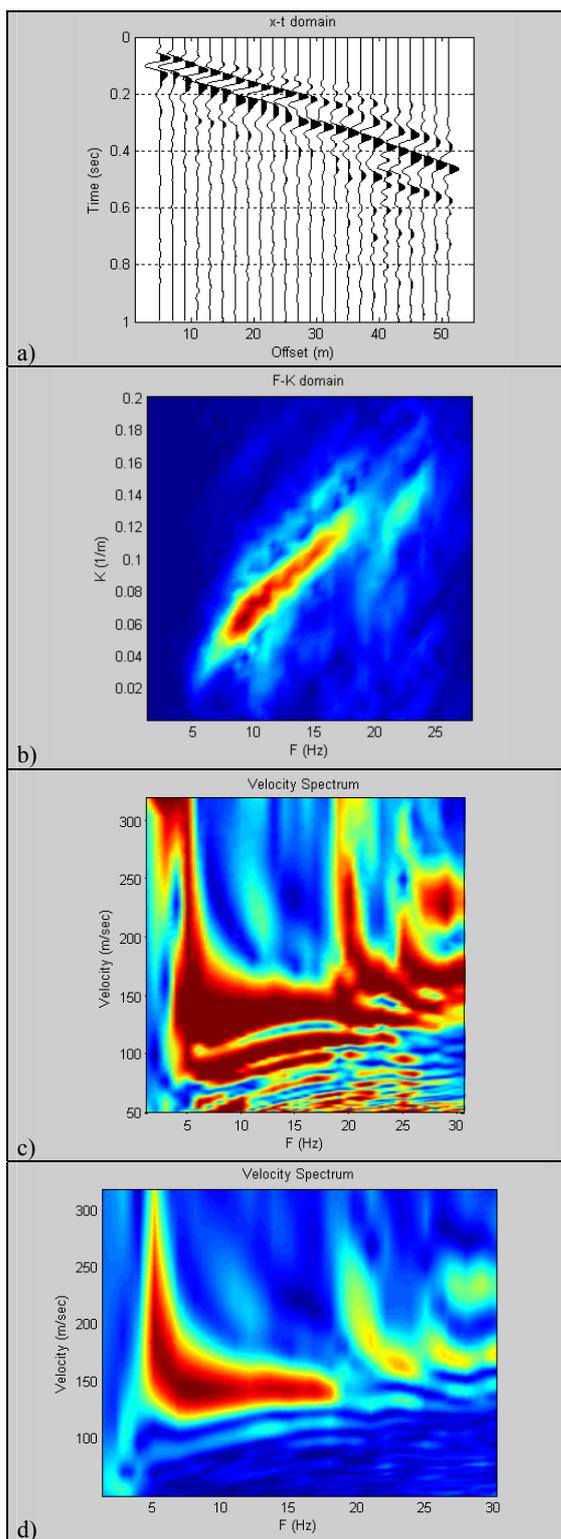


Fig.2. a) 24-trace common receiver shot bandpass filtered (0-2-20-30 Hz) and amplitude corrected; b) F-K domain; c) velocity spectrum via Tau-p transform; d) velocity spectrum via phase shift.

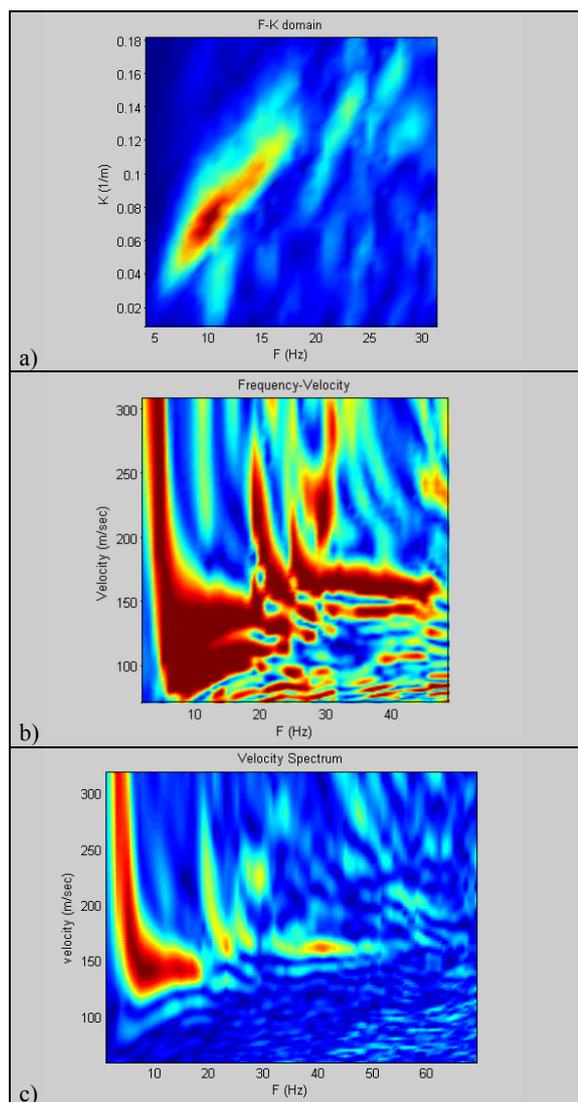


Fig.3. 24-trace gather, bandpass filtered (0-3-50-70 Hz) and amplitude corrected; a) F-K domain; b) velocity spectrum via Tau-p transform; c) velocity spectrum via phase shift.

### Conclusions

We evaluated the effectiveness of three computational schemes for phase velocity computation based on F-K spectrum, Tau-p transform and phase shift.

Results evidence that the phase shift approach is poorly sensitive to data processing and maintains very good performances even when a limited number of traces is considered. Computation times and noise content result very small in comparison with the other two methods. Velocity spectra calculated via Tau-p transform exhibit quality decrease mainly due to number-of-trace reduction, which is also responsible for severe aliasing in

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the F-K domain. In conclusion, when fundamental mode detection is the primary concern and high frequency overtones can be neglected, phase shift method is a robust and cost-effective solution capable of providing accurate phase velocities even with a reduced number of traces, thus optimising acquisition and processing costs.

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### Acknowledgement

This research was supported by CNR (Italy), National Group for defence against chemical, industrial and ecologic hazards, grant n. 00.00623.PF37 and by the European contract EVK4-CT-2001-00046, HYGEIA. Giancarlo Dal Moro presently benefits from a fellowship granted by CNR (Italy).

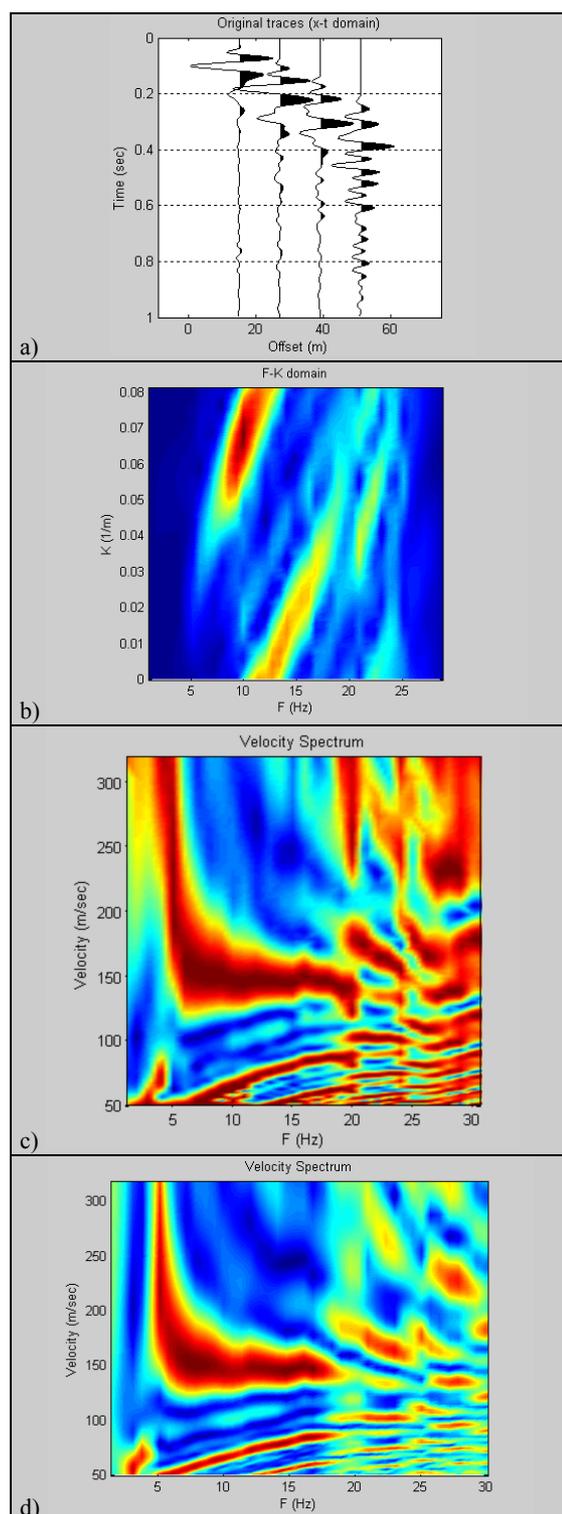


Fig. 4. a) 4-trace common-receiver shot (amplitude corrected); b) F-K domain; c) velocity spectrum via Tau-p transform; d) velocity spectrum via phase shift.