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High Resolution Seismic Imaging of Very Shallow Highly Contrasted Structures

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SUMMARY

Imaging very shallow highly contrasted structures with seismic methods stands for a difficult task because of the interpretation complexity. In particular, body waves carry the main part of information about the structure while they are much less energetic than surface waves which dominate the data.
In this study we assess the performances of two different imaging techniques for the characterization of concrete foundations. Relying on 2D-synthetic examples, we show Full Waveform Inversion behaves well on structures with low properties contrasts but fail to image realistic contrasts of concrete in soft sediments. We also apply elastic reverse time migration and conclude on its ability to characterize the geometry of the upper part of foundations.

Introduction

Imaging structures located in the near-surface is an important challenge for geotechnical applications because the ground may contain strong heterogeneities and the contrast between ground and structures is often really high. Near-surface generates therefore complex seismic data, strongly dominated by surface waves, that are difficult to exploit with conventional imaging techniques.
Full Waveform Inversion (FWI) (Pratt, 1990) extracts information from the whole seismogram and is classically used for reservoir characterization. In order to overcome the difficulties of conventional techniques, on the one hand, we assess how FWI can be applied to these near-surface targets. On the other hand, FWI technique can appear to be computationally intensive and sensitive to the inversion non-linearities. Therefore, we may be interested in considering non-quantitative results of Reverse Time Migration (RTM).
We are interested in imaging concrete foundations in soft sediments. In such near-surface environments, these structures can have contrasts up to 10 for V_p - the velocity of pressure waves - and 15 for V_s - the velocity of shear waves. In this work we assess how FWI can image synthetic concrete foundations with contrasts up to 5 and 1.2, when considering an infinite medium or a medium with free surface, respectively. We also illustrate the performances of RTM while considering realistic contrasts : RTM focuses the edges of the foundation without been affected by the high impedance contrast.

Theory

FWI recalls : FWI tries to update iteratively a soil model - V_p and V_s in our study - so as to minimize the misfit between observed and modeled data. In our study, synthetic data are computed using a 2D finite element Discontinuous Galerkin (DG) method implemented in the frequency domain. The misfit function considered is the classical L2-norm.

$$\mathscr{C} = \frac{1}{2}\Delta\mathbf{d}^t\overline{\Delta\mathbf{d}}$$

where $\Delta\mathbf{d} = \mathbf{d}_{obs} - \mathbf{d}_{calc}$ is the data misfit vector. In order to perform local optimization of the problem, we compute the gradient of the misfit function, based on the adjoint formalism (Plessix, 2006):

$$\mathscr{G}_{m_i} \quad = \quad -\Re\left\{\mathbf{s}^t\mathbf{A}^{-1}\frac{\partial\mathbf{A}^t}{\partial m_i}\mathbf{A}^{-1}\mathbf{S}^t\overline{\Delta\mathbf{d}}\right\}$$

where $\Re$ denotes the real part of a complex number and $\mathbf{A}$ is the discrete forward-problem matrix. The gradient can be seen as an intercorrelation between the incident wavefield $\mathbf{A}^{-1}\mathbf{s}$ from the source vector $\mathbf{s}$ and the adjoint wavefield $\mathbf{A}^{-1}\mathbf{S}^t\overline{\Delta\mathbf{d}}$, using residuals at receiver positions as a composite source. The radiation pattern of the diffraction by the model parameter m_i is denoted by the sparse matrix $\partial\mathbf{A}/\partial m_i$. The gradient is then used in a quasi-Newton method (L-BFGS) that has proven relevant for imaging structures with low illumination (Brossier et al., 2009).

RTM recalls : The RTM (Baysal et al., 1983) used in this study is a classical extrapolation migration technique. However we perform an elastic migration that requires to take into account the elastic properties of the wavefield. Our RTM is performed in 2D in the frequency-domain (both modeling and imaging principle). Our imaging conditions takes into account the radiation pattern of the P and the S-wave diffractor points by using the same $\partial\mathbf{A}^t/\partial m_i$ as in FWI to correlate the incident and backpropagated wavefields. Consequently, the migrated image ($\mathscr{I}$) is very close to a FWI gradient ($\mathscr{G}$). The RTM image is given by the equation

$$\mathscr{I}_{m_i} \quad = \quad -\Re\left\{\mathbf{s}^t\mathbf{A}^{-1}\frac{\partial\mathbf{A}^t}{\partial m_i}\mathbf{A}^{-1}\mathbf{S}^t\overline{\mathbf{d}}_{obs}\right\}$$

Therefore, from an implementation point of view, the only difference between $\mathscr{I}$ and $\mathscr{G}$ comes from the excitation term of the backpropagated wavefield.

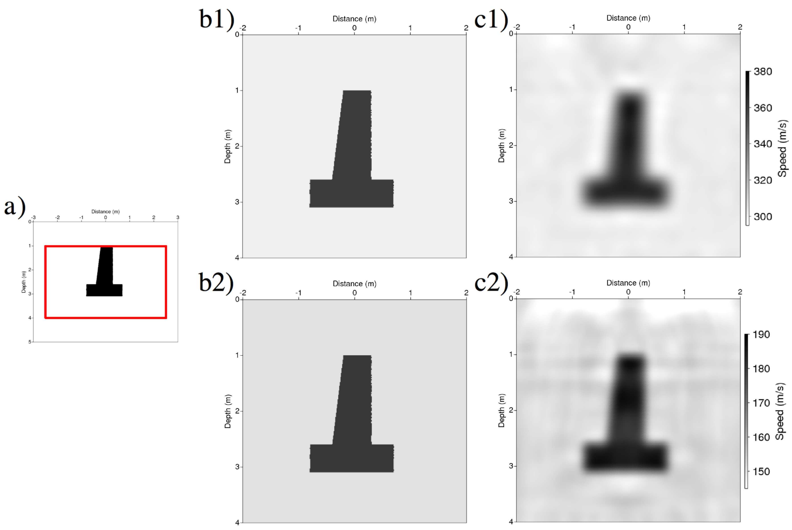

Figure 1 *True models (b) and reconstructed models (c) for V_p (1) and V_s (2) for a rectangle acquisition (a) and foundation/background properties ratios of 1.2*

In order to limit the effect of geometrical spreading of the wavefields on the amplitude of the migrated image, a correction term is applied, based on an estimation of the diagonal part of the Hessian matrix of FWI (Shin et al., 2001).

FWI Results

For all FWI tests, data are computed with DG-P1 interpolation in unstructured mesh that fit the shape of the foundation. Inversion is computed with DG-P0 interpolation in structured mesh. The background considered has homogeneous elastic properties of $V_p = 300m/s$ and $V_s = 150m/s$. The initial model of our inversions is this background.
Infinite medium : A first test focuses on performances of FWI in an infinite background. The geometry of the concrete foundation is illustrated on Figure 1. The acquisition perfectly illuminates the target with 161 sources and 161 receivers located all around the foundation. Inversion is performed with 14 frequencies from 29.3Hz to 567Hz.

A first test (Figure 1) considers low properties contrasts between concrete and background (1.2). Results from successive inversions of single frequency show acceptable performances with a reliable estimation of the shape and properties of the foundation in this favorable configuration. In a second test, we increase the properties contrasts to 5.

Results (Figure 2) show however that single frequency inversion lacks to reconstruct reliable images when properties contrasts increase, adding significant non-linearity in the problem which cannot be considered as a small perturbation problem any more. Inverting group of frequencies (2 consecutive frequencies) allows to mitigate these non-linearity, giving better focused images particularly for V_s that has more resolution.

Medium with free surface : The free surface effects increase significantly the non-linearity of inversion due to complex wave propagation. Hence, we progressively introduce later arrivals thanks to the complex-frequency factor that acts as a time-windowing factors (Brossier et al., 2009). The factors used in this study are { 10 , 33.3 , 100 } ms. We consider a contrast of 1.2 between the properties of the foundation and the background. The Figure 3 shows FWI results for different acquisition geometries : surface acquisition or combination of short-offset acquisition and borehole acquisition. The results show that the lack of illumination provided by the surface acquisition gives mitigated images, both for single frequency or group of frequencies (2 frequencies per group) : it is difficult to identify the shape of the foundation and the properties are underestimated. Using a better illumination provided by the combination of short-offset and borehole acquisition, we can clearly see the improvement in the reconstruction of the foundation shape and properties.

These tests show that high contrast imaging is a difficult task with classical FWI, which relies on small perturbations assumption. Adequate acquisition surveys are required to improve illumination and optimal use of the data is needed to retrieve the foundation shape and properties. However, we currently fail to image foundation with realistic contrasts. That motivates us to tackle the shape identification task with an elastic RTM technique.

RTM

To evaluate the performances of elastic RTM using both body and surface waves, we tested several acquisition geometries with realistic properties contrasts : 13 for V_p and 20 for V_s. The same frequency range as FWI test is considered : 29.3Hz to 567Hz. Note acquisition geometry was chosen to record only backward scattered wavefield.

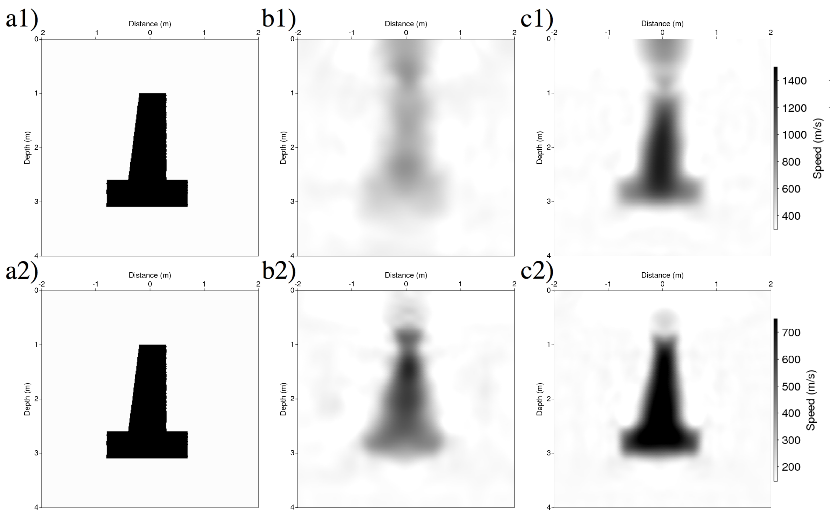

Figure 2 *True models (a), reconstructed models inverting consecutive frequencies (b), inverting pairs of consecutive frequencies (c) for V_p (1) and V_s (2), with a rectangle acquisition and foundation/background properties ratios of 5*

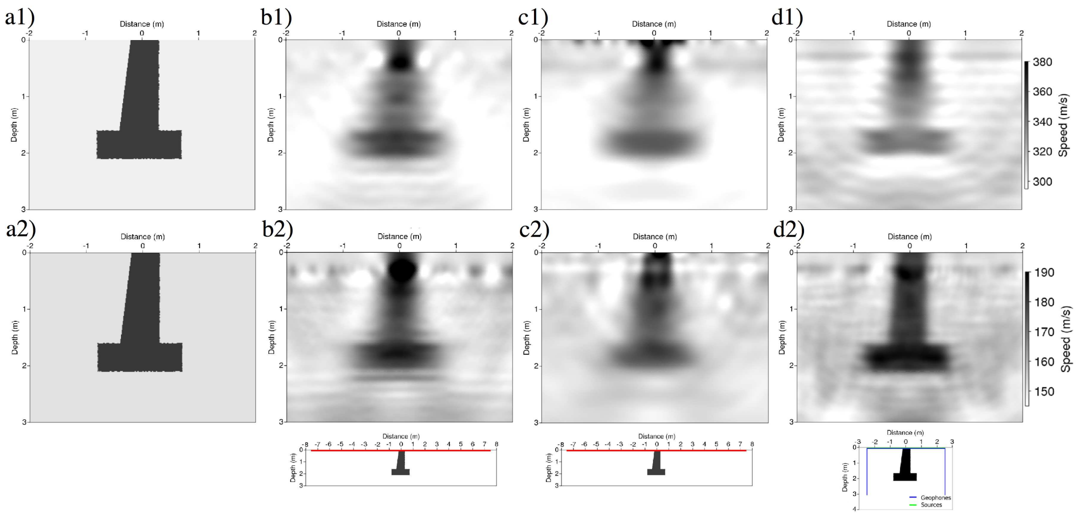

Figure 3 *FWI results for a medium with free surface and foundation/background properties ratios of 1.2. True models (a) and reconstructed models (b,c,d) for V_p (1) and V_s (2), with a surface acquisition and using single frequency groups strategy (b) or couples of frequencies group strategy (c). Column (d) shows the results with a better illumination using single frequency groups inversion.*

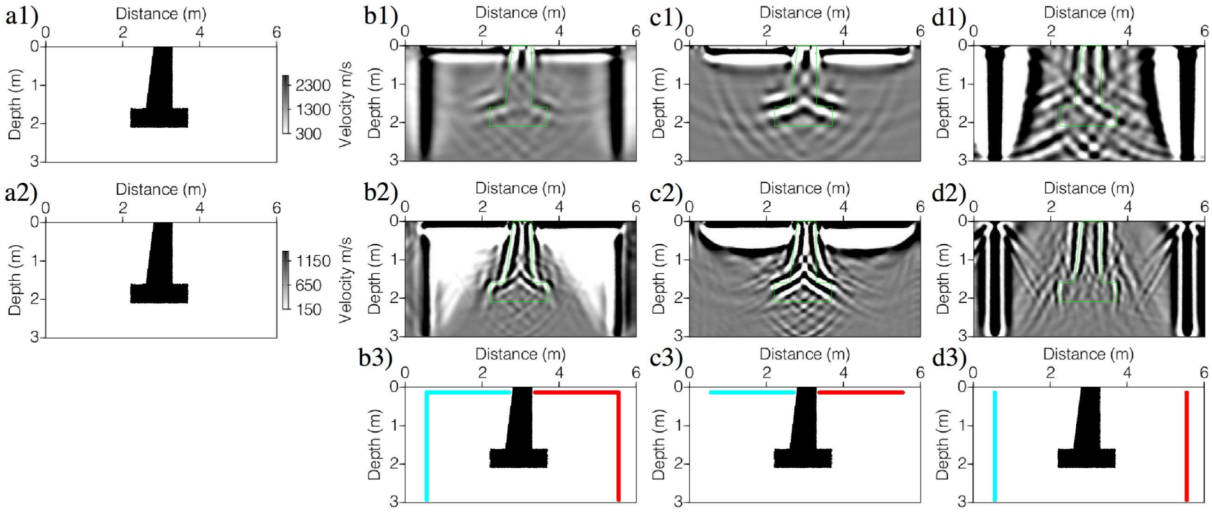

Figure 4 *RTM results for a medium with free surface and realistic contrasts. True models (a) and reconstructed models (b,c,d) for V_p (1) and V_s (2) for a given geometry of acquisition (3). (b) surface and borehole acquisition, (c) surface acquisition only with the vertical and horizontal geophones. (d) borehole acquisition with vertical geophones only.*

On Figure 4, we can see that using both surface and boreholes data - column (b) - makes it possible to focus both the quasi-vertical edges of the foundation (both the chimney and the base) and also the horizontal edge of the base's top. The V_p image allows to focus only the top of the vertical edges of the chimney and the diffracting angles of the base, at a lower resolution than V_s. If we do not take into account boreholes data, we get the images of column (c) where V_p does not give much information about the geometry of the foundation while V_s seems to localize the two corners of the top of the base. When we migrate only the vertical components of the boreholes data - column (d) - we note that V_p does not carry any information while V_s provides a good focusing of the vertical elements of the foundation, that is to say the chimney and the vertical edges of the base. This result is coherent with the positions of the sources and receivers which mimics a quasi-reflection configuration, with the specificity of using both surface and body waves.

Conclusions

Very shallow near-surface imaging of highly contrasted objets is a challenging topic for non-destructive geotechnical applications. FWI appears to be an elegant alternative to classical imaging techniques. Nevertheless, when dealing with highly contrasted targets such as concrete in soft sediments, the small perturbation assumption is no more verified and *a priori* information should be taken into account. An alternative relies on elastic RTM that allows to focus target edges from borehole and surface acquisition without been affected by high impedance contrasts.

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