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Feasibility study of using AVO inversion for S-wave information from UHR seismic data

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Summary

The development of many offshore wind-farms around the world is one way to reduce CO₂ emissions in the atmosphere. Each new offshore wind-energy site needs to be characterized to find the optimal locations for the monopiles or other wind-turbine infrastructure. For a global investigation this characterization is usually done with seismic surveys, in order to get a good view on the first 100m of the subsurface. The main seismic parameter that can be well defined from acoustic reflection measurements is the P-wave velocity of the subsurface layers, while the subsurface strength is much better coupled to the shear wave velocity or the related shear-wave modulus. One way to obtain such information from marine reflection seismic data is via AVO information embedded in PP reflections. However, the typical low values for the S-wave velocities in the first 10s of meters below the sea-bottom make it not a favorable parameter to estimate. Therefore, based on synthetic data modeling, the feasibility of estimated S-wave velocity information from marine reflection data is investigated. Different scenarios with varying maximum offset are investigated, where the conclusion is that the ability to retrieve accurate S-wave velocity information is limited, but can be improved by acquiring more offsets

Feasibility study of using AVO inversion for S-wave information from UHR seismic data

Introduction

The development of many offshore wind-farms plays an important role in the energy transition. Each new offshore wind-energy site needs to be characterized to find the optimal locations for the monopiles or other wind-turbine infrastructure (Power et al., 2011). For a global investigation this characterization is usually done with seismic surveys, in order to get a good view on the first 100m of the subsurface (Monrignal et al., 2017). However, from acoustic reflection measurements mainly the P-wave velocity of the subsurface layers is well-determined, while the subsurface strength is better coupled to the shear wave velocity or the shear-wave modulus. To a lesser extent, also the density of the subsurface layers plays a role.

Seismic data has a long history of extracting all 3 elastic parameters from the angle-dependent amplitudes via so-called amplitude-versus-offset (AVO) analysis, making use of the Zoeppritz equations, or its approximations (Aki and Richards, 2002). However, compared to the traditional AVO inversion as used for deep reservoir characterization, the situation of wind-farm sites is quite different: the near-surface target window is more of an unconsolidated layer, where shear wave velocities are pretty low. In the Dutch North Sea, we see S-wave velocities ranging from 80 to 200m/s in the shallowest layers, which is much lower than the P-wave velocities in that area (typically 1500 – 2000 m/s). This provides completely different AVO behaviour compared to deep reservoir situations, where S-wave velocities could reach their maximum values (being $\frac{1}{2}\sqrt{2}$ of the P-wave velocity). Thus, it is expected that low S-wave velocities will be more difficult to estimate from the AVO response from UHR seismic data.

In recent year, we see a growing interest and application of AVO inversion methods to UHR seismic data to infer shear-wave related properties, in order to compare them also with the Cone Penetration Tests (CPTs) that are used as the ‘ground truth’ of the subsurface resistance (Robertson, 1990; Cox et al., 2024). It is found that that there is a reasonable correlation of the soil resistance with the shear wave velocity (or the shear-wave modulus) and less with the P-wave velocity (see e.g. Kelsey et al., 2024). In this paper we will investigate, based on forward modelling, imaging and AVO analysis to what extent S-wave velocity information can be extracted from the seismic AVO response and how the maximum offset (typically 100m) is a limitation.

Review of the linearized AVO expression

If we have small contrasts in the medium parameters between two half spaces, we can accurately describe the angle-dependent reflection properties of an elastic medium by the linearized Zoeppritz equations (Aki and Richards, 2002). We follow here the notation of Gisolf (2016), where the PP reflectivity is given as a function of the horizontal ray-parameter s_h :

$$R_{PP}(s_h) = \frac{1}{2} (1 - 4\beta_0^2 s_h^2) \Delta \ln \rho + \frac{1}{2} \frac{1}{1 - \alpha_0^2 s_h^2} \Delta \ln \alpha - 4\beta_0^2 s_h^2 \Delta \ln \beta, \quad (1)$$

with α, β, ρ being, respectively, P-wave velocity (V_p), S-wave velocity (V_s) and density (ρ) and $\alpha_0, \beta_0, \rho_0$ being the values related to the smooth background model. For our experiments, we have taken these background values as the average of the two values of the two half-spaces.

Note that the $s_h = \frac{\sin \gamma}{\alpha_0}$, where γ is the angle of incidence at the interface. So given the values for the elastic parameters at both sides of an interface, we can calculate the corresponding contrasts, $\Delta \ln \rho, \Delta \ln \alpha, \Delta \ln \beta$ and calculate from those, via equation (1) the AVO curve as a function of ray-parameter. For reservoir characterization, this equation is used in reverse mode: from the observed AVO curve we try to extract the three contrast values for a certain interface.

Methodology

For our analysis we generate seismic data for a 1.5D elastic model, simulating the situation of the Dutch North Sea, where a typical water depth is about 30m. Also we utilize the values for P-wave velocity, S-wave velocities and densities as can be found in that region. Given such a 1.5D model we can generate surface seismic reflection data, assuming hydrophone measurements. The modeled results mimic the situation that source and receiver directivity are taken into account, data has been perfectly deghosted and demultiplied and the wavelet deconvolution generated a nice, zero phase wavelet with a flat spectrum.

Next, knowing the exact P-wave velocity model, we can apply angle-dependent migration, such that we can extract for each known interface the AVO curve. In addition, for QC purpose, we can match the obtained AVO curve with the predicted curve from the Zoeppritz equation. As we are dealing with relatively low contrasts, we employ the linearized model as shown in Equation (1). However, the main objective of this analysis is to make many versions of our 1.5D model, where each layer is perturbed in its properties and we repeat the imaging and AVO-curve extraction process. Then we can investigate to what extent the AVO is sensitive for such parameter change, indicating the ability to recover the parameter via AVO inversion.

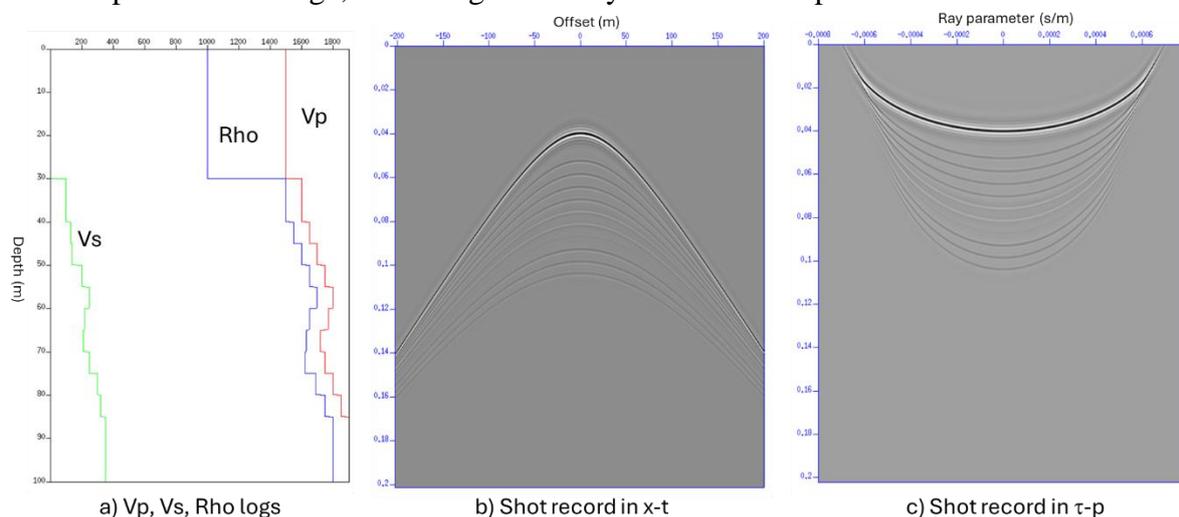


Figure 1: a) Synthetic well-log of the first 100m of a typical North Sea layering, showing the P-wave velocity, S-wave velocity and density. b) Modeled shot record with 200m maximum offset. c) Linear Radon domain transform, used as input for angle-dependent imaging.

Figure 1 shows the main datasets for our analysis. Figure 1a shows the synthetic well-log that has been created based on typical values for the elastic parameters in the North Sea. Note that the water bottom is at 30m depth. Figure 1b shows the corresponding synthetic shot record with offsets up to 200m. The maximum frequency is 800 Hz, where the wavelet has been deconvolved. Figure 1c displays the linear Radon transform of this shot, showing zero-phase reflection events, which can be used as input for an angle-dependent imaging process, from which AVO curves can be extracted. All directivity effects have been corrected and an optimum calibration factor was found to link amplitudes directly to Zoeppritz curves.

Results

As mentioned above, we have perturbed the parameters in each of the 11 layers below the sea floor a little (in the order of 0.3% change in medium parameter). Next, the modeling was repeated and the AVO curve was extracted. The change in AVO curve is a measure of the sensitivity of that parameter in that specific layer for the AVO behavior. These AVO changes are then normalized by the actual parameter change.

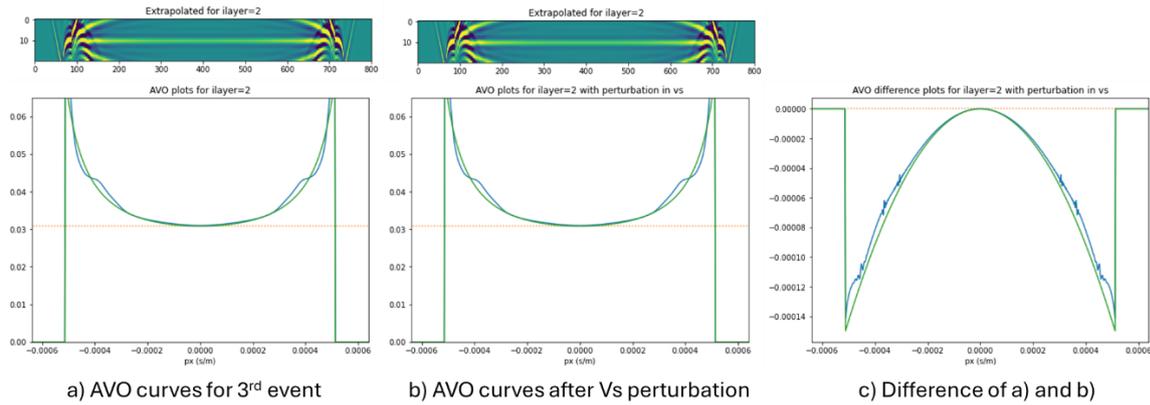


Figure 2: AVO curves extracted from synthetic data (with maximum offset 200m) for the 3rd event. a) AVO curve from the data in Figure 1b,c. The small panel on top shows the flattened event in the linear Radon domain (obtained from Figure 1c). The blue line is the AVO curve extracted from the data, the green line is the curve predicted from the linearized Zoeppritz equations. b) AVO curves for the situation the layer below the reflector has a small change in Vs. c) Difference of both AVO curves, indicating the AVO sensitivity for this parameter change.

As an example of the procedure, Figure 2 shows some plots of the process for the third reflection event in the data (Figure 1b, c). First, the data in the linear Radon domain is phase shifted to align the event at $\tau = 0$ (see Radon panel above Figure 2a). The middle line in this Radon panel defines the AVO curve, which is plotted as a blue line in Figure 2a. In green we plot the expected linearized Zoeppritz curve, which shows a good agreement. Next, we change the value of the Vs in the layer below the reflector, such that the reflection properties change slightly. This is the AVO curve extracted in Figure 2b. Finally, these two AVO curves are subtracted and the sensitivity is calculated as

$$S(\sigma) = \sqrt{\sum_{s_h} (A(\sigma + \Delta\sigma, s_h) - A(\sigma, s_h))^2 / \Delta\sigma}, \quad (2)$$

where parameter σ represents α, β or ρ and $A(\cdot)$ is the AVO curve. The resulting value is plotted in the small boxes in Figure 3c in the column of Vs at layer number 3. This process is repeated for all 11 reflections and for each of the three elastic parameters, and for the different offset ranges. Note that each offset range has a different range of usable s_h values.

Figure 3 shows these sensitivities on a logarithmic scale, where a change of -1 means 10 times lower sensitivity. What we clearly see is the overall improvement in sensitivity for all parameters going from input data with limited offset (Figure 3a maximum offset of 100m) to data with large offsets (Figure 3d maximum offset of 300m). When looking at the values, we see an increase of ~ 0.6 (factor 4) along these offset ranges. This is mainly due to the fact that larger offset provides a wider range of angles and, thereby, provides more discrimination in the parameters via the AVO curves.

If we compare the sensitivity for the Vs values – which is the main concern of this study – we see that for 100m maximum offset the sensitivity for Vs (with dark-blue values) is -1.0 lower than those of Vp and Rho, meaning a factor of 10. For the larger offsets, we observe a similar difference for Vp and Vs (-1.0 on algorithmic axis), although the sensitivity compared to Rho is a bit less (about -0.6). Thus, it seems the sensitivity for Rho has smaller increase with offset.

One aspect that we did not investigate is the fact if a change in Vs can be misinterpreted by a change in Vp and/or Rho. With other words, the cross-talk between the parameters. The above analysis assumes that all parameters are well decoupled in the AVO curves, which is not always the case. A final step for using such analysis in actual survey design is finding the noise level of the inversion. Our data was obtained under perfect conditions, without deghosting artifacts

and other noises. So the detectable threshold in sensitivity will finally determine, for example, which minimal offset is required for a reliable AVO inversion.

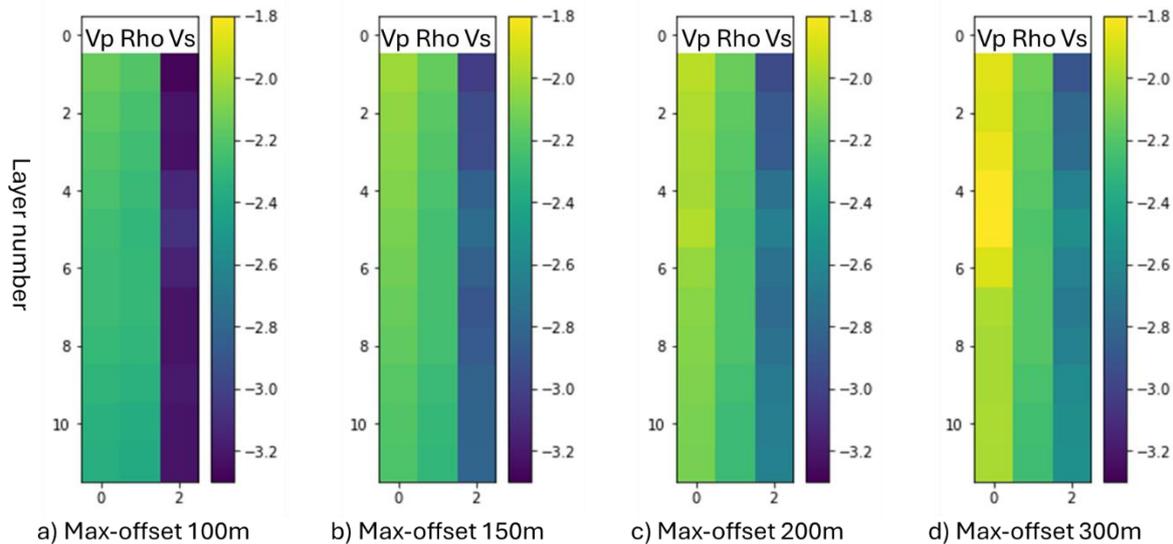


Figure 3: The sensitivity of the change of a medium parameter (V_p , Rho , V_s) to the observed AVO response. The color represents a logarithmic scale, where a change of -1 means 10 times lower sensitivity. Each panel shows the AVO-sensitivity of the three elastic parameter for each of the 11 layers in the model shown in Figure 1a. The sub-panels consider the seismic input data with a maximum offset of a) 100m, b) 150m, c) 200m and d) 300m.

Conclusions

Based on the synthetic data study, we analysed the ability of UHR seismic data to estimate the S-wave velocity via AVO inversion. For typical maximum offsets of 100m we see that the sensitivity of AVO curves for getting S-wave velocity information is roughly 10 times smaller than those for P-wave velocity and density.

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