# Benefits of the horizontal component in quantitative imaging of near-surface interfaces with lateral variations: synthetic model inversion and reduced scale modeling

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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 tangential 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 results of the horizontal component are presented.

# 1 Introduction

Knowledge of mechanical properties of the first meters underground is useful for civil engineering and landscape management topics. In this aim, seismic imaging methods are well adapted to recover mechanical parameters and intern variations of the subsurface media. In these shallow contexts and with classical seismic sources, the size and the depth of the objects are approximatively similar to propagated wavelength. This features are very different from the contexts of the deep seismic imaging issues (e.g. for oil prospection) and need a particular approach dedicated to near surface imaging studies. For this reason, we focus on a two-layer medium typical of the subsurface contexts : the boundary between the two layers is shallower than one half of the mean surface saves wavelength. In such a medium, most of information is expected to be encoded in the surface waves but classical inversion methods based on the surface wave dispersion analysis fail in case of strong lateral variations. In such complex media when assumptions of classical seismic method can not be assumed, inversion of Full-Waveform (FWI) based on a local optimization [3] 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 issues and first adaptation works on near surface applications are dedicated to cavity detection [1]. This works highlights the prominent part of the surface waves in the inversion and the need to develop new strategies for taking them into account in the FWI method. Following this work, we propose to study the potential benefits of the horizontal component for the Full Waveform Inversion of data carried out in a two-layer medium typical of the subsurface contexts. Concerning the experimental aspects, a small scale experimental laboratory (MUSC) [2] has recently been improved to record the horizontal component with a laser interferometer [5]. This facility has already been validated for the case of the measurement of the vertical component, and first experimental results of the horizontal component are presented.

# 2 Numerical model and data description

## 2.1 Model and acquisition descriptions

The model is a two layer model. The longitudinal and transversal seismic wave velocities are increasing with the depth whereas the density remains constant for both layers, the numerical values of medium properties are summarized in Table 1 and parameters $V_P$ and $V_S$ velocities are depicted in Figures 1 and 2. The seismic sources are normal point forces located at 11 different positions along the surface and 29 geophones are placed on the free surface with a spacing of 2 meters. Considering the shallow depths, the low number of propagated wavelengths and the effect of the free surface, it can be assumed that the surface waves will be prominent in the inversion process.

Table 1: Medium properties.

| Medium properties | Top layer | Bottom layer |
|---|---|---|
| Longitudinal wave velocity | 2300 $m.s^{-1}$ | 1050 $m.s^{-1}$ |
| Transversal wave velocity | 2700 $m.s^{-1}$ | 1170 $m.s^{-1}$ |
| Quality factors | 100 | 100 |
| Density | 1300 | 1300 |

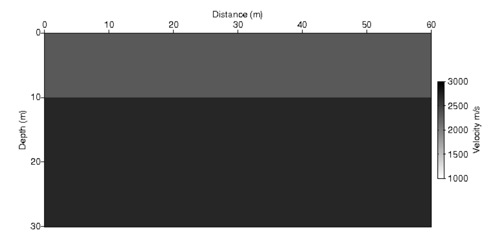


Figure 1: Spatial distribution of the $V_P$ parameter

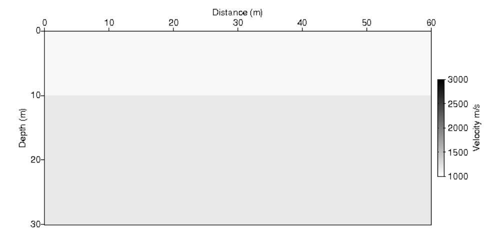


Figure 2: Spatial distribution of the $V_S$ parameter

## 2.2 Numerical modeling and inversion tools

The numerical modeling engine used to generate the data is a program developed by Brossier [3] based on discretization of the frequency domain visco-elastodynamic equations using a discontinous Galerkin finite elements method with low order of interpolation. In the presented study only P1 and P0 elements are used. The inversion tools are based a non linear minimization of a quadratic functional $\mathcal{E}(\boldsymbol{m})$ :

$$\mathcal{E}(\boldsymbol{m}) = \frac{1}{2}||\mathcal{G}(\boldsymbol{m}) - \boldsymbol{d}_{\text{mes}}||^2 + \frac{1}{2}\varepsilon\left\|\boldsymbol{m} - \widetilde{\boldsymbol{m}}_{\text{prior}}\right\|^2 \quad (1)$$

Where : $\boldsymbol{m}$ is the model parameters vector (in this study parameters are $V_P$ and $V_S$), $\mathcal{G}(\boldsymbol{m})$ is the direct problem operator (mapping the model space to the data space), $\varepsilon$ is a regularization trade-off parameter, $\boldsymbol{d}_{\text{mes}}$ are the measured data and $\widetilde{\boldsymbol{m}}_{\text{prior}}$ is the a-priori model. The optimization process is a local iterative optimization process based on a pseudo-Newton optimization method called the l-BFGS method. A complete description of the modeling and inversion tools is given in [3].

## 2.3 Inversion parameters

With FWI method, it is necessary to consider an initial model which is getting iteratively updated during the inversion process. The model considered is a homogeneous model with the velocities of the bottom layer of the "true" model. This choice is in practice relevant, because it is easy to estimate the velocity of the bottom layer with the refraction method. The inversion process begins with the first frequencies (70 Hz) and then higher frequencies are introduced while still keeping the lower frequencies (Bunks's approach). The regularization parameter $\varepsilon$ is chosen equal to 0.1% because the data are only corrupted by very low level numerical noise. To prevent artifacts, the gradient is filtered at each iteration by a Gaussian filter with a correlation length equal to 10% of local longitudinal wave wavelength. Also, 15 iterations are computed for each frequency group and up to 10 former gradients may be stored for the estimation of the Hessian by the l-BFGS method. The source signal is a Ricker shaped signal with a central frequency of 100 Hz. The spectrum considered for the inversions is composed of 9 frequencies between 70 Hz and 190 Hz.

## 2.4 Data analysis

In order to better interpret the inversion results, it might be useful to first analyze the information content of the signals. Figures 3 and 4 show respectively the vertical and the horizontal component of the simulated seismograms. In both figures, the dominant amplitude of surface wave (arrows B) and dispersion effects of the Rayleigh waves due to depth velocity variations (arrows C) are visible. The change of slope of the "P-wave" (arrows A) is very slight, so it makes difficult to estimate the $V_P$ parameters of the upper part from the refracted waves analysis.

It is also useful to analyze the data in the frequency domain, because the inversion is sequentially done from the low frequencies to the high frequencies. Figures 5 and 6 depict the real part of the difference between the velocity fields (i.e. residue between data generated by the initial model and by the true model). First, it is possible to notice that the amplitudes at the surface are decreasing with the depth much faster in Figure 6 than in Figure 5. This phenomenon is explained by the frequency dependency of

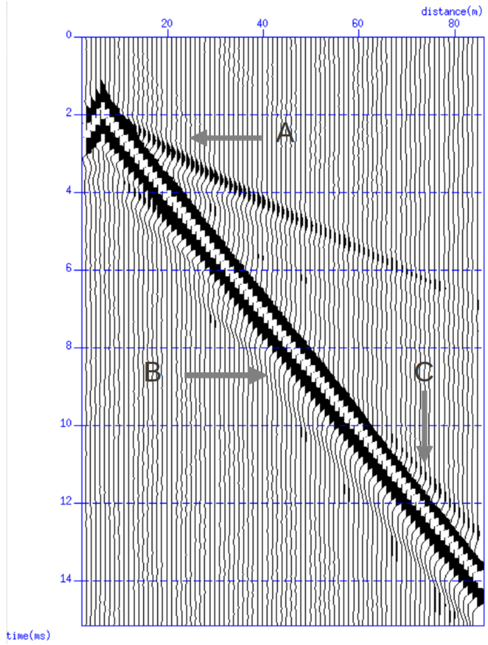


Figure 3: Seismograph of the vertical velocity component

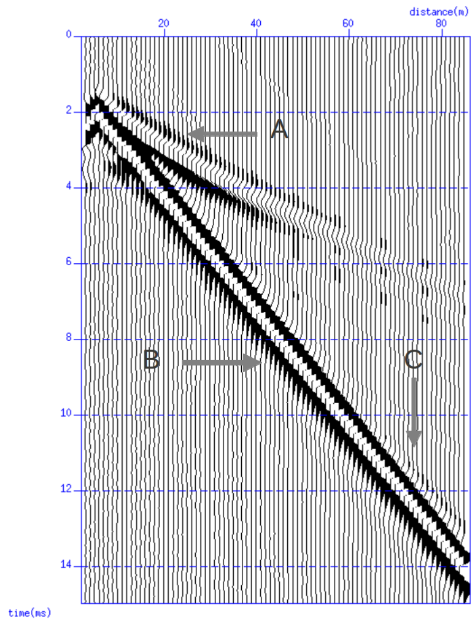


Figure 4: Seismograph of the horizontal velocity component

the penetrating energy of surface waves: the higher is the frequency the lower is the penetration depth. Concerning the amplitudes of the residue along the surface (x-axis), two different behaviors are visible. In Figure 5 the amplitude of the residue increases with the offset, whereas in Figure 6 first the amplitude increases until reaching a maximum around 30m offset and then the amplitude of the residue decreases. One possible explanation might be the following: in case of a frequency of 70Hz the residue is dominated by the surface waves whose dispersion increases with the offset whereas in case of a frequency of 150Hz, the surface waves penetration depth is not large enough to be sensitive to the interface dispersion effects. Further investigations are needed to better explain this effect.

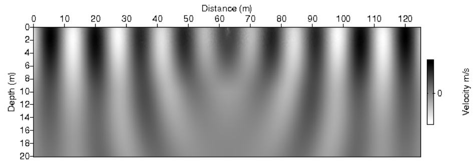


Figure 5: Real part of the vertical component of the residue at a frequency of 70 Hz

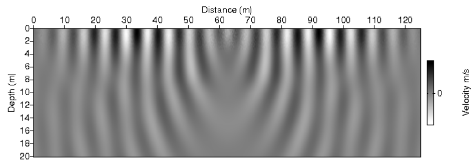


Figure 6: Real part of the vertical component of the residue at a frequency of 150 Hz

# 3 Inversion results

In order to estimate the benefices gained by taking into account several components in the inversion process, inversion results using only the vertical, only the horizontal component and both components are presented. In figures 7, 8, 9, 10, 11, 12 are depicted depth velocity profiles localized at 30m in figure 1, where different colors are used to represent the data:

- the red curves corresponds to the true values.
- the green curves corresponds to the initial values.
- the blue curves corresponds the inverted values.

## 3.1 Using data with the vertical component only

Figure 7 shows that $V_P$ parameter is globally underestimated (except for the 3 first meters). The deeper part (after 25 meters) of the inversion shows a divergent behavior to the initial model. Concerning the $V_S$ parameter, the figure 8 shows a very good agreement between the inverted parameters and the $V_S$ parameter estimation for the 20 first meters. For deeper depths, the inverted parameters show a strong divergent behavior to the "true" model but also to the initial model.

## 3.2 Using data with the horizontal component only

Figure 9 shows that $V_P$ parameter is well recovered for the 17 first meters but for deeper depths the model but down to approximatively 17m, results show a divergent behavior overestimating the velocities. In figure 10, the transversal velocities for the first layer is are very well recovered but for the area deeper than 15m inverted parameter diverges from the exact and initial models.

## 3.3 Using data for both components

Figure 11 depicts the estimation of $V_P$ parameter versus depth. Even if the estimation of the $V_P$ parameter is not very accurate, the divergent behavior shown in depth is much less pronounced than for the previous cases. Concerning the $V_S$ parameter (figure 12), the inversion results fit very well the exact model until a depth of 25m.

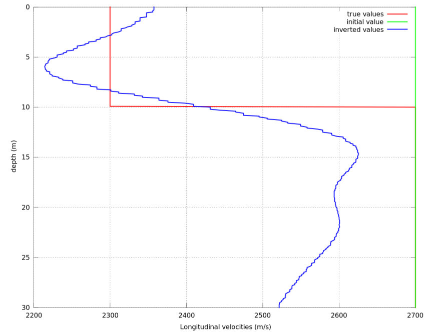


Figure 7: Inversion results of the $V_P$ parameter for the vertical component only

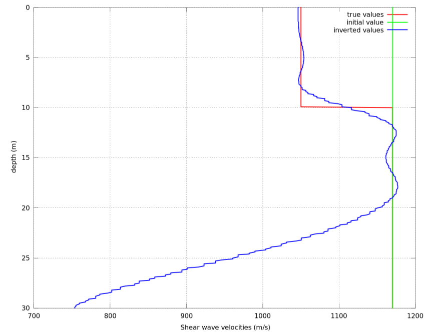


Figure 8: Inversion results of the $V_S$ parameter for the vertical component only

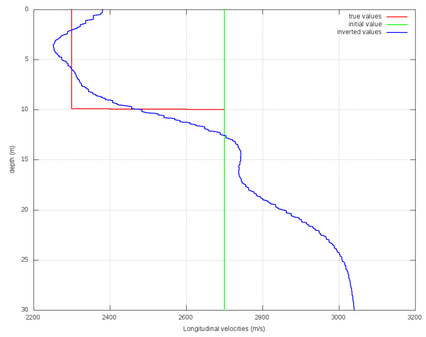


Figure 9: Inversion results of the $V_P$ parameter for the horizontal component only

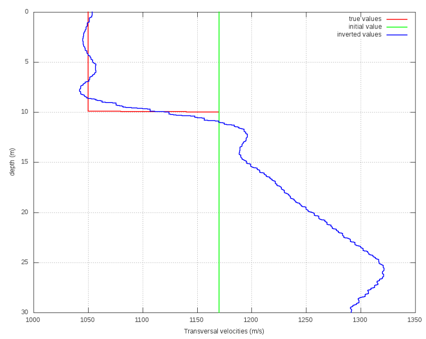


Figure 10: Inversion results of the $V_S$ parameter for the horizontal component only

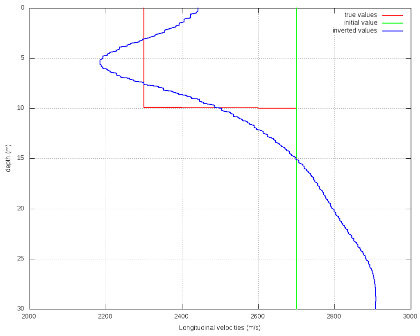


Figure 11: Inversion results of the $V_P$ parameter for both components

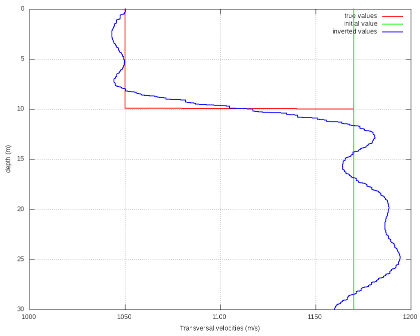


Figure 12: Inversion results of the $V_S$ parameter for both components

## 4 Experimental measurement of multicomponent data at reduced scale

Most of the conventional measurement setup are not able to measure the horizontal and vertical components of displacement field simultaneously. A new measurement process [4] 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 a point source force 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 $\mu m$. 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 in figures 14. 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 in figures 15, 16 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 in figures. Simulations have been computed through the finite elements code previously described [3]. The source shape used is calculated from the deconvolution of experimental data by using a linear least-mean square regression 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.

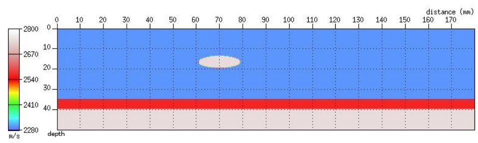


Figure 13: Representation of the longitudinal velocities of the physical model

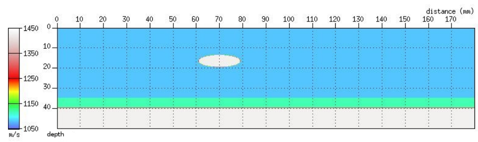


Figure 14: Representation of the transversal velocities of the physical model

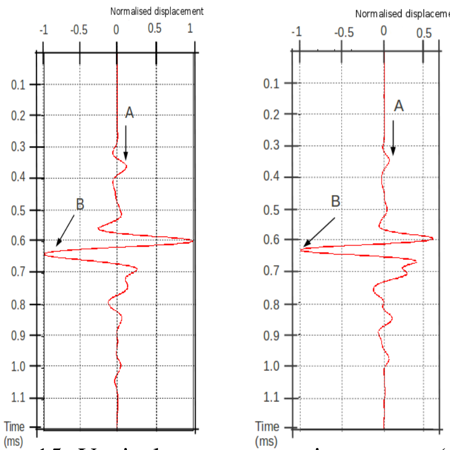


Figure 15: Vertical component seismograms (numerical and experimental results respectively

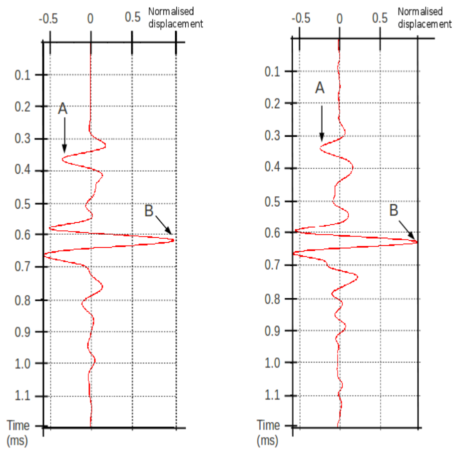


Figure 16: Horizontal component seismograms (numerical and experimental results respectively

# 5 Conclusions and perspectives

The conclusions of the presented study are split into two categories : conclusions and perspectives about the inversion results and the conclusions about the experimental measurement of the horizontal component at reduced scale.

These numerical inversion results suggest that the FWI method might be an interesting alternative approach to surface waves analysis to quantitatively estimate the near-surface parameters. However, further investigations are needed, especially to evaluate the benefits of this method for laterally varying structures, structures with strong velocity/impedance contrasts and to evaluate the robustness of this approach to noise. Additional results about laterally varying structures will be presented during the oral session. The analysis of the inversion results shows a divergent behavior to exact model for the deeper areas of the model. This phenomenon might be explained by the very low damping factor ($\varepsilon = 0.1\%$) used for the inversion giving a much stronger weight on data than on the a-priori model (which is exact for the deeper zones).This choice has been done in order to maximize the resolution of the estimated models and due to the great quality of the data that are affected only by very small numerical noise. However, in the case study data do not provide enough information on the deeper part of the model, therefore the ill-posed nature of the diffraction inverse problems induces instabilities. Development of efficient regularization strategies should be processed in further works to stabilize the inverse problem without affecting the resolution. Resolution is a key issue especially for inverting the $V_P$ parameter which is sensitive to much larger wavelengths than the $V_S$ parameter. Concerning the multicomponent data approach, it has been showed that multicomponent data can help to better constrain the inversion. As a consequence, inversion of the deeper areas of the model is much more stable. The next research perspective concerns the optimization of the inverse problem formulation in order to better introduce the multicomponent information in the FWI method.

The presented results suggest that multicomponent measurement can effectively be applied to reduced physical scale modeling approach. However, a quantitative validation of the amplitudes measurements is needed in order to better estimate the quality of the measurements. This approach is currently conducted using very low attenuation materials and 3D elastic wave propagation models.

# Acknowledgments

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