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Near-surface Full Waveform Inversion Using Surface Waves and Reflected Waves

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SUMMARY

We investigate the capacity of extracting near-surface shear-wave velocity by considering dispersive surface waves and non-dispersive reflected waves. We show that indeed the full waveform fitting of these waves requires a dedicated approach by using lateral spatial and frequential coherence for surface waves and by explicitely introduces the fitting of reflected waves in the inversion formulation. On a simple example as a two-layers model, lateral variations of the velocity are reconstructed while the low-wavenumber content of the velocity could be improved through reflection waves. Combining these two sources of information on the shear-wave velocity could improve our shear-wave velocity imaging in the near-surface context.

Introduction

In spite of the dramatic increase of the amount of acquired seismic data both at the academic and industrial level, the near-surface ranging from fractions of meters (vadose and critical zones) to few hundreds of meters (weathered zone) is still a disguised object at these different scales. A better physical reconstruction of this layer is mandatory for social issues as territory management, natural risk assessment and resources and wastes optimization as well as pollution remediation. Therefore, many attempts have been performed for improving images of the near surface using different remote sensing tools based on various physical phenomena in order to probe beneath the surface where direct access is not permitted or too expensive to be performed.

The spectral analysis of surface waves (SASW & MASW) based on an interpretation of dispersion curves for 1D or locally 1D structures has met an increasing interest as these waves carry a significant amount of energy (McMechan and Yedlin, 1981; Heisey et al., 1982; Nazarian and Stokoe, 1984) with many interesting illustrations and key parameter identifications (Park et al., 1999; Socco and Strobbia, 2004; Boiero and Socco, 2010). These analysis have been combined with other image techniques as refraction travel-time tomography or reflection travel-time tomography upto the integration of all of them in a simultaneous reconstruction (Fabien-Ouellet and Fortier, 2014).

We may not restrict ourself to the phase information through travel time for non-dispersive waves and through dispersion curve for dispersive waves. We may be interested in amplitude as the near surface suffers from strong attenuation and significant heterogeneities. Very few attempts have been performed on amplitude analysis on surface waves as this attribut is more difficult to assess. O'Neil (2004) has conducted an analysis using full waveform on surface waves for 1D media reconstruction. In this investigation, the spectral analysis is performed in the τ-p domain (as proposed by McMechan and Yedlin (1981)) while other domains as the ω-k domain could have been considered (Gabriels et al., 1987).

We shall illustrate how to formulate the full waveform inversion for surface waves with an illustration of smoothly laterally varying properties of the shear-wave reconstruction. As we may observe strong reflections coming from interfaces with high impedances between two layers, we shall focus our attention on possible SH propagation and the related full waveform inversion by considering explicitly the existence of reflections. We may conclude on potential perspectives to combine these two phases for better reconstruction of the near-surface shear-wave velocity.

Full waveform inversion of surface waves

In the case of slow surface waves propagating in the low velocity medium of the near surface, the problem of an accurate initial model, local minima and cycle-skipping is quite challenging. Alternative misfit functions have been proposed to tackle this cycle-skipping issue, relying for example on cross-correlation of signals as done for seismological applications at large sale with weak anomalies(Bozdag et al., 2011). At the near-surface scale with higher heterogeneities, attenuation and dispersion, array processing and lateral coherency of seismic arrivals can be exploited (Masoni et al., 2013; Perez Solano et al., 2013).

The FWI misfit function is often defined as the L2 norm of the difference between the observed and the calculated data in a given domain such as $\tau - p$, $\omega - p$ and $\omega - k$ domains, for example.

To minimize the misfit function and update the model, the gradient needs to be computed. The adjoint-state method (Chavent, 1974; Plessix, 2006) is often used in FWI, as it is more efficient than computing Fréchet derivatives. The adjoint states correspond to a back-propagated field, the source of which is directly linked to the choice of the misfit function. A new adjoint source formulation has been designed by (Masoni et al., 2014) for these different transformations.

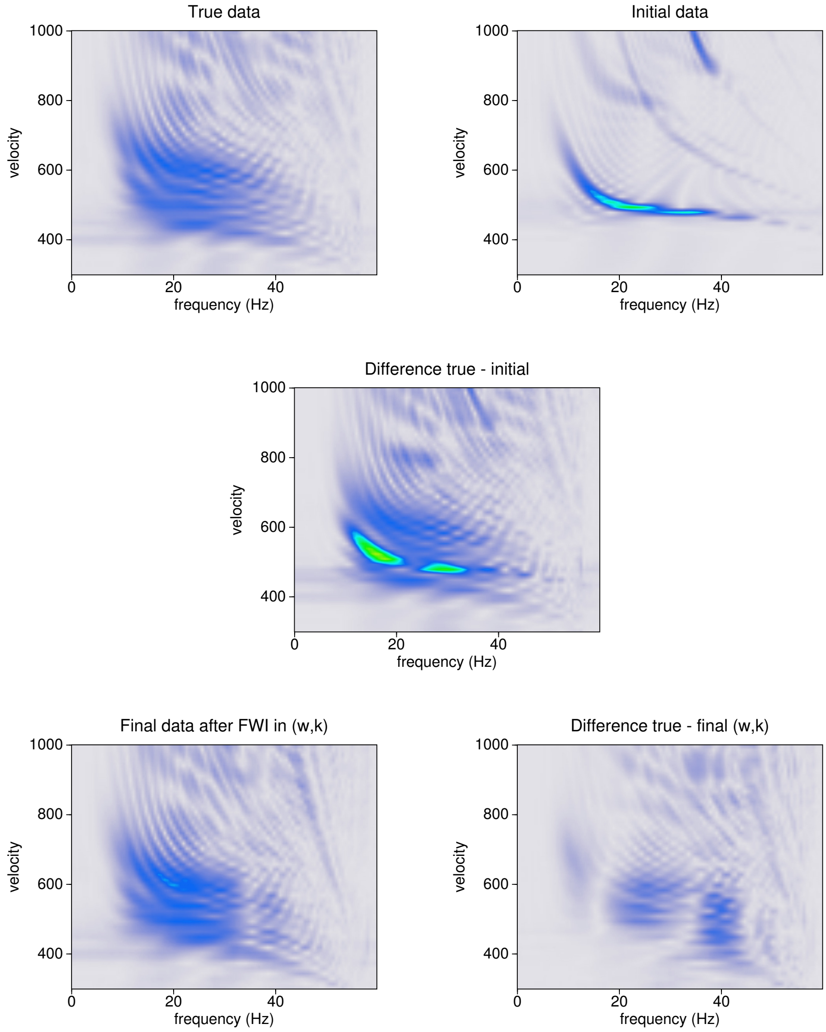

Figure 1 *Velocity-frequency diagram: on top left panel, true data while on top right panel, initial data. Middle panel shows initial differences while the bottom left shows final data after FWI and the bottom right the final differences. Data fitting has beeb performed in the* $\omega - k$ *domain.*

A simple inversion test illustrates the possible performances of the alternative FWI approach. A simple two-layer velocity model is defined with an arbitrarily oriented velocity gradient in the first layer. An acquisition has been deployed at the surface. Synthetic data are built using a 2D finite differences elastic wave propagation tool.

Only the shear velocity (Vs) parameter is inverted for, since surface waves are most sensitive to it, while Vp and density, as well as the source signal are considered as known. The initial model for Vs contains a homogeneous layer at the surface with the same thickness as the true model.

We may discuss the velocity reconstruction but, on the data side, the figure 1 shows that the fit of phase velocity-frequency diagram is improved. We may notice that we extract more information than when we consider dispersion curves following this approach.

Full waveform inversion of reflected waves when available

Often we may notice strong impedance between sediments or soft materials on top of a hard bedrock. We may consider reflected waves in order to improve the smooth background velocity structure, especially at depth. SH configuration of acquisition might take benefit of such formulation and will provide interesting constraints on the shear wave depth variation, complementing nicely the surface waves analysis. The method relies on an explicit scale separation between a smooth velocity macromodel and reflectivity, which is assumed to be known, and an explicit data separation between the short-spread reflections and the wide-angle arrivals (i.e., diving waves and subcritical reflections). We shall describe how this formulation might help us in the goal of the shear-wave velocity reconstruction.

Conclusions

Seismic traces acquire a dramatic complexity when traveling inside the near surface which suffers from strong variations of material properties. We have shown that indeed one can take benefit of surface waves as they are the most energetic phases. We illustrate potential capacity for extracting more information than those deduced from dispersion curve analysis. We complement this extraction by one which may come from reflected in case of high contrasts between soft materials on top of a hard bedrock. We show that indeed considering explicitly these waves might extend our capacity of reconstruction of the background velocity. In the future for cases where this will occur, combining the two approaches might improve our capacity of reconstruction of seismic parameters for near-surface targets.

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