Mitigating the effects of guided waves in OBN data for acoustic FWI using data reconstruction: A data example from the Yggdrasil area

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Summary

Ocean bottom node (OBN) data in a shallow water environment can be contaminated by near surface elastic effects such as guided waves. The presence of these waves may present a challenge for acoustic full waveform inversion (FWI) because modelling these guided waves accurately can be expensive and attempts to remove them can harm refractions. We present a method to mitigate the effects of the guided wave in shallow water OBN data in a computationally efficient manner. Application of this method for FWI to NOAKA OBN dataset from the Yggdrasil field in the North Sea is also presented.

Introduction

Linearization makes FWI computationally (Lailly 1983; Tarantola 1984; Pratt, Shin & Hick 1998) feasible. Assuming that the Earth is acoustic further reduces the computational cost of FWI. However, near surface elastic effects such as guided waves might not be negligible in the observed shallow marine data, (Klein et al. 2005). Accurately modeling these elastic effects is costly and methods like FK-filtering might damage the data while removing the noise, especially if the guided waves are dispersive.

In this study we show that the effects of guided waves in shallow water OBN can be mitigated using data reconstruction in acoustic FWI. We reconstruct the acoustic equivalent data by matching the observed to the modeled (using acoustic propagation) data. The observed data consist of the hydrophone component of the OBN data, and the modelled data were simulated using an acoustic finite difference modelling with free-surface boundary condition. For computational efficiency, we performed FWI with receiver and sources interchanged by invoking reciprocity. We derive a filter for each receiver gather and apply it to the observed data.

In a shallow water OBN experiment the data can be dominated by reverberations in the water column along with the elastic effects from the solid-fluid interface at the water bottom. The matching/reconstruction filter is therefore driven by the guided wave. Applying this filter to the observed data gives a matched observed data, which are an approximate acoustic equivalent of the data. In other words, the effects of guided waves that cannot be explained by acoustic modelling have been mitigated by the matching filter in the reconstructed data. These reconstructed data are used as observed data for acoustic FWI. The matching filter is equivalent to the source inversion filter with modelled and observed data interchanged. An application of this method to the NOAKA dataset from the North Sea will be presented in this paper.

Theory

Let $\boldsymbol{u}_o^e$, $\boldsymbol{u}_o^a$ and $\boldsymbol{u}_s^a$ be the observed elastic, *acoustic equivalent* of observed, and synthetic acoustic wavefields, respectively. The bold font indicates that the wavefields are vectors at all receivers for a single source. All wavefields in the derivation below are in frequency-space domain (complex quantities). The symbol † in superscript represents a Hermitian adjoint (complex conjugate + transpose), a $\hat{}$ symbol on a vector indicates a unit vector and a $|\cdot|$ indicates absolute value. The observed elastic data can be written in terms of its acoustic equivalent for a given source as follows

$$\boldsymbol{u}_o^e = h\boldsymbol{u}_o^a = h|\boldsymbol{u}_o^a|\widehat{\boldsymbol{u}_o^a}, \tag{1}$$

where h is a filter that relates the acoustic equivalent of the observed elastic wavefield at all receivers for a given source. Note that we only observe $\boldsymbol{u}_o^e$, the terms on the right-hand side of equation (1), h and $\boldsymbol{u}_o^a$, are unknown. However, for acoustic FWI we would like to use the acoustic equivalent of the observed wavefield, that is $\boldsymbol{u}_o^a$, because the simulated wavefield would be acoustic. One option would be to calculate a reconstruction filter (inverse of h), that is $h^{-1} = \frac{\boldsymbol{u}_s^{e\dagger}\boldsymbol{u}_s^a}{\boldsymbol{u}_s^{e\dagger}\boldsymbol{u}_s^e}$, using both synthetic acoustic and synthetic elastic ($\boldsymbol{u}_s^e$) wavefields and apply it to the synthetic elastic data to reconstruct the acoustic equivalent (e.g. Agudo et al. 2018) of the synthetic elastic data. However, to avoid elastic modeling, we shall use $\boldsymbol{u}_o^e$ instead of $\boldsymbol{u}_s^e$ in the calculation of the reconstruction filter f, that is

$$f = \frac{\boldsymbol{u}_o^{e\dagger}\boldsymbol{u}_s^a}{\boldsymbol{u}_o^{e\dagger}\boldsymbol{u}_o^e} = \frac{\left(h|\boldsymbol{u}_o^a|\widehat{\boldsymbol{u}_o^a}\right)^\dagger \boldsymbol{u}_s^a}{(h|\boldsymbol{u}_o^a|)^2} = \frac{|\boldsymbol{u}_s^a|}{h|\boldsymbol{u}_o^a|}\left(\widehat{\boldsymbol{u}_o^a}^\dagger \widehat{\boldsymbol{u}_s^a}\right). \tag{2}$$

Then convolving the filter f from equation (2) with $\boldsymbol{u}_o^e$ will give the reconstructed acoustic equivalent ($\boldsymbol{u}_{ro}^a$) of the observed elastic data, that is

$$\boldsymbol{u}_{ro}^a = \boldsymbol{u}_o^e f = |\boldsymbol{u}_s^a|\left(\widehat{\boldsymbol{u}_o^a}\cdot\widehat{\boldsymbol{u}_s^a}\right)\widehat{\boldsymbol{u}_o^a} = \widehat{\boldsymbol{u}_o^a}\left(\widehat{\boldsymbol{u}_o^a}^\dagger \boldsymbol{u}_s^a\right). \tag{3}$$

Mitigating guided waves in acoustic FWI

The reconstructed data in equation (3) is just a projection of the synthetic acoustic data onto the acoustic equivalent of the observed data, which can then be used in the objective function for FWI to give the misfit between two acoustic datasets, that is the simulated acoustic and acoustic equivalent of the observed.

The filter calculated in conventional source inversion has the same form as equation (2) with $\boldsymbol{u}_o^e$ and $\boldsymbol{u}_s^a$ interchanged (Pratt 1999). By applying this filter directly to the data simulated with the trial wavelet, we get

$$\boldsymbol{u}_{rs}^a \equiv \boldsymbol{u}_s^a f' = \widehat{\boldsymbol{u}_s^a}\left(\widehat{\boldsymbol{u}_s^a}^{\dagger} \boldsymbol{u}_o^e\right), \qquad (4)$$

where f' is the filter for conventional source inversion with observed and synthetic data interchanged in equation (2). The right-hand side of equation (4) is invariant with respect to a prior convolution of $\boldsymbol{u}_s^a$ with a scalar complex function, however, the true source is present through $\boldsymbol{u}_o^e$. Therefore, the conventional source inversion effectively replaces the synthetic source function in the modeled data with the true source. The reconstructed data in equation (3) can be written as

$$\boldsymbol{u}_{ro}^a = \boldsymbol{u}_o^e f = \widehat{\boldsymbol{u}_o^e}\left(\widehat{\boldsymbol{u}_o^e}^{\dagger} \boldsymbol{u}_s^a\right), \qquad (5)$$

where f has been substituted from equation (2). The reconstruction filter replaces the true source with the synthetic source since the right-hand side of equation (5) is independent of the true source, thus providing more control over the source spectrum.

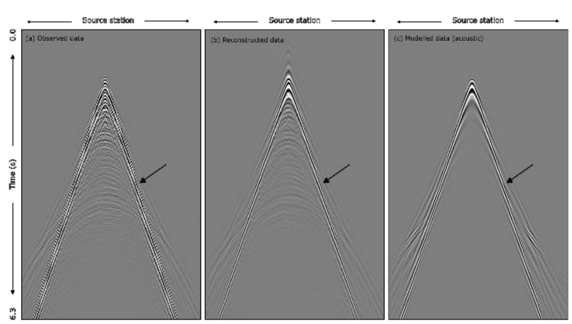

Figure 1: A receiver gather from the Yggdrasil area showing (a) the hydrophone p-wave data (c) the acoustic FWI modelled data and (b) the resulting acoustic equivalent hydrophone data fed into FWI. The arrows indicate the guided wave.

In shallow water the guided waves can dominate the OBN data (Klein et al. 2005). The reconstruction filter (equation 2), in that case would be dominated by the guided waves. The application of the reconstruction filter to the observed data would thus modify the guided wave response in the observed data to match the acoustic synthetic, as shown in Figure 1. Figure 1a shows the raw receiver gather and the

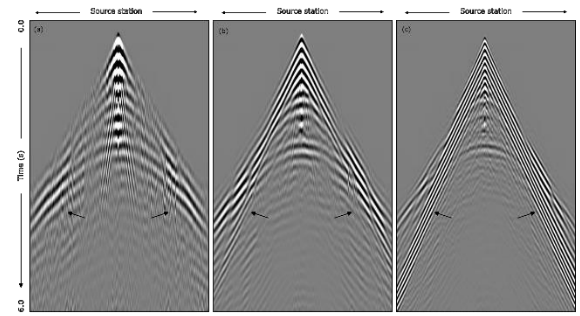

Figure 2: A receiver gather filtered to (a) 2 Hz (0.9-1.8-2.5-3.5) (b) 4 Hz (0.9-1.8-4.0-5.6 Hz) and (c) 6Hz (0.9-1.8-6.0-8.4 Hz). The arrows point to the guided wave, whichis not significant below the 6 Hz band.

strong guided waves therein. The reconstruction filter applied to the raw data is shown in Figure 1b and the modelled acoustic data are shown in Figure 1c. Note the reconstruction filter is only a single filter for each gather, however it was sufficient to produce a reasonable match between the guided wave response, which can be seen by comparing Figures 1b and 1c. Therefore, the assumption made in equation (1) that the acoustic-elastic equivalence can be represented by a single filter for each gather is reasonable for the case of guided waves in shallow water OBN data.

Example

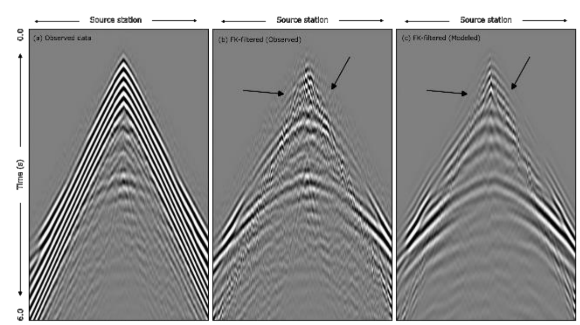

Figure 3: A receiver gather filtered to 6 Hz (a) the raw hydrophone data (b) FK-filtered observed data and (c) FK-filtered modeled data. The arrows indicate some of the events that are noisy and have not been modeled correctly after FWI using the FK-filtering method.

The data reconstruction method was applied in FWI for OBN data acquired in the Yggdrasil area of the North Sea in 2021 (also known as NOAKA). The data were acquired in a shallow water environment with a seafloor depth of around 150 m using a triple-source acquisition. The source spacings were 150 m between source lines and 25 m (flip-flop-flap) within source line. The four component OBNs were placed with 300 m spacing between receiver lines and 50 m spacing within receiver lines. The FWI was performed in time domain with an acoustic approximation. We also invoked reciprocity of the Green's function and swapped source and receivers to reduce the computational cost because the number of OBNs was smaller than the number of sources. The objective function used was dynamic matching (Mao et al. 2020).

First pass of FWI was performed in stages of increasing frequency bands starting from an initial band of 4 Hz (0.9-1.8-4.0-5.6 Hz), using the hydrophone data only. The second band was 6 Hz (0.9-1.8-6.0-8.4 Hz); however, the data were contaminated by the guided waves. This is where the data reconstruction method was used. Figure (2) shows that the guided waves are not contaminating the hydrophone data until 6 Hz band shown in Figure 2c. Figure (3) shows that FK-filtering has introduced noise, especially in the small offset and earlier times. To avoid these issues, we used the data reconstruction method described above.

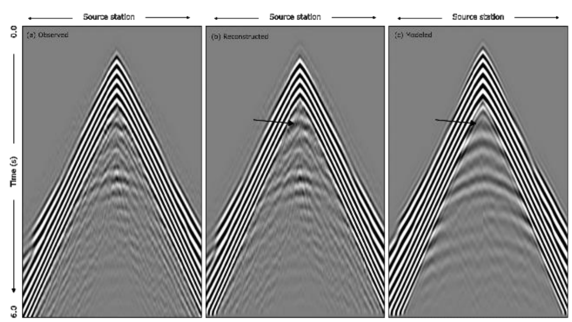

Figure 4: A receiver gather filtered to 6 Hz (a) the raw hydrophone data, (b) the reconstructed data (b) the acoustic FWI modeled data. The arrows inducate one of the events that have been correctly modeled after FWI using the reconstructed data.

The initial velocity for the second frequency band FWI was used in forward modeling to generate the synthetic data for the data reconstruction process. The synthetic data were generated for a broad frequency band (0.9-1.8-12.0-20.0 Hz). The reconstruction filters were then calculated according to equation (2) for each receiver gather, where the raw hydrophone data used for matching had only deblending and de-bubbling processes applied to it. The calculated reconstruction filters were then applied to the observed data according to equation (3), and band limited to 6 Hz. The reconstructed data filtered back to 6 Hz are shown in Figure 4. These are the reconstructed data that were used in the 6 Hz FWI as the observed data.

6 Hz FWI (second band) was also tested using input data after FK-filtering. For both FK-filtering and data reconstruction methods, the offsets used were 1000-2000 m. The resulting final velocity perturbations are shown in Figure 5. Figure 5a shows that FK-filter resulted in velocity perturbations that are contaminated with noise. This is because the FK-filtered data (Figure 3b) have noise events in the near-offsets and earlier times. On the other hand, using the reconstructed data (Figure 4b) as the input resulted in a cleaner update in velocity, which is shown in Figure 5b. The final velocity models are shown in Figure 6. Figure 6a shows that the vertical stripes in the shallow region (indicated by the top black arrow) causes undulations in a deeper horizon (Contourites, indicated by the bottom black arrow). By using the data reconstruction method, however, we avoided spurious shallow updates and thereby avoided the undulations in the deeper horizon.

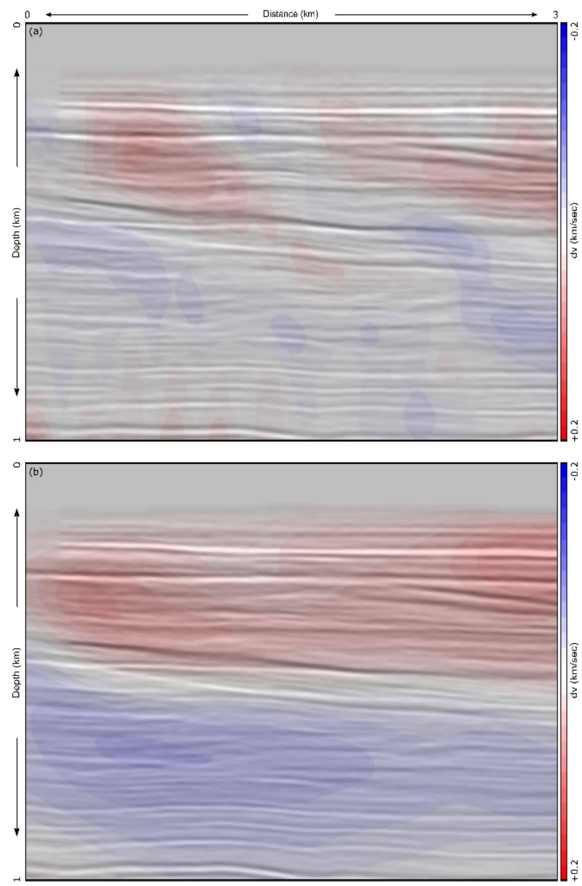

Figure 5: An inline comparing the difference between initial and final velocity after 11 iterations for acoustic FWI using (a) FK-filtered data (b) reconstructed data. Kirchhoff migration stacks are overlaid on the velocity differences

Conclusions

In conclusion, using reconstructed acoustic equivalent data for each receiver can mitigate the effects of guided waves in shallow water OBN datasets. Resolving the near surface velocity is important to achieve a good FWI result at depth. In shallow water OBN, accurately dealing with guided waves can be challenging because modeling can be too expensive and removal methods like FK-filtering can be inaccurate, especially if the noise is dispersive. Under such circumstances the methods proposed in this study provide a cost-effective tool to perform acoustic FWI on shallow water OBN data. The additional computational cost of the proposed approach is comparable to the conventional FWI including source inversions for each receiver gather.

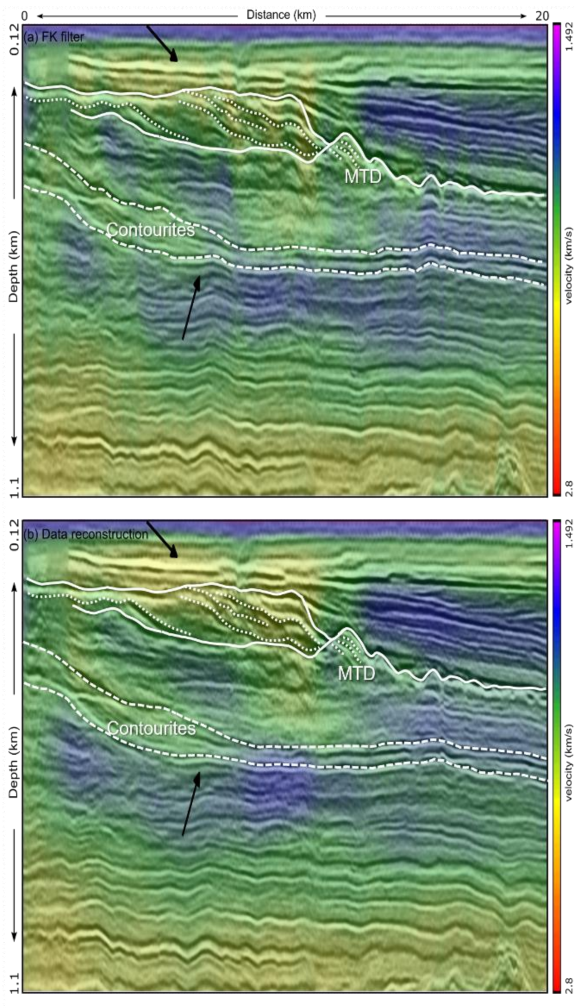

Figure 6: An inline comparing the final inverted velocities using (a) FK-filtering and (b) data reconstruction with corresponding Kirchhoff migration sections overlaid. The arrows in the shallow part indicate the regions where the inverted velocity is less noisy in the reconstruction filter, and the deeper black arrows show that the reflectors have less undulations as a result. Distinct mass transport deposits (MTD) are reflected as high velocity features.

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