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Velocity Model Building with Guided Wave Inversion

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Summary

Guided wave inversion (GWI) estimates accurate P-wave velocity in the near surface by analyzing the dispersion curves of guided waves. However, the GWI problem is highly non-unique without proper treatment of both fundamental and higher-order modes. To reduce the non-uniqueness of the inversion, a two-stage inversion scheme is used. The water velocity and depth are inverted first using a picked dispersion curve of the fundamental mode. Secondly, higher modes are incorporated to invert for sub-waterbottom velocities with a fixed water column. In our example from the North Sea, near-surface P-wave velocity from the GWI is introduced to the initial model for Full Waveform Inversion (FWI) of towed steamer data. In addition to producing high resolution shallow velocity for interpretation, the GWI adds a long-wavelength change to shallow near-surface velocities which reduces cycle skipping for 4-6 Hz FWI. Consequently, 6 Hz FWI converges faster and produces more geologically plausible velocity perturbations. The example shows GWI improving the seismic image and gather flatness for both shallow and deep targets.

Introduction

Accurate seismic velocity estimation in the near surface is important to detect or delineate shallow hazards such as trapped gas or over-pressured lithology. For seismic imaging, the near surface acts like a lens through which deeper formations can be viewed. In shallow water or onshore data, near-surface velocities are difficult to estimate using reflections as standard acquisition geometries do not provide sufficient near angles for this part of the subsurface. Refraction tomography and full-waveform inversion (FWI) can struggle to resolve the near surface due to strong acquisition footprint, errors in initial water velocity and seabed depth estimates, and a sharp velocity contrast at the seabed. Consequently, shallow velocities are often inaccurate and this impacts on deeper targets both by distorting the wavefield in migration, and by propagating velocity errors to deeper regions when velocity model building.

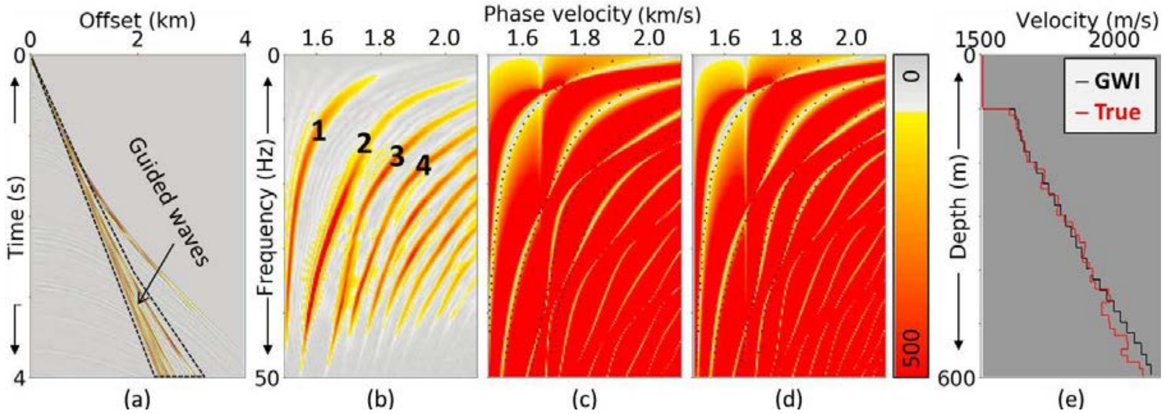

Figure 1 *(a) Guided waves from a synthetic shot gather; (b) Frequency-velocity dispersion curves of the guided waves (1: fundamental mode; 2-4: higher order modes); (c) Secular function with inverted water-column velocity (colour) overlaid with picked dispersion curves (black dotted lines); (d) Secular function with inverted sub-bottom velocity (colour) overlaid with picked dispersion curves; (e) Comparison between inverted and true velocity.*

The near surface can act as a waveguide, particularly in shallow marine environments (roughly 100 m water depth or less). The near-surface waveguide can contain complex geological and lithological variations below the seabed. Although responsible for a strong package of guided-wave energy (Haddon, 1984) that processing geophysicists usually wish to remove prior to imaging, guided waves can provide useful information for near-surface velocity estimation (Muyzert, 2007).

Figure 1 shows an example of guided waves and their corresponding frequency-velocity (f-v) spectra for synthetic shallow marine data. As frequency decreases, guided waves have phase velocities that increase relative to that of the water layer. Guided wave inversion (GWI) can be used to extract shallow P-wave velocity from the dispersion curves of guided waves (Muyzert, 2007) in a manner that is distinct from standard seismic tomography but which is complementary to tomographic (including FWI) velocity model-building workflows.

The following sections describe a method of multi-modal GWI and discuss practical aspects of its implementation, including reduction of the non-unique model space. GWI is used to initiate a shallow velocity model for further analysis with FWI, and shows appreciable impact on the results of the FWI workflow both for near-surface and for full-depth P-wave velocity-model building.

Method

GWI provides a 3D P-wave velocity volume by inverting for 1D P-wave velocity profiles which may vary from location to location in a survey. Similar to the workflow of multi-modal surface wave inversion described by Hou et al. (2016), GWI consists of two key steps. First is a dispersion analysis of guided waves using frequency-velocity spectra produced with a superposition method based on

Neducza (2007). Second, dispersion curves are inverted to estimate P-wave velocity using principles similar to that of Boiero et al. (2013).

Guided waves propagate as leaky modes defined by complex roots of the elastic Eigen-equation of motion (Aki and Richards, 1980), referred to as the secular function. Maraschini et al. (2010) propose inverting for guided-wave velocity using a misfit function based on the Haskell-Thomson matrix method by minimizing the determinant of the secular function. This misfit function takes into account the leaking modes without directly seeking complex roots. This allows a multi-mode inversion without modal identification, but comes with an increase in the number of local minima in the problem (Zheng and Miao, 2014).

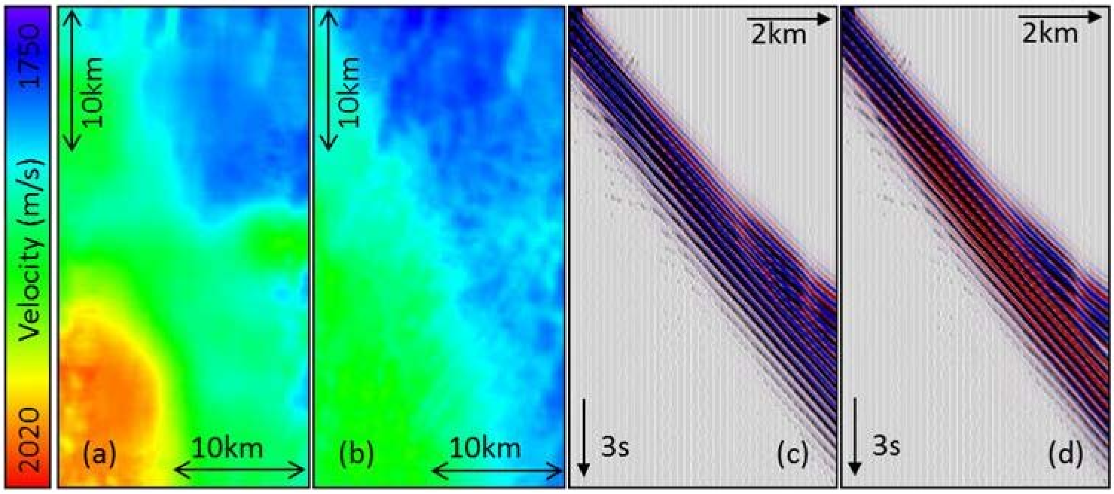

Figure 2 *(a) GWI P-wave velocity model at 40m below the seabed; (b) Vintage P-wave velocity model at 40 m below the seabed; (c) 6 Hz synthetic shot in red (positive amplitude) and blue (negative amplitude) using model (a) overlaid with the real data (positive-filled wiggle); (d) 6 Hz synthetic shot using model (b) overlaid with the real data*

To reduce the set of non-unique solutions in GWI, we propose a two-step workflow for the dispersion-curve inversion of guided waves. Step 1: The inversion estimates the velocity of the water column, including the seabed depth, using the fundamental mode of guided waves. A-priori information about the water column can be incorporated in the first step, including temperature and salinity measurements as well as seismic observations of the water wave. Step 2: Once the water column is fixed, the inversion proceeds to estimate a velocity model for the layers below the seabed using all modes of the picked dispersion curves, which penetrate deeper into the earth and bring new sensitivity below the water bottom.

In this scheme, velocities in the water column and sub-seabed are inverted separately. Fixing the water-column after the first stage of inversion reduces the set of non-unique solutions significantly. Figure 1 shows the secular function of the inverted velocity at the two inversion steps, overlaid with dispersion curves picked from the spectral analysis.

Results

Our GWI example uses towed streamer data acquired in the Norwegian Sea. The water depth varies from 80 m to 120 m. Comparing the GWI model (Figure 2a) with a vintage velocity model produced from well logs and reflection tomography (Figure 2b) we see quite a difference in both detail and long-wavelength velocity trend in some regions of the model. By modelling synthetic shots through the two models (Figure 2c & 2d) it is apparent that the synthetic data, plotted in red (positive amplitude) and blue (negative amplitude), achieve much closer phase alignment with the recorded data after GWI. Specifically, the red should be masked by positive-filled wiggle if the synthetic shot matches the real shot as shown in Figure 2c. This suggests a better starting model for subsequent velocity updates using FWI, as cycle-skipping of guided waves is significantly reduced. The top part of the GWI model (from sea-surface to 40 m below waterbottom) is merged into the remainder of the vintage velocity model to obtain the initial model for FWI and to investigate the effect of the near surface on the deeper velocity estimation. The GWI model provides a long-wavelength change to the near-surface sediment velocity, and also provides a sharp boundary at the seabed due to its broad-band dispersion analysis and multi-modal inversion.

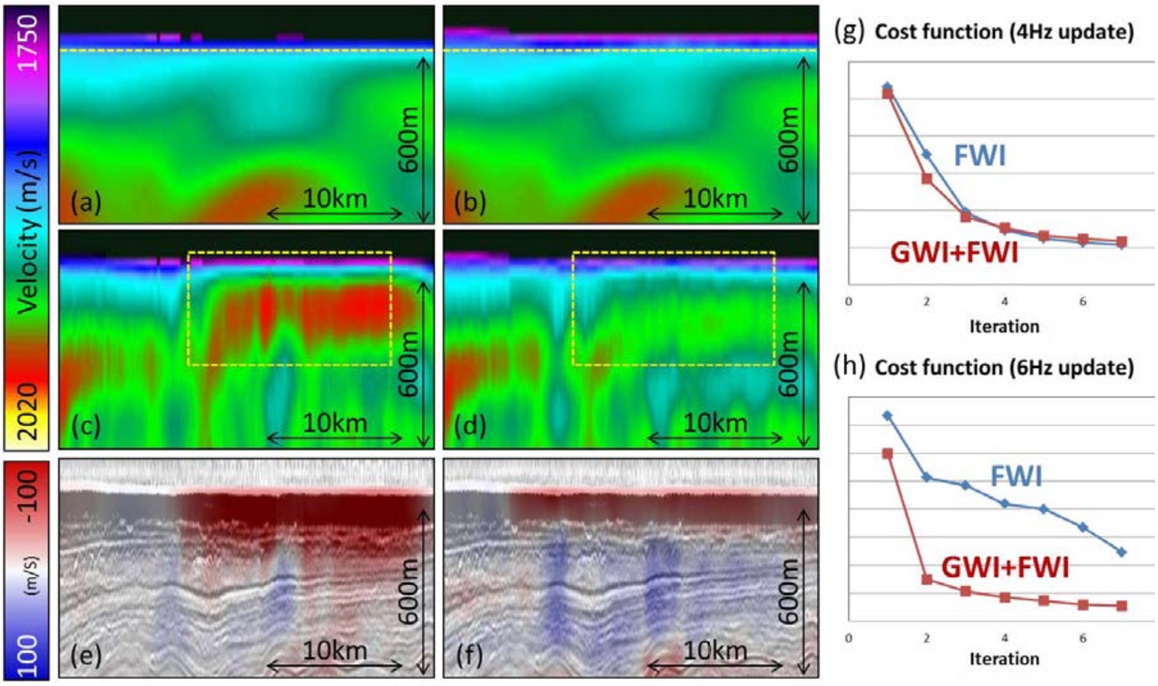

Figure 3 *(a) Initial FWI model using vintage P-wave velocity model; (b) Initial FWI model using vintage P-wave velocity model with near-surface replaced by the GWI model above the yellow dashed line; (c) 4-6 Hz FWI using initial model (a); (d) 4-6 Hz FWI using initial model (b); (e) FWI perturbation between 4 Hz and 6 Hz in (c); (f) FWI perturbation between 4 Hz and 6 Hz in (d); (g) FWI cost functions from models (a) and (b) in 4 Hz updates; (h) FWI cost functions from models (a) and (b) in 6 Hz updates .*

In section view (Figure 3a & 3b) the contribution from GWI looks insignificant as it impacts only the first 150 m of the FWI starting model. However, from the 4-6 Hz FWI it becomes clear that this near-surface lens has an appreciable impact on the deeper velocity estimation (Figure 3c & 3d). This is due to long-wavelength bulk changes in shallow velocity produced by the GWI, which has improved the initial model and decreased cycle skipping for the FWI. Perturbations from the two FWI updates at 6Hz (Figure 3e & 3f) show better delineation of the high-velocity (red) perturbation within the shallow unconformity in the seismic image, suggesting greater geological plausibility for this result. Furthermore, while the FWI cost functions at 4Hz are comparable for both starting models (Figure 3g), faster convergence is evident at 6 Hz when using the GWI starting model (Figure 3h).

After Kirchhoff pre-stack depth migration (Figure 4), the data show changes to both positioning and focus in the stack. The GWI starting model has produced a better FWI result, with flatter gathers in both the shallow and the deep. Residual curvature in the gathers may be due to inaccuracies in the near-surface anisotropy model, which is not updated by the GWI since this uses isotropic forward modelling. Subsequent inversion for anisotropy using standard methods can further flatten gathers where necessary.

Conclusions

GWI provides accurate P-wave velocity information at the near surface obtained from a wide frequency band of data. Intuitively, lower frequencies help GWI penetrate deeper whilst higher frequencies lead to improved vertical resolution in the near surface. Due to its local 1D nature, GWI is able to invert for water-column velocity and waterbottom depth with high vertical resolution without requiring large 3D models to complete the calculation.

In our example, multi-modal GWI conducted in two steps produced long-wavelength bulk changes of velocity compared with a model built from well-log data and reflection tomography. This near-surface information is not easy to obtain with other methods. Subsequent FWI converged faster with the GWI starting model at 6 Hz and produced flatter gathers in both the deep and the shallow part of the image.

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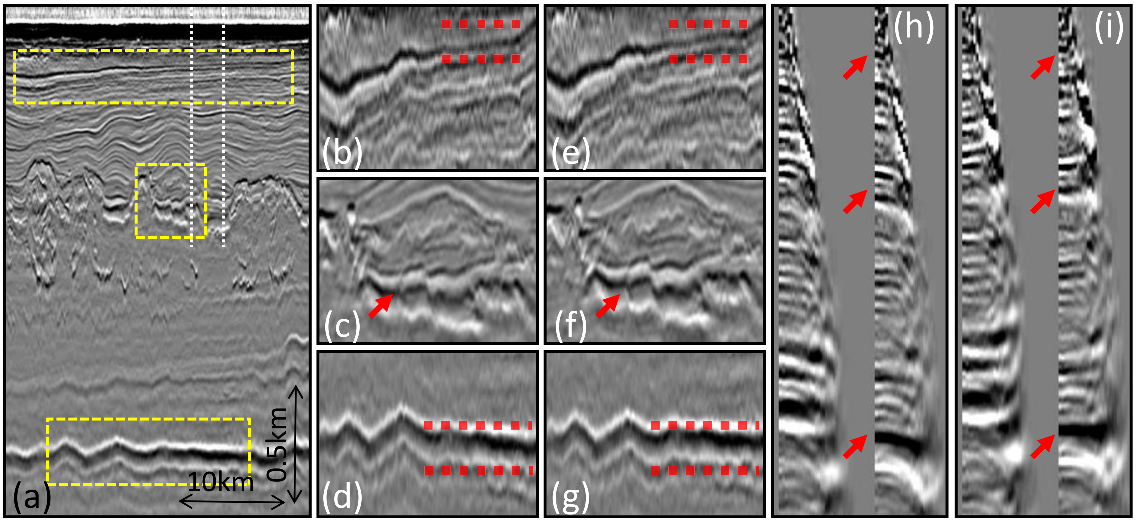

Figure 4 *(a) Near-surface seismic image using the velocity in Figure 3(d); Elements of the image marked by yellow dashed boxes are shown in zoom panels (b) to (g). Panels (b), (c) and (d) show data imaged using the velocity model in Figure 3(c). Common image-point gathers at the white dashed lines in (a) are shown (h) using the velocity model in Figure 3(c), and (i) Figure 3(d).*