

## Seismic inversion in offshore wind: implications of complex near-surface soils on AVO approximations

### Introduction

The application of amplitude versus offset (AVO) inversion to ultra-high resolution seismic (UHRS) data in offshore wind farm development is a promising method for improving the understanding of near-surface geology (Karkov et al., 2022). The elastic properties calculated through AVO inversion can improve the ability to differentiate between soils, identify hazards and predict CPTs and can potentially be used directly in foundation design. One uncertainty associated with commonly applied AVO inversion algorithms is related to the underlying equations that are used to model the observed seismic response. The Aki-Richards (1980) approximations to the exact Zoeppritz (1919) equations have been applied to oil and gas exploration studies for decades, however the assumptions associated with this approximation in the context of the complexity of offshore wind is not well understood. In order to have a more complete understanding of UHRS data, it is required to investigate how these approximations may impact quantitative seismic interpretation. In this study, we explore the impact of the Aki-Richards AVO approximation from synthetic seismic computation through to AVO inversion. The synthetic examples chosen for this study include a glauconite sand within a sand background and an interbedded cemented and uncemented carbonate, but the idea and analysis is potentially relevant in any geologic context where extreme velocity contrasts are present.

### Theory

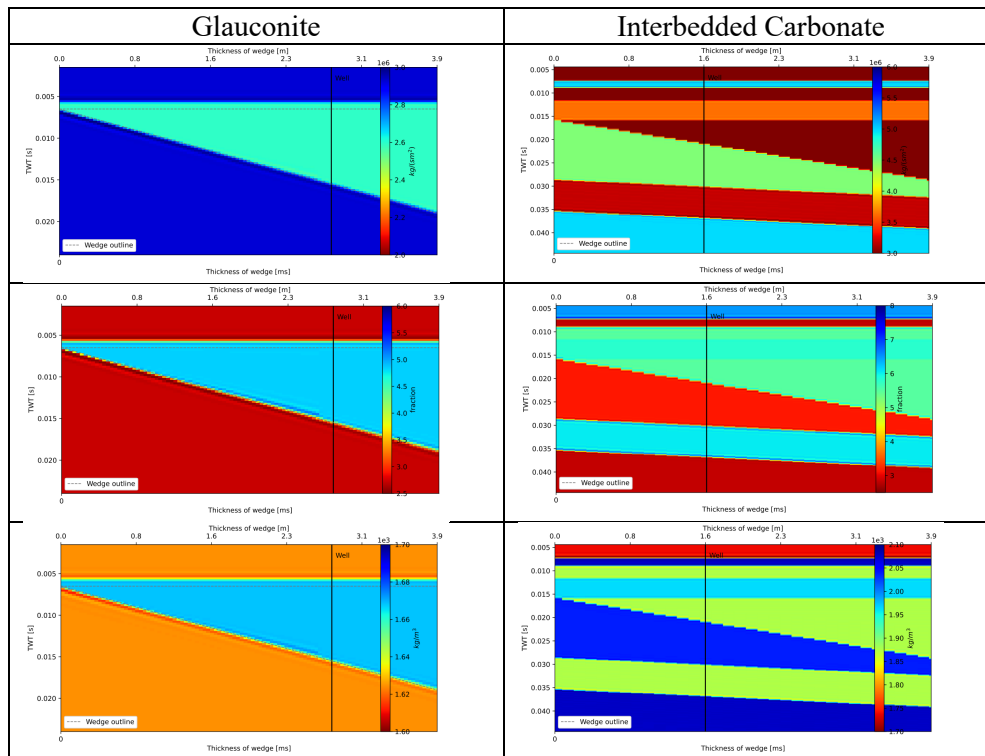
Zoeppritz's equations exactly calculate the amplitudes of reflected and transmitted plane waves at a planar boundary of two elastic media where the boundary is non-slip. The widely used three term Aki-Richards equation expresses the angle-dependent reflection coefficient as a combination of density, shear and compressional velocity contrast however, the approximation is valid only for weak contrasts and small angles of incidence. Whilst the assumption of weak velocity contrasts generally holds for hydrocarbon exploration, where compaction with depth generally leads to less contrast in elastic properties, Booth et al. (2016) demonstrated that in other geologic contexts, where velocity contrasts are much higher, the error between the Aki-Richards equations and exact Zoeppritz could become much larger. In the context of offshore wind, one of the goals of seismic interpretation is to use UHRS data to remotely detect rocks/soils that may impede foundation installation. These soils may represent strong elastic property contrasts that violate a primary assumption of the Aki-Richards equations. In this study, we examine interbedded carbonates and glauconite sand, both which can pose significant risk to foundation installation and performance.

To obtain reasonable elastic properties for glauconite sands in the context of offshore wind, which are not publicly available, we applied a workflow described by Houssain et al. (2011). This workflow allows for accurate modelling of quartz, glauconite mineral mixing using a Hertz-Mindlin contact model. After the dry rock elastic properties are calculated, we apply Gassman fluid substitution to obtain water saturated rock moduli – and assume no cementation has taken place. As part of the method, we need to estimate values for porosity, effective pressure, and grain contact (coordination) number. For this study, we used porosity of 40%, a depth of 20 meters with no overpressure and a grain contact number of 8. We also assumed a bulk and shear modulus for a glauconite grain of 7 GPa and 5 GPa, respectively. Ideally, the grain contact number would be derived experimentally by comparing observed to modelled moduli, but this data was not available. These input parameters are sources of uncertainty in the modelled elastic properties.

For the interbedded carbonate response, representative values were taken from geotechnical studies performed in offshore Australia. The acoustic properties of the units of variably cemented carbonate sediments were derived from the ARC ITRH for Transforming energy Infrastructure through Digital Engineering (TIDE) database, which contains geotechnical data from over 1700 sampling locations. These values are consistent with those previously reported in the literature for similar variably cemented sediments (Gregor et al., 2003; Hamilton et al., 1982).

## Results

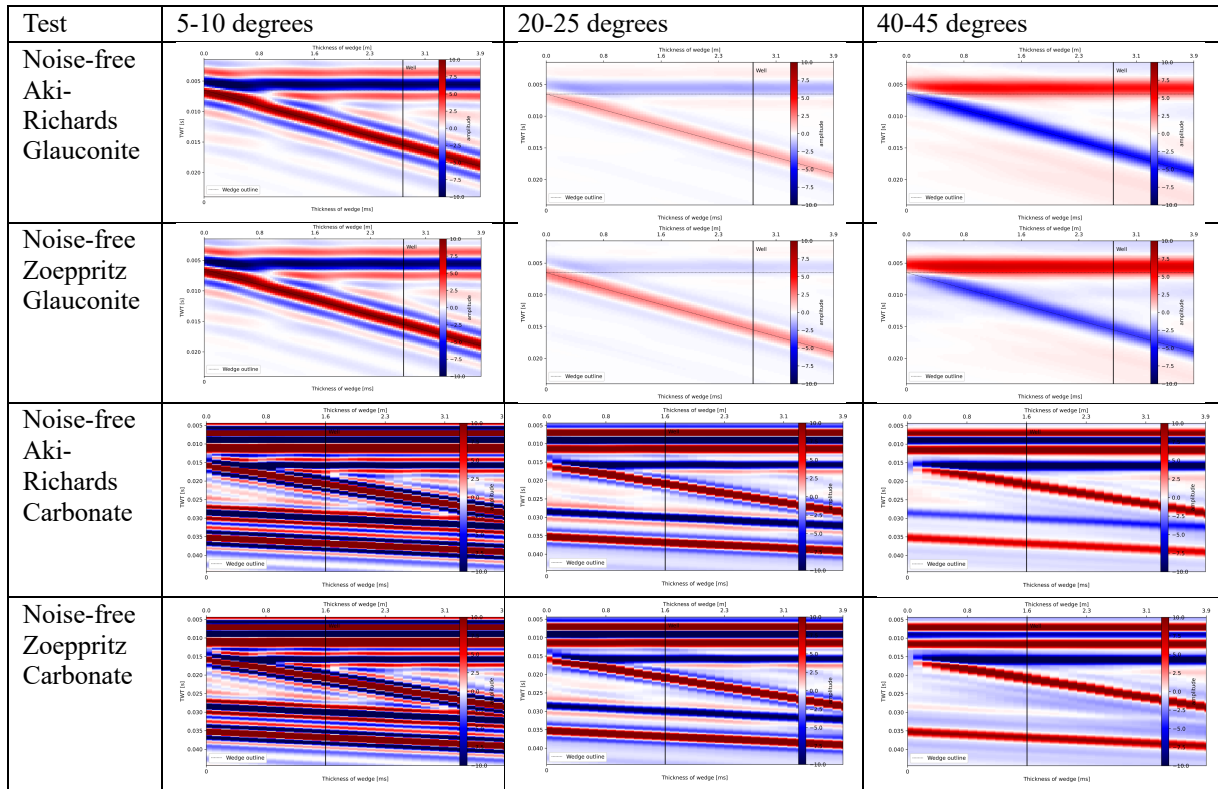
For realistic synthetic experiments, the modelled glauconite test case and a representative soil profile for an interbedded carbonate in Western Australia were used to create synthetic seismic representative of true UHRS data. The glauconite model was a simple glauconite wedge within a quartz background. The interbedded profile contained 8 layers with 5 distinct sets of elastic properties, all derived from the TIDE database. The layers are of varying thickness and the fifth layer is modelled as a dipping wedge. The dipping wedges in each model are not included to suggest that either glauconite or carbonate layers deposit as wedges, but to test the impact of seismic resolution on the experiment. The true profiles of each experiment are shown in Figure 1.



**Figure 1** Acoustic impedance (top),  $V_p/V_s$  (middle) and density (bottom) models for glauconite within a quartz background and an interbedded carbonate profile.

Using the elastic properties of the soil profile, we calculate angle-dependent reflectivity using Aki-Richards and Zoeppritz AVO equations and then convolve the calculated reflectivity with angle-dependent wavelets computed from true UHRS data from a dataset in the North Sea. Although the geology of the North Sea differs substantially from the test profile, the use of wavelets from a true UHRS dataset makes the synthetic seismic experiment more comparable to real data. The angle-dependent wavelets have provide a representative UHRS bandwidth, in this case approximately 50Hz-800Hz as well as representative background amplitude and frequency decay with angle.

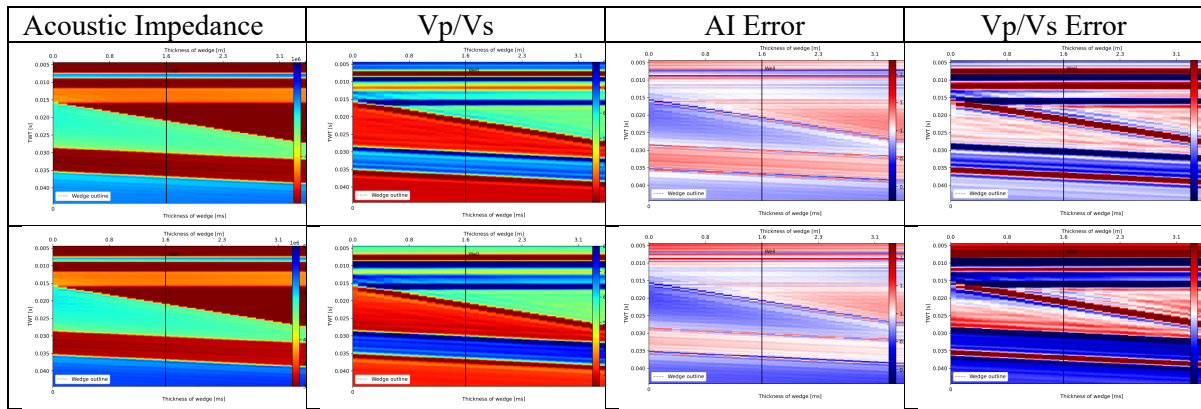
The results for noise-free synthetic seismic for angle-stacks from 5 to 45 degrees are shown in Figure 2. Modelling indicates differences in seismic amplitudes beginning at 25 degrees and increasing thereafter up to 45 degrees where we observe large amplitude differences at the thin layer transition from cemented to uncemented and at the base of the wedge where the Aki-Richards model shows a strong trough, while the Zoeppritz show a polarity reversal to a peak.



**Figure 2** Wedge modelling of noise-free synthetic seismic angle-stacks using Aki-Richards and exact Zoeppritz for test cases shown in Figure 1.

To test the implication of using the incorrect AVO model when performing inversion, the carbonate synthetic angle-stacks were inverted using a deterministic inversion algorithm. The carbonate example was chosen as it showed larger difference in both shear wave velocity and resulting synthetic seismic angle-stacks, and the glauconite model contains the added uncertainty that the elastic properties are modelled, whereas the carbonate properties were taken directly from true geotechnical. For this test, we compare the inversion results of inverting Zoeppritz modelled seismic using the Zoeppritz equations compared to the same Zoeppritz modelled seismic with the Aki-Richards equations. The idea is to understand how using an incorrect AVO model in inversion will lead to errors in inverted soil properties. Note that no low-frequency model was included therefore the results even for the exact Zoeppritz inversion show observable differences between observed model and inverted result. This is mostly due to the missing frequencies in the seismic data. The wavelets are bandlimited to 50Hz-800Hz, which produces an inversion result that is lacking the frequencies necessary to characterize the thinnest and the thickest zones. The inversion is performed with a three-term parameterization of acoustic impedance (AI), the ratio of the compressional and shear wave velocity ( $V_p/V_s$  ratio) and density. This is a standard parameterization for seismic inversion studies, but any other meaningful elastic property parameterization is also possible, but the testing of these various parameterizations is not the purpose of this study.

Figure 3 shows the results of this inversion experiment. This synthetic example shows that inverting the Zoeppritz modelled seismic data with Aki-Richards approximations leads to a large decrease in inversion accuracy, particularly for  $V_p/V_s$  ratio, as demonstrated by the dramatic increase in error. Specifically, the increase in error is most noticeable at the layers with the largest  $V_p/V_s$  ratio contrast. For the standard Zoeppritz inversion, the error in these layers is approximately 10-15%, but when using the Aki-Richards approximation the error increases to upwards of 30%. The error in inverted  $V_p/V_s$  ratio is more apparent than the difference in the input seismic as the inversion is particularly sensitive to mid and far angle seismic data.



**Figure 3** AVO inversion of exact Zoeppritz synthetic seismic angle-stacks using exact Zoeppritz (top) and Aki-Richards (bottom) equations for the interbedded carbonate profile shown in Figures 1 and 2.

## Conclusions

This synthetic case study clearly demonstrates the impact that near-surface soil physics has on the seismic responses that should be considered when modelling and inverting UHRS seismic data. We observe that if the geology contains very strong contrasts in shear wave velocity between soils or rocks, then large difference may result between Aki-Richards and Zoeppritz AVO models. Inverting these data with the wrong model in these contexts can lead to large increases in inversion error and decrease the ability to accurately characterize important facies and geologic boundaries. Future work in this area should focus on tests using real UHRS seismic data and could include extending the modelling to include spherical wave propagation, which could be critical to characterizing the seafloor.

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