Near-surface characterization by elastic full-waveform inversion of surface waves

A. Sedova[1], O. Leblanc[1], M. Reinier[1], D. Donno[1], G. Lambaré[1], D. Carotti[1]

[1] CGG

Summary

We present the use of elastic full waveform inversion (FWI) of surface waves to create a detailed shear velocity model of the near surface in the Middle East, where the shallow geology features strong velocity contrasts, making traditional velocity model building techniques challenging. The approach uses low-frequency virtual data from 3D interferometry and active surface waves to update the shear velocity model, providing valuable information for velocity model building and imaging. The study demonstrates the effectiveness of elastic FWI by comparing the results with the legacy velocity model and migrated images, showing improved resolution of the subsurface and simplified geological structures. The integrated Vs velocity model helps flatten shallow reflections and provides a good fit with well markers. The method has potential for application in areas with similar complex geology.

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Introduction

In the Middle East, the shallow geology often features strong lateral and vertical velocity contrasts from layered shales, carbonates, and anhydrites, leading to complex wave phenomena including wave mode conversions and multiples. Moreover, data from this region generally contain very strong and relatively fast surface waves (a.k.a. ground roll) that overshadow much weaker diving and reflected waves. Typically, this part of the data is treated as noise and removed before applying velocity model building techniques such as tomography or acoustic full-waveform inversion (FWI) (Stopin et al., 2014; Sedova et al., 2019; Hermant et al., 2020). In this region, the strong elastic effects in the shallow geology make the application of acoustic FWI using diving and reflected waves challenging. Accurately modelling the near surface is essential for seismic imaging, and one proposed approach was to use multi-wave inversion (MWI) (Bardainne, 2018) before applying acoustic FWI (Masclet et al., 2021; Farooqui et al., 2021). While MWI can provide a reliable velocity model of the near surface by jointly inverting first breaks and surface-wave dispersion curves, it has some limitations: the dependence on the quality of picking, the restriction to the fundamental mode when higher-order modes cannot be picked, and the 1D assumption of surface-wave dispersion curve forward modeling (Socco and Strobbia, 2004).

We propose elastic FWI of surface waves to characterize the complex near surface in the south of the Sultanate of Oman. Elastic FWI offers several advantages over methods such as surface wave inversion (SWI) and MWI, including 3D full-wavefield modeling and no requirement for picking. Also, since the propagation of surface waves depends almost exclusively on shear-wave velocity (Vs), it provides a favorable context for elastic FWI, which is often hampered by the coupling between parameters, particularly compressional-wave velocity (Vp) and Vs. Further, surface waves dominate passive virtual data from interferometry (Le Meur et al., 2020), allowing the use of frequencies as low as 0.5 Hz. While elastic FWI of surface waves is not a new topic in academia (Pérez Solano et al., 2014; Borisov et al., 2018), it has only gained attention in the industry recently (Adwani et al., 2022). Advances in elastic FWI for land data (Leblanc et al., 2022) have made it possible to exploit surface waves to create a detailed near surface Vs model, providing valuable information for model building. This study demonstrates the effectiveness of this approach and its potential to enhance subsurface characterization.

Elastic FWI of surface waves

In many areas in the south of the Sultanate of Oman, the complex near surface is characterized by shallow fast carbonates and anhydrites interleaved by slow-velocity shale layers, resulting in sharp velocity inversions and an extremely challenging context for imaging and velocity model building. To overcome the limitations of traditional methods such as SWI or MWI, this study proposes using elastic FWI of surface waves. The data set was acquired with a typical dense blended acquisition of vibroseis sources and a minimum frequency of 1.5 Hz, and vertical geophones as receivers. For this data, surface waves account for nearly 95% of the total recorded energy, making them attractive to exploit. These waves propagate parallel to the Earth's surface at a velocity slightly smaller than Vs and penetrate down to a depth roughly equal to the shear wavelength. By utilizing virtual data reconstructed by interferometry of the ambient noise recorded during blended continuous acquisitions (Le Meur et al., 2020), we can access surface waves with frequencies as low as 0.5 Hz. Incorporating virtual data into our workflow allows us to update the Vs model to greater depths and avoid cycle-skipping issues.

Figure 1 compares shot gathers from virtual data and deblended active data at the same location. The virtual shot in Figure 1a is very similar to the active one in Figure 1c, despite the virtual data having a lower frequency content. Figures 1b and 1d show time slices at 2.4 s of virtual and active data, respectively, low-pass filtered at 1.5 Hz (the minimum frequency of the active source). The active data in Figure 1d contain almost no coherent signal, while the reconstructed virtual data contain clear signal (Figure 1b). The virtual data exhibit strong directionality (perpendicular to the closest coastline in this case), indicated by the red arrow. This dominant direction is attributed to the orientation of ocean waves hitting the shoreline, which likely is the main generator of the low-frequency ambient noise.

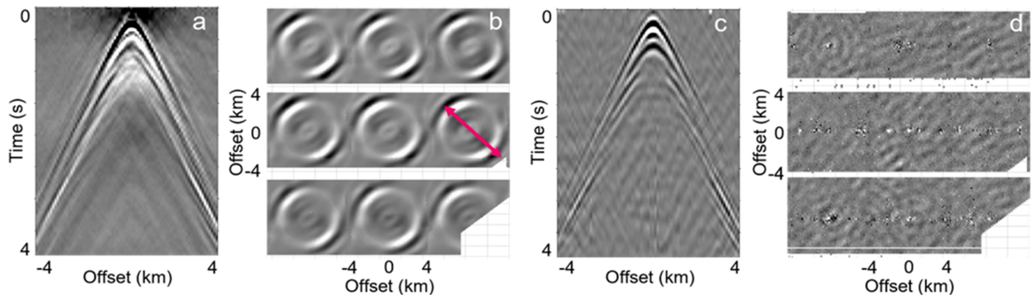

Figure 1: *Virtual data from interferometry: (a) shot gather, and (b) time slice at 2.4 s of several shot gathers low-pass filtered at 1.5 Hz, with the red arrow indicating the dominant direction of energy of the interferometry-reconstructed data. Active deblended data: (c) shot gather, and (d) time slice at 2.4 s of several shot gathers low-pass filtered at 1.5 Hz.*

The first step of our workflow is an elastic FWI (Leblanc et al., 2022) using the ultra-low frequency virtual data created by 3D interferometry. For the observed input data, we select the traces of the virtual shot gathers along the dominant-energy azimuths (red arrow in Figure 1b), to avoid including traces with less reliable kinematic information from interferometry. We update the Vs model by inverting the virtual data from 0.5 to 2 Hz, starting from very smooth regional velocities (Figure 2a). This step provides us with a long-wavelength Vs update nearly down to 2 km. In the second step, the Vs model is then updated by elastic FWI of ground roll from the active data from 2 to 7 Hz. It provides a detailed shallow Vs model characterized by both lateral and vertical velocity variations (Figure 2c). The data fit QC in Figure 2d, obtained by overlaying the observed and modelled data, shows that we were able to successfully fit not only the surface waves but also later reflection arrivals, corresponding to S-S reflections (yellow arrows in Figure 2d). These energetic reflections are likely generated by the strong velocity contrasts both in the shallow and deeper sections (Figure 2c).

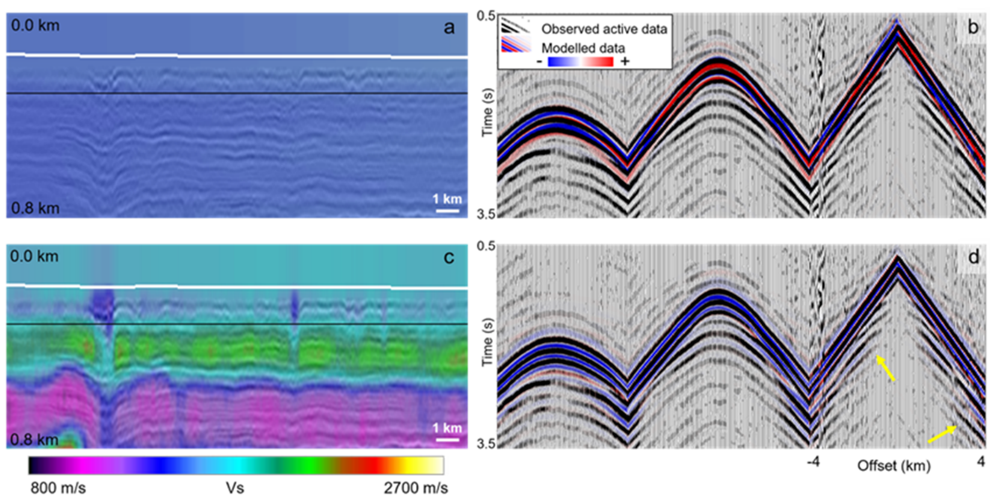

Figure 2*: (a) Initial Vs model, and (b) corresponding data fit QC at 7 Hz between modelled data and observed active data. (c) 7 Hz Vs elastic FWI updated model, and (d) corresponding data fit QC at 7 Hz between modelled data and observed active data.*

Figures 3a and 3c show a depth slice at 150 m below the surface of the legacy Vs model (obtained with MWI in the shallow part) and the associated migrated image. The corresponding depth slice of the Vs updated by elastic FWI of surface waves up to 7 Hz displays high-resolution velocity variations that correlate with shallow features visible in the satellite image, marked by pink arrows (Figure 3b and 3d). These features were not detected by the conventional model building workflow (Figure 3a).

Going beyond the results of Adwani et al. (2022) and Leblanc et al. (2022), Figures 2 and 3 demonstrate the vertical and lateral Vs resolution that can be obtained using elastic FWI of surface waves. This result outperforms the update obtained with MWI (Figure 3a) as it better correlates with the shallow features visible on both the migration and the satellite image (Figures 3c and 3d). This is attributed to the robustness of elastic FWI of surface waves, which requires minimal data pre-processing (as surface waves are the strongest energy) and takes advantage of the ultra-low frequencies of virtual data. In contrast, MWI relies on a more complex and cumbersome workflow.

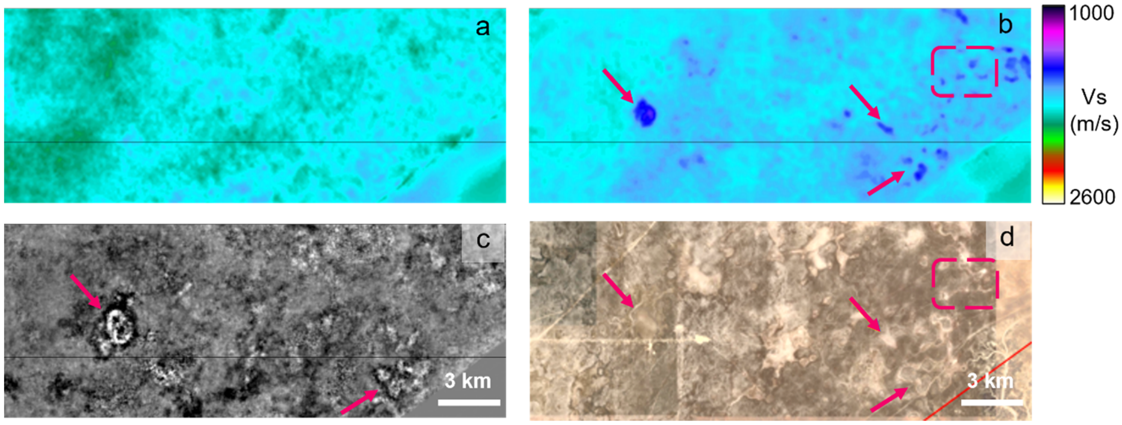

Figure 3: *Depth slice at 150 m depth of the Vs model obtained: (a) with MWI, and (b) with elastic FWI of surface waves. (c) Depth slice at 150 m of the reference migration using MWI velocity. (d) Satellite image of the same area.*

Near-surface characterization for velocity model building

Elastic FWI of surface waves is a first step to overcome the challenge of velocity model building in the south of the Sultanate of Oman. This method strongly benefits from the inherent decoupling of Vp and Vs and the strength of the surface waves. Going a step further with elastic FWI by incorporating diving or reflected waves poses a challenge due to parameter coupling (Adwani et al., 2022). In this study, we integrate the Vs model obtained by elastic FWI into a conventional Vp velocity model building workflow. We scaled the first 500 m of the inverted Vs model by a constant Vp/Vs ratio, ensuring the calibration of PP reflections with the well markers. The resulting shallow Vp model was combined with the legacy Vp model, and a pass of global tomography below 500 m ensured the seamless integration of the shallow update into the legacy velocity model.

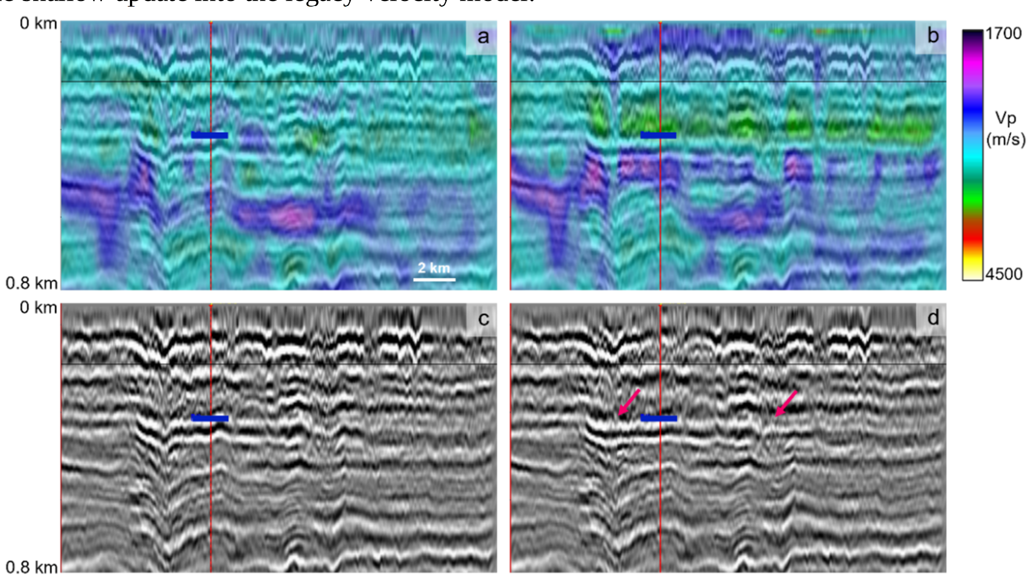

Figure 4*: Shallow section: (a) before, and (b) after the integration of the scaled Vs elastic FWI model in the legacy migration model, with the associated PP-migrated stack sections in (c) and (d), respectively. The red vertical line represents the location of a well, with a formation marker in blue.*

The results of the described workflow are shown in Figure 4. For comparison, the data were migrated with the legacy Vp model (obtained with the combination of MWI, acoustic FWI and reflection tomography) and with the proposed approach integrating the scaled Vs model into the legacy Vp model. The migrated inline section indicated by the black line in Figure 3 is shown in Figure 4. We note that the shallow velocity variations help flatten the shallow reflections and simplify the geological structures. The red arrow in Figure 4d indicates the position of Rus horizon, typical of this region at shallow depth, which marks a strong vertical velocity contrast. This reflector is flattened and more continuous along the whole section with our proposed approach.

Conclusion

In many areas of the Middle East, the complex near surface, characterized by very strong lateral and vertical velocity contrasts, poses challenges for seismic imaging. The recent advancements in elastic FWI for land data permit the inversion of surface waves to create a detailed Vs model. The very energetic surface waves observed in the region require minimal pre-processing, allowing the model building flow to start shortly after deblending. Our approach benefits from the ultra-low frequencies recovered by interferometry to get a deeper update. We demonstrate the effectiveness of this workflow to enhance the imaging of the shallow subsurface. The inverted Vs model could be used for shallow hazard and geotechnical studies or as starting point for subsequent Vp update by elastic FWI.

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