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Seismic Horizontal Component Measurement - Reduced Scale Modeling and Benefits in Full Waveform Inversion

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SUMMARY

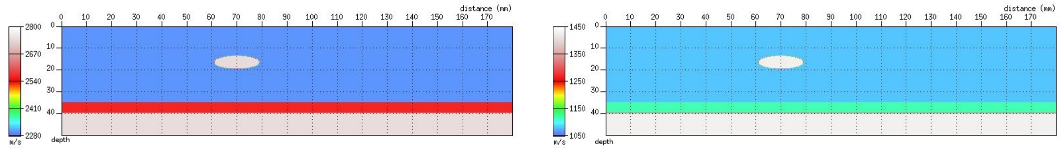
The study concerns the investigation of the benefits of the horizontal particle displacement component for the seismic velocity parameters imagery using the Full waveform inversion method. A geological consistent model has been firstly numerically modeled. A comparison of the FWI inversion results using either the vertical component measurements or the horizontal component shows that the two components provide complementary information to recover the P wave velocity parameters even if the benefits are less visible for transversal wave velocity.
Furthermore, a novel laser interferometric measurement process allowing to measure simultaneously the vertical and horizontal components has been implemented in a reduced physical scale measurement bench previously designed to validate experimentally seismic inversion strategies with a great accuracy: the laser interferometer records the seismic particular displacement, the source is a 100 KHz piezoelectric sensor, the minimum incremental displacement of the sensors is 100 µm with an accuracy of 10 µm. Experimental measurement on the same geological consistent model has been conducted and data are compared to numerical ones. The results show a great accordance between numerical and experimental signals concerning both of the components and suggest that this new measurement method can be applied to a whole experimental campaign at reduced scale.

Introduction

Recent advances in seismic inversion methods allow us to get high-resolution quantitative representations of mechanical parameters of the Earth. One of the most promising inversion method is the Full-waveform inversion (FWI) method which basically consists of an iterative data fitting process based on a local optimisation (Tarantola, 1984) and all the information available in the data can be handled unlike conventional methods (e.g. first arrival times tomography). This method has been first applied to depth exploration (Virieux and Operto, 2009), but some authors already applied it to quantitatively image the near-surface. For example, Gélis (2005) succeeded to image cavities using synthetic data including surface waves arrivals. However one of the most important remaining challenges is the validation of the method with "real" field data that presents many difficulties: field data are often measured on not well-known media composed of high heterogeneity degree, important intrinsic attenuation and with prominent three dimensional effects. Considering all these difficulties, the necessity to have an experimental intermediate validation step becomes obvious. The aim is to reproduce the field experiments in a well-controlled environment at a smaller scale using a well-defined spacio-temporal scalling. The physical reduced scale modeling has several advantages compared to field-measurements: first the model physical parameters are well controlled, thus numerically repeatable; secondly, the great flexibility of the setup enables to experiment easily novel measurement configurations. This validation approach has already been first applied for geophysical imaging purposes by French (1974). Recently Bretaudeau (2010) designed an ultrasonic measurement bench called MUSC with several features that enable an excellent reproducibility of field measurements from the surface. For instance, a special attention has been paid to select a source that can be assimilated to a point source and the sensors displacements are controlled with an accuracy of 10 μm. Using this experimental setup, Bretaudeau (2010) showed promising results on the inversion using the vertical component. Due to recent technological improvements (Blum et al., 2010), it is now possible to record the vertical and the horizontal components simultaneously using a new laser interferometer device which has been implemented in the MUSC measurement bench. In this context, the aim of the study presented here is to investigate numerically the benefits of each component in the frame of the FWI method and to present the recent advances on measurements of both components on reduced physical scale models. First, the physical reduced scale model and its numerical representation will be described, then a numerical study will present the benefits provided by each component for velocities reconstructions and finally measurements of the vertical and horizontal components on the reduced physical scale model will be presented and compared to numerical simulations.

Numerical and physical models description

The physical model is an epoxy-resin block (500*400*260 mm) composed of three layers and a rigid inclusion. The longitudinal and transversal seismic wave velocities (respectively called V_P and V_S) are increasing with the depth (V_P increases from 2300 $m.s^{-1}$ to 2740 $m.s^{-1}$ and V_S from 1080 $m.s^{-1}$ to 1427 $m.s^{-1}$), velocities are represented in Figures 1-a and 1-b. Attenuation factors have been estimated in the top layer: $Q_P = 55$ and $Q_S = 22$. The inclusion is located in the top layer and its properties are the same as the lowest layer ($V_P = 2740\ m.s^{-1}$ and $V_S = 1427\ m.s^{-1}$). The source is a Ricker shaped signal with a central frequency of 120 kHz. To model the wave propagation a finite element model has been used, its parameters are those of the physical scale model and it takes into account the free surface effects. Using proper scaling factors, this model is fully consistent with the geological reality, for example if a scale factor of 1/2 is applied on velocities, 1/2000 on frequencies and 1000 on distances, we get an investigation medium of 180 m long and 50 m depth, on longitudinal waves, velocities varies from 1150 $m.s^{-1}$ to 1400 $m.s^{-1}$, for transversal waves from 540 $m.s^{-1}$ to 713 $m.s^{-1}$ and the excitation signal would have a central frequency of 50 Hz. Such inclusion may be representative of foundations in a geotechnical context or of archeological remains located at $14m$ depth.

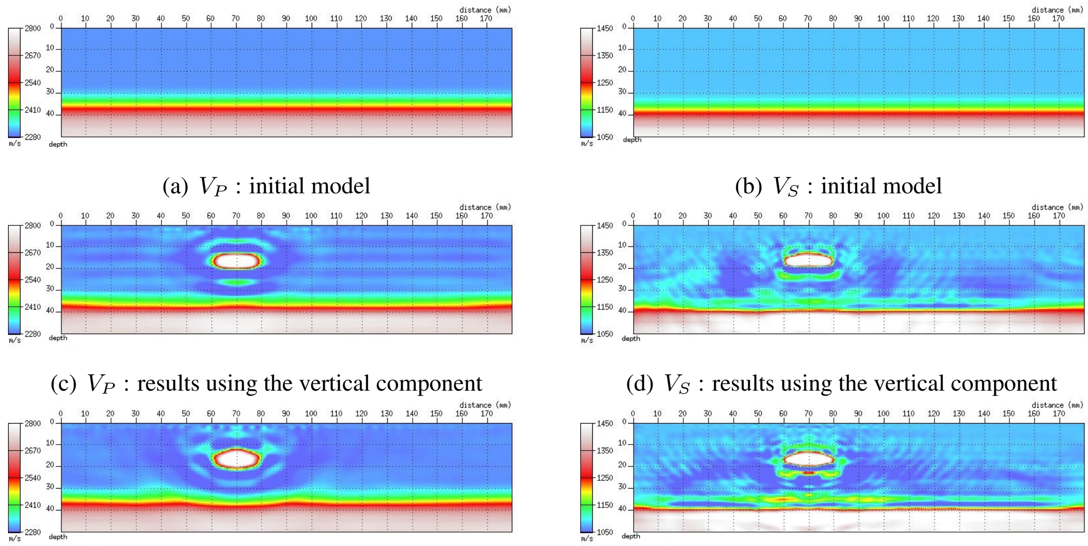


(a) V_P (b) V_S

Figure 1: Exact spatial distributions of the velocities

Numerical evaluation of the benefits of each component

The inversion program (Brossier, 2010) is based on an implementation of the FWI in the frequency domain (Pratt et al., 1998) using a modified version of the conjugate gradient method with a pseudo-hessien estimation for the non-linear optimisation process and a forward solver (visco-elastodynamic equations) based on discontinuous Galerkin finite elements. In order to investigate the contribution of vertical and horizontal components in the inversion results, Figures 2 depicts inversion results from the initial models (Figures 2-a and 2-b) which are blurred versions of the exact velocity models without the inclusion. The methodology used for the inversion is based on a sequential inversion process from low frequencies 29 kHz to 156 kHz, using 14 different frequencies and 5 iterations for each frequency. The seismic source is a punctual normal force moved all along the surface at 37 different positions and the receivers are 180 points sources sampled every millimeter. Concerning the reconstruction of the V_P parameter, both component inversions provide well resolved images (Figures 2-c and 2-d) but we can distinguish differences as described below. Inversion of the vertical component (Figure 2-c) provides an ellipsoidal inclusion shape that is symmetric but "flattened" : artifacts appear around the cavity, due to the sharp variations of the velocity. We can also notice permanent horizontal oscillations in the first layer even far from the inclusion. Inversion of the horizontal component (Figure 2-e) provides an inclusion shape that is better resolved at its bottom part than at its top part. Moreover, the artifacts strongly decrease when the horizontal distance to the inclusion increases: no oscillation occurs in the surrounding medium. However, bellow the inclusion, the shape of layers boundary is strongly disturbed. Concerning the reconstruction of the shear waves velocities (Figures 2-d and 2-f), the most noticeable differences concern the shape of the inclusion which is better resolved when inverting the horizontal component (Figure 2-f) but bellow the inclusion, the resulting image is affected by more severe artifacts in the case of inversion with the horizontal component.



(a) V_P : initial model (b) V_S : initial model

(c) V_P : results using the vertical component (d) V_S : results using the vertical component

(e) V_P : results using the horizontal component (f) V_S : results using the horizontal component

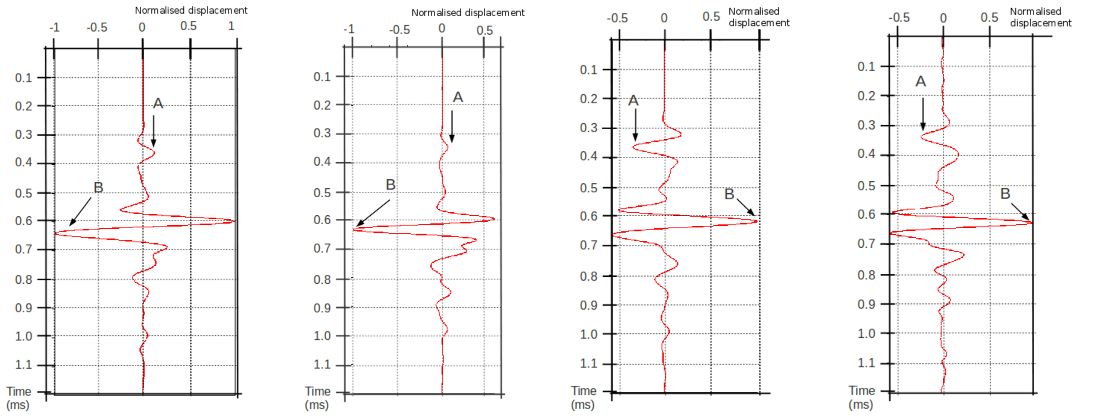
Figure 2: Initial model used for the initialisation of the inversion (a-b) and results of the inversion of the velocities (V_P and V_S) using different components (from numerical simulations) (c,d,e,f)

Experimental investigation on physical reduced scale model

Most of the conventional measurement setup are not able to measure the horizontal and vertical components of displacement field simultaneously. A new measurement process (Blum et al., 2010) that enables to measure simultaneously the vertical and one horizontal component has been integrated to the MUSC measurement bench for the reduced physical scale experimentation. The MUSC measurement bench is composed of three main elements: a measurement table, a piezoelectric seismic source and a measurement device based on a laser interferometer. The source is small enough to consider it as punctual for the frequencies that are being used (from 15 kHz to 250 kHz). The laser interferometer is a commercial interferometer (Tempo-2D, Bossa-Nova), which is based on two-wave mixing in photorefractive crystal technology and a linear array of 16 photodiodes. Information on the in-plane component are deduced from the difference of optical intensities measured between each couple of symmetric photodiodes. The source and interferometer displacements are electronically controlled with a precision of 10 μm. Due to the high sensitivity of laser interferometer (Ångstrom order displacements can be measured) it was necessary to design a measurement table placed on a specific damping system to isolate the sample under investigation to external vibrations. In order to evaluate the suitability of this new facility, measurements in a common shot gather configuration have been carried out on the physical model presented above (Figure 1). The source is placed at the positions x=0 mm (i.e. an offset equal to 70 mm from the inclusion axis) and the particular displacement is recorded every millimeter by moving the laser interferometer from the source position along a profile crossing the inclusion with a sampling frequency of 10 MHz. The measured seismic signals presented Figures 3-b and 3-d correspond to an offset equal to 54 mm from the source point. They have been low-pass filtered by a zero-phase sine squared filter up to 250 kHz and the signal average has been removed. The signal to noise ratio is much more important for the vertical component (around 30 dB) than for the horizontal component (around 10 dB). This ratio could be improved by averaging over several similar measurements, in that study signals are stacked over 1500 measurements. For comparison with numerical results, a common shot gather has been simulated and the signal corresponding to the offset equal to 54 mm are presented Figures 3-a and 3-c. Simulations have been computed through the finite elements code previously described (Brossier et al., 2008). The source shape used is calculated from the deconvolution of experimental data by using a linear least-mean square regression (Pratt, 1999) in order to take into account the coupling effects of the piezoelectric source to the model. The comparison between numerical and experimental data shows great similarities that we can describe with characteristics that occur in experimental and numerical tests : 1) concerning the first arrival between (arrow A), i.e. the direct P wave, the signal shape is opposite phase between the horizontal component and the vertical component ; 2) surface wave arrival (arrow B) has a higher amplitude than direct P-wave arrivals ; 3) Concerning the horizontal component, the waveform is opposite phase between the P wave arrival and the Rayleigh wave arrival ; 4) surface wave shapes are symmetrical for the horizontal component whereas it is not for the vertical one. However the anti-symmetry on the vertical component is less pronounced for the measured data. Due to the three dimensional nature of the source, Loves waves can occur and the signal amplitude decreases faster with distance than in a perfect 2D configuration. In this preliminary study these effects have neither being corrected on measured data nor on simulations. Other discrepancies remain because of low frequency noise in the signal and generate oscillations for the first time arrivals as well as in the last time arrivals that make the experimental data not coherent to the numerical one for recording time greater than 0.9 ms.

Conclusions

In the presented study, two main conclusions may be drawn. First, a comparison of inversion results on a simplified but geologically consistent model of a rigid inclusion located in the near surface shows that the horizontal and vertical components provide complementary information for the inversion of the longitudinal wave velocity parameter. Whereas the benefits of each



(a) Vertical component synthetic (b) Vertical component experimental (c) Horizontal component synthetic (d) Horizontal component experimental

Figure 3: Seismograms (with sensor coupling effects for the simulated data)

component are less visible for the shear velocity reconstruction, these numerical results illustrate that further theoretical investigations have to be conducted in order to get a clear understanding of the influence of each component on the FWI method and thus to design inversion strategies that combine optimally both components. Secondly, a novel measurement process that enables to measure the horizontal and the vertical components simultaneously has been implemented in the MUSC bench and an analysis of the quality of measurements has been initiated. The presented results suggest that this new method can effectively be applied to reduced physical scale modelling approach. Further experimental studies are currently conducted in order to validate the method with a larger set of data.

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