MULTI-PARAMETER FULL-WAVEFORM INVERSION FOR COMPLEX SHAPED SHALLOW TARGETS: PRELIMINARY RESULTS AND CRITICAL ASPECTS

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Introduction. Full-Waveform Inversion (FWI) is a non-linear data-fitting technique based on the full wavefield comparison between observed data and synthetic solution obtained by solving the wave equation (Tarantola, 2005). It provides quantitative seismic images of the subsurface physical parameters with a theoretical local half-wavelength resolution (Born and Wolf, 1970; Virieux and Operto, 2009). While the fitting is mainly driven by body waves for upper crust imaging (Sirgue *et al*., 2010; Warner *et al*., 2013), data for shallow targets are dominated by surface waves (SWs) which require a specific investigation for quantitative geotechnical imaging, especially in noisy environments.

For shallow environments reconstruction, elastic propagation should be considered because shallow heterogeneities and topography impact strongly the wavefield. The elastic multi-parameter FWI is facing two main challenges: the first is related to the differential sensitivity of the algorithm with respect to each parameter class; the second is the increasing computational cost when considering needed visco-elastic propagation embedded into the optimization workflow: only linearized formulation based on Newton methods are currently considered. In this local optimization, an initial model is needed and it should be accurate enough to avoid local minima issues. Although techniques are developed to overcome cycle-skipping effects induced by a crude initial model for upper crust imaging (van Leeuwen and Herrmann, 2013; Métivier *et al*., 2016,), near-surface applications are still very sensitive to the initial model design. The complex structure of the wavefield with many phases combined altogether makes the building of the initial model as an important crucial step for FWI.

For shallow structures, the analysis of the dispersion curves (DCs) of SWs fundamental mode provides shear velocity structures. Recently, Socco *et al*. (2017) and Socco and Comina (2017) have proposed a workflow to extract as well compressive velocity structures using a wavelength-depth relationship sensitive to Poisson's ratio. The mitigation of the strong lateral variations is performed by a clustering analysis (Khosro Anjom *et al*., 2017). Are these S-wave and P-wave velocity models kinematically compatible for preventing cycle-skipping issues (Virieux and Operto, 2009)? This is the purpose of the present work while the influence of frequency window and offset range should play an important role when progressively building the image.

Dataset, Methodology and Tools. Synthetic data are built as observed data on a conceptual model (Fig.1a) inspired by the CNR test site nearby Turin (Italy) and has already been presented in previous studies (Teodor *et al*., 2017; Khosro Anjom *et al*., 2017). For such propagation simulation, a spectral-element code (SEM46) is used where attenuation could be described by combining standard-linear-solid mechanisms and where anisotropy could be considered if needed (Trinh *et al*., 2018). In this initial feasible synthetic investigation, only isotropic elastic propagation is considered, but more complex propagation would be expected when facing real data analysis. A vertical point source characterized by a Ricker wavelet with a central frequency of 16 Hz is used for 11 shots recorded by 72 stations.

Following the previously mentioned procedure based on dispersion curve analysis, Teodor *et al*. (2018) built an initial P-wave velocity model (Vp) and S-wave velocity model (Vs) which are shown in figure 1c. The density is taken as constant with a value of 1800 kg/m^3. Figures 1b and 1d show vertical traces for the first shot in the target model and in the initial model, respectively. One can appreciate some similar structures of waveforms, thanks to the DC analysis.

Full-Waveform Inversion tests and results. We started the FWI of the synthetic dataset from the 1 – 40 Hz frequency range in the frame of a multi-scale approach. The density is

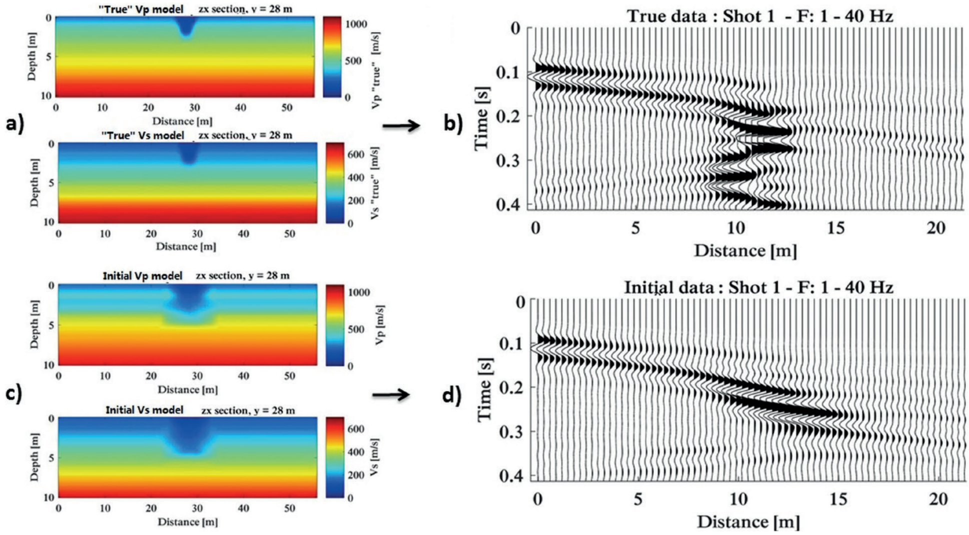

Fig. 1- a) 2D slices of the synthetic ("true") Vp and Vs models that mirror the CNR geometry; b) Seismic data corresponding to the "true" model – shot 1; c) Initial Vp and Vs models built from DCs clustering and data transform; d) Seismic data corresponding to the initial model - shot 1.

kept constant (1800 kg/m^3) while inverting simultaneously for Vp and Vs parameters. The Ricker wavelet stays as the true source up to now. The time sampling is set to 4.8*e-05 in agreement with to the CFL stability condition. A total number of 8600 time steps correspond to an acquisition duration of 0.412 s (the same as the field one). The quasi-Newton technique is selected in the SEM46 code. The gradient is smoothed using a Bessel filter (Trinh *et al.*, 2017). In Fig. 2a we show the first gradient with respect to Vp parameter (left) and to Vs parameter (right). The small artefact presents in the shallow Vs gradient (Fig. 2a right) may cause the update of the Vs model in the wrong direction. To solve this potential issue we applied depth-variable boundary constraints on model parameters.

After performing multi-parameter inversion without any data hierarchy, the Vp model is not improved significantly, although the Vs model is updated in the correct direction (Fig. 2b and 2c). Further, an alternative workflow can be designed, involving integrated data-oriented strategies (by frequency filtering, time windowing and offset selection and weighting) and/or model-oriented strategies by parameter selection.

In the frame of the model-oriented strategies, we perform a mono-parametric Vs reconstruction which improves the shallow Vs model down to 2.5 m depth. With this improved Vs and the old Vp from DCs analysis, a multi-parameter inversion is performed again (without any data hierarchy or model depth pre-conditioning). By doing so, the model is updated in the right direction and below 2.5 m depth.

In Fig. 3a and 3b we show a 2D vertical section of the improved Vp and Vs models, while in Fig.3c and 3d we show the 1D profiles for the true, initial and final Vp and Vs models in correspondence of the target. In Fig. 3e and 3f we show the comparison of the matching between true data and initial data and, respectively, between true data and final FWI data. The data misfit shows an improvement not only in correspondence of the target but also for far offsets. This preliminary results make us confident that further data-fitting should improve the inversion behaviour by integrating model driven strategies with designed data selection.

Conclusions and Perspectives. The results of the FWI tests highlight some key features of the multi-parameter FWI for near surface complex shaped targets:

- The Vp and Vs models retrieved from DCs analysis seem to be good candidates as starting models. Nevertheless, a robust FWI workflow cannot be performed blindly from this

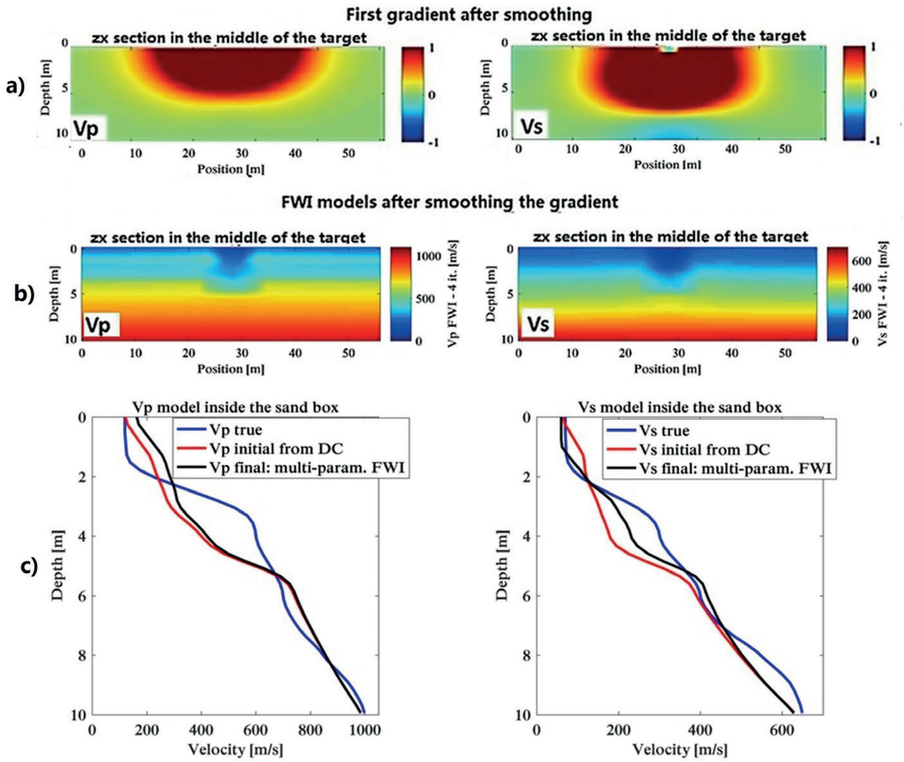

Fig. 2 - a) First FWI gradient with respect to Vp parameter (left) and Vs parameter (right) after applying the Bessel smoothing filter; b) The FWI models reconstructed by multi-parameter FWI; the black rectangles indicate the position of the target; c) 1D Vp (left) and Vs (right) profiles in correspondence of the target.

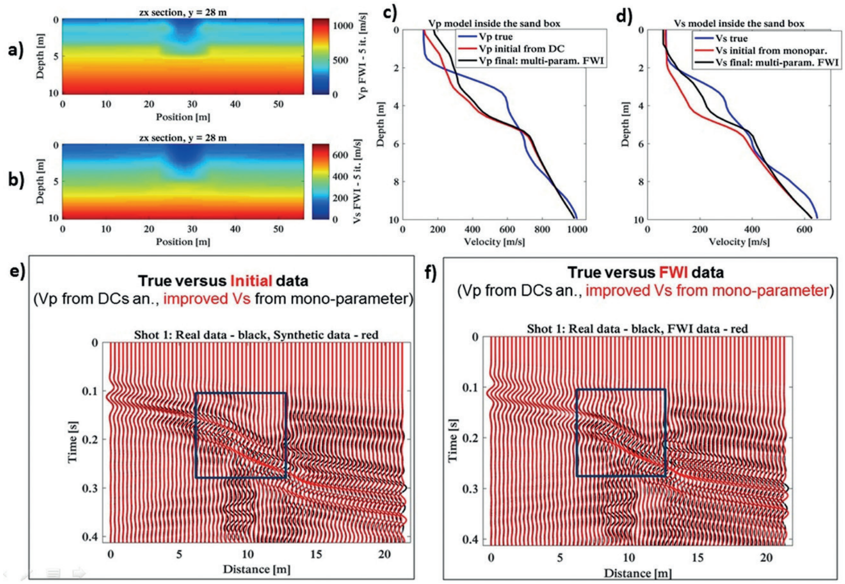

Fig. 3 - Vp model (a) and Vs model (b) after multi-parameter FWI; 1D profiles for Vp parameter (c) and Vs parameter (d) after FWI; e) True versus Initial data comparison for the improved initial model; f) True versus FWI data comparison after starting from the improved initial model.

models. Progressively improved initial models should be investigated by introducing into the inversion algorithm selected data (frequency sweeping, time windowing and offset weighting are options to be investigated).

- Regarding the model-oriented strategy based on parameter selection, the sensitivity of the inversion with respect to the Vs parameter is greater than the sensitivity with respect to the Vp parameter, coming from the physics of SWs propagation and it can be exploited to improve the initial Vs model in the shallow part.
- Using the improved Vs model (from mono-parameter FWI) allows a greater and deeper update of both Vp and Vs models. Data-misfit is reduced both in correspondence of the target and for far offsets. Nevertheless, there is still room for improvement.

Further analysis might integrate model selection with data hierarchy as follows:

- Data-windowing to exploit Body Waves (BWs) for a better reconstruction of the Vp parameter, in parallel with a Vp improvement from the new Vs parameter by using the Poisson's ratio. These alternatives are expected to be case-dependent.
- Offset weighting should be designed to avoid, initially, the effects of far offset data and to increase their influence at later stages of the inversion.
- Thanks to the starting Vp and Vs models, SWs could be introduced smoothly during the inversion by a Gaussian weighting around their arrival times.
- Frequency sweeping from low to high frequency will also mitigate the cycle-skipping issue.
- Additional constraints based on prior information on the model description could also help the reconstruction, which is difficult for near-surface data because all phases are mixed.

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