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Quantitative Imagery of Shallow Structures with Multicomponent: Full Waveform Inversion and Physical Scale Modeling

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SUMMARY

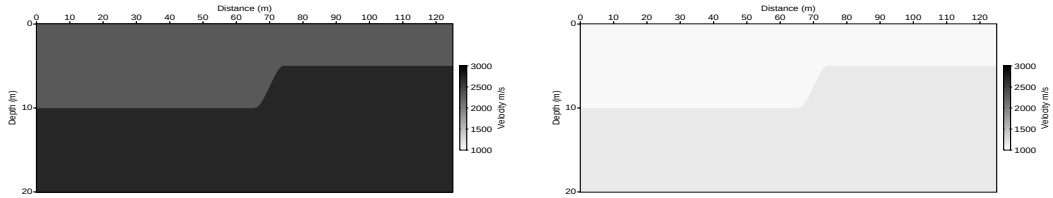
In near-surface quantitative seismic imaging, the mechanical properties of an heterogeneous medium are usually inferred from the measure of the normal velocity component at different locations.
In this study, it is proposed to investigate the benefits of measuring also the horizontal velocity component. For that purpose, a realistic synthetic model is defined and the benefits of each component are analyzed in the framework of seismic imaging by Full Waveform inversion. The model is a shallow two-layer medium close and the synthetic data are generated using a visco-elastic finite elements code. An analysis of the information contained in the signals is carried out and the behavior of the inversion algorithm is studied for each component.
The last part concerns the experimental modeling facility developed in order to experimentally validate the imaging methods. This measurement bench reproduces seismic measurement configurations at a reduced scale using an ultrasonic source and a laser interferometer. This facility has already been validated for the case of the measurement of the vertical component, and first experimental validation results of the horizontal component are presented.

Introduction

Surface seismic imaging methods are a priori well adapted to recover mechanical parameters of the first meters underground, e.g. for civil engineering and landscape management topics. Because of the highly dissipative media composing shallow structures, classical seismic sources in these contexts generate seismic waves with long wavelengths compared to spatial dimensions. This property is opposite to deeper seismic imaging topics like oil prospection where the seismic wavelengths are small compared to size and depth of heterogeneities. Due to these features, imaging methods for near surface applications need to be studied with a particular approach. In this framework, we focus on a two-layer medium typical of the subsurface contexts, i.e. where the upper layer is very thin. In such a medium, most of information is expected to be encoded in the surface waves but 1D assumption needed for classical surface waves dispersion inversion methods can not be assumed in case of lateral variation (Bodet, 2005). However, inversion of Full-Waveform inversion (FWI) method based on a local optimization (Virieux and Operto, 2009) is a promising quantitative imaging method because it takes into account all the recorded signal without distinction between body or surface waves. It has been developed for deep exploration issues and since a decade adaptation works on near surface applications have begun. These studies (Bretaudeau, 2010) show the prominent part of the surface waves in the inversion for near surface contexts and the need to develop new inversion strategies for optimizing their contribution in the FWI method. In this context, the following study is dedicated to the analysis of the impact of horizontal seismic component for the Full Waveform Inversion applied to a two-layer medium with a very shallow interface. In a first part of the study, a description of the numerical shot gather features obtained in case of a laterally varying interface (figure 1) is presented. In a second part, a numerical study of the benefits of the multicomponent inversion in case of a thin upper layer is exposed. In a parallel task, a small scale modeling bench (MUSC for Mesures Ultrasonores Sans Contact in French) developed by (Bretaudeau et al., 2011) has been upgraded in order to record the seismic horizontal component. In a last part of the paper, we present experimental results that contribute to validate the capacity of this measurement bench to generate high quality multicomponent experimental data. One aim of this experimental facility will be to study the robustness of inversion strategies using experimental controlled data.

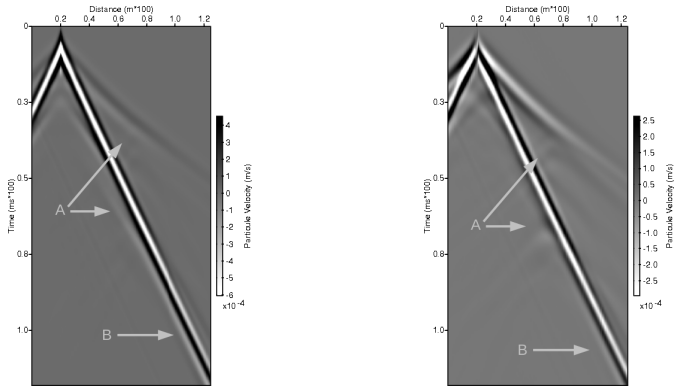
Analysis of seismograms for a media with lateral variations

The two layer medium shown in figure 1, where the interface variates laterally, is typical of the subsurface media. Figure 2 presents numerical simulations of a seismic shot gather on this medium calculated with a numerical code based on the discontinuous Galekin's finite elements method (Brossier, 2011). The source is a vertical point force located at the free surface, at the position x=65m, simulated by a Ricker shaped wavelet . The smallest wavelengths (S-waves) are about 3.5m and the longest wavelengths (P-waves) are about 135m but the main part of the mechanical energy is propagated through the surface waves, with corresponding wavelengths about 10m for the central frequency. Thus, the surface waves should be affected by the interface of the shallowest part of the model (5m deep). The perturbation due to the lateral heterogeneity (arrows A) is clearly visible in the horizontal component seismograph (figure 2-b) but it is less visible on the vertical component seismograph (figure 2-a). The Surface Waves dispersion effect due to the interface is clearly visible and increases with large offsets (arrow B). In order to investigate the capabilities of FWI method for this kind of context and the benefits of processing multicomponent data, two simplified configurations have been studied. Both configurations are layered media, one corresponding to the medium at the left side part (interface located at 10m under the surface) and the other one corresponding to the right part (interface located at 5m under the surface). Concerning results obtained for the 10m deep interface we can refer to (Valensi et al., 2012). Results obtained for the 5m deep interface are presented in the next section.



(a) V_P parameters (b) V_S

Figure 1 *Spatial distributions of velocities*



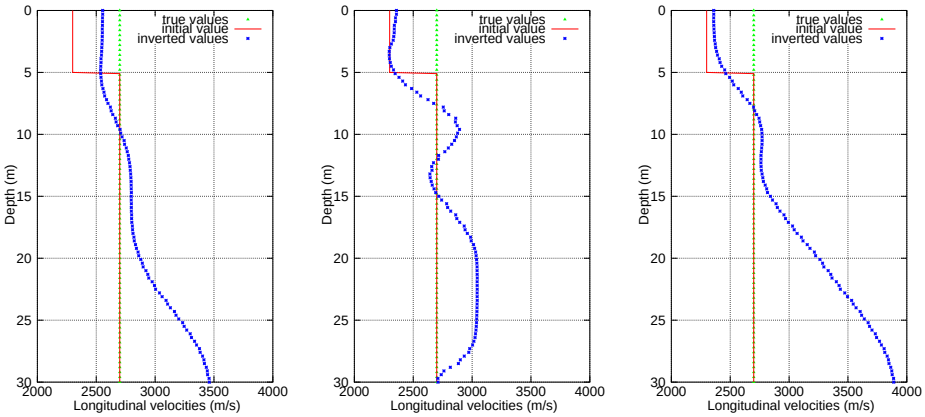
(a) Vertical component (b) Horizontal component

Figure 2 *Synthetic seismograms*

Numerical investigation of the benefits of the horizontal component for a shallow stratified media

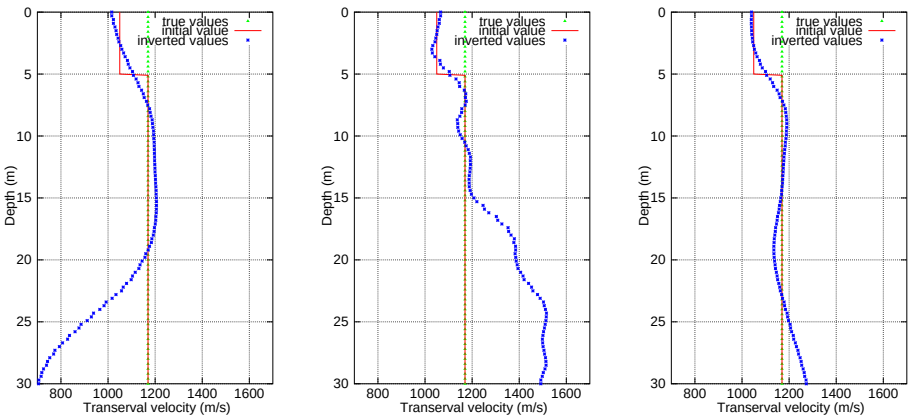
The FWI inversion software (Brossier, 2011) is based on an implementation of the FWI method in the frequency domain. It calculates the gradient of the misfit functional using the adjoint-state formalism. The inverse Hessian computations are based on a quasi-Newton method (l-BFGS) initialized with the diagonal terms of the Hessian. The inversion process follows a Bunks's approach in the frequency domain: it starts with the lowest frequencies and then higher frequencies are introduced while still keeping lower frequencies. The initial model for the inversion corresponds to the deeper layer, supposing that V_P parameter in this layer can be assessed with the refraction method. The Levenberg-Marquard regularization parameter is chosen equal to 0.1 % considering that the numerical noise is weak. The gradient is filtered at each iteration by a Gaussian filter with a correlation length equal to 10 % of the smaller longitudinal wavelength. 9 frequency groups in the range [70 Hz-190 Hz] are considered for the inversion. For each one, the iteration process is interrupted when the global misfit reaches a value less than 5 % or for a maximal number of 12 iterations. The inverted zone is 60m long and 30m deep. The measurement setup is composed of 24 sources (vertical point sources) and 29 geophones (horizontal and vertical components) with a regular spacing. Inverted results of the V_P and V_S parameters are presented in figure 3 and in Figure 4 respectively. We can summarize the results in three remarks. 1) For the deepest part (deeper than 15m), almost all inversion results strongly diverge from the true values as well as from the initial model. This phenomenon may be explained by a lack of information in the data to properly constrain the inverse problem in this area. 2) Concerning the V_P depth profile : the vertical component inversion (figure 3-a) provides results that overestimate the V_P parameter for both layers whereas the horizontal component inversion (figure 3-b) provides results that fit well the top layer but oscillate a lot in the zone deeper than the interface. Actually, the V_P depth profile is almost recovered by inversion when using both components (figure 3-c). Particularly, the resulting profile does not suffer any more from an oscillatory behavior even if the sharp transition between the two media remains strongly smoothed (about 5m long). 3) Concerning the V_S depth profile (figure 4): the same features than for V_P appear (i.e. the smoothed interface and the oscillations) but it is systematically much better recovered than the V_P parameter. To sum up, these first results are promising concerning the benefit of using both

of the component even if further investigations are needed for better understanding and optimizing the FWI method for very shallow media.



(a) Vertical component only (b) Horizontal component only (c) Both components

Figure 3 *Inversion results for longitudinal velocity parameters*



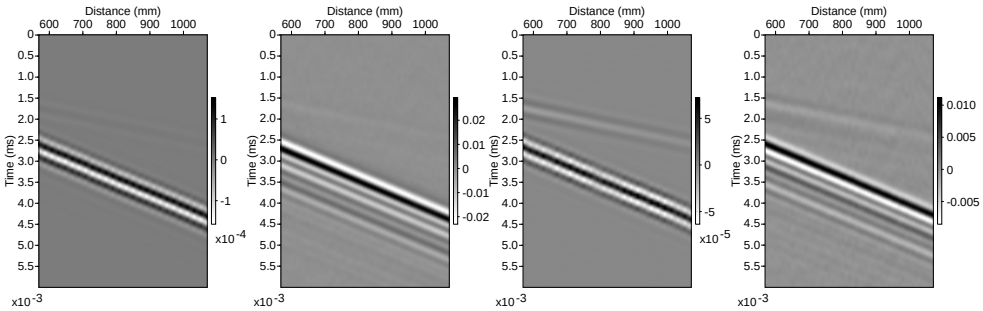
(a) Vertical component only (b) Horizontal component only (c) Both components

Figure 4 *Inversion results for transversal velocity parameters*

Small scale modeling

The MUSC measurement bench we developed (Bretaudeau et al., 2011) is composed of three main elements : a measurement table, a piezoelectric ultrasonic source and a measurement device (Tempo-2D, Bossa-Nova) based on a heterodyne laser interferometry (two-waves mixing in photorefractive crystal technology). A new measurement process (Blum et al., 2010) that enables to measure simultaneously the vertical and horizontal component (P-SV configuration) has been recently integrated in it. Valensi et al. (2011) presented the first results and compared numerical and experimental data for vertical and horizontal components with this new bench. Following this first step, a recent upgrade allows now to measure complete seismic shots with a great reproducibility and stability. These kind of new results are presented here : figure 5-b-d depicts the measurements of the displacement field at the free surface of an aluminum sample resulting from a vertical point source (impact diameter equal to 1mm) with a Ricker shaped excitation and a central frequency of 250kHz. The records have been passband filtered by a zero-phase sine squared filter between in the range [85kHz-500kHz]. For every receiver position, a stack of 256 signals has been applied in order to improve the signal-to-noise ratio. Figure 5 shows a good agreement between numerical and experimental data in this configuration but some discrepancies remain : 1) the relative amplitudes are not fitting because the numerical data are 2D simulations (i.e. generated by an infinite source line) whereas the experimental source is a point source. Thus, the mechanic wave geometrical-spreading is not well accounted by the numerical model; 2) the source signal is distorted due to the coupling effect of the sensor; 3) ringing oscillations occur after the Rayleigh wave arrivals in case of experimental data but not in numerical results. They might be due to the finite surface of the source

and only affect the Rayleigh wave because of the ratio between the Raleigh wavelength and the source diameter. The enumerated bias between experimental and numerical simulations may be removed by 1) using 3D simulations, 2) inverting the source signature (Virieux and Operto, 2009) and 3) considering a source with a finite extend.



(a) Vertical numerical (b) Vertical experimental (c) Horizontal numerical (d) Horizontal experimental

Figure 5 *Experimental and numerical seismographs*

Conclusions and perspectives

The inversion of the V_P and the V_S parameters in case of a very-shallow structure with the FWI method has been investigated using a layered medium example. Inversions results of the vertical or horizontal component separately have been compared to inversion results with both components and show the benefits of the latter for recovering the V_P and V_S depth profiles. Further investigations are currently in progress in order to better understand the behavior of the inversion algorithms and then to optimize inversion strategies for these particular contexts. As a parallel task, advances for validating a novel small scale physical modeling device have been presented. The current experimental works concerns the formulation of an analytical model in order to quantitatively validate this measurement device and avoid the source and amplitude discrepancies.

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