AVO compliant processing and elastic inversion of UHRS data for an OWF quantitative ground model

Introduction

In 2023, the Netherlands Enterprise Agency (RVO) acquired 5000 km of 2D ultra-high resolution seismic (UHRS) data over the 283 km^2 area Nederwiek Wind Farm Zone Zuid (NWWFZ), located approximately 100 km off the west coast of the Netherlands. The data were acquired with a Multi-Layer Stacked Sparker (MLSS) source firing on a nominal 1 m shot point interval into a 96-channel streamer with hydrophones spaced at 1 m intervals, and a Nyquist frequency of 4 kHz. The acquisition was part of a multi-disciplinary geoscientific campaign to enable the development of an Integrated Ground Model (IGM) and Geotechnical Interpretation Report (GIR) to inform of subsurface soil properties and ultimately de-risk the offshore windfarm (OWF) site ahead of a competitive leasing round. To model the site-wide soil properties in an efficient and non-intrusive manner, the 2D UHRS data was carefully prepared through an amplitude-variation-with-offset (AVO) compliant pre-stack seismic processing sequence to enable UHRS pre-stack inversion to quantify the geotechnical properties of the subsurface. Here we present the key processing methodologies utilised to optimise the seismic data quality for pre-stack inversion, along with preliminary inverted elastic parameters and their subsequent geotechnical predictions.

AVO Compliant Processing

Pre-stack inversion of multichannel seismic data exploits variations in the amplitude of the reflected seismic wavefield with angle of incidence to estimate the elastic properties of the subsurface (Yilmaz, 2001). To ensure the reliability of the inverted properties of the NWWFZ data, an AVO compliant, pre-stack UHRS processing sequence was carefully developed to ensure amplitude preservation of the recorded wavefield, while sufficiently minimising acquisition artefacts which contaminate the amplitude fidelity of the data, such as: swell and cable-related noise, ghost reflections, wavefield directivity, instrumentation statics and free surface multiples.

Receiver ghosts, set up by reflections of the primary wavefield off the water-air interface, have offset varying delay times determined by the apparent depth of the streamer (which is a combination of instrumentation depth and sea state) but also angle of incidence. These ghost delay times are expressed as $t = 2d\cos(\theta)/v_w$ (where v_w is water velocity in m/s, d is depth to receiver in m and θ is the angle of incidence in degrees), from which it can be seen that the delay time from a constant receiver depth will be greater at smaller angles of incidence than larger angles of incidence. Therefore, to accurately deghost multichannel data in an AVO compliant manner, both the varying hydrophone depth and the angle of incidence must be taken into account. To achieve this, the nominal streamer profile is used to guide an automated, data driven update of the accurate receiver depths for every pre-stack trace within the survey, which in turn then drives an inversion based deghosting algorithm performed in the 2D *f-p* domain, where the ghost delay variation with angle of incidence is addressed.

The 2D-UHRS data were acquired using a MLSS source which generates its acoustic wavefield through the discharge of electrical pulses between positive and negative electrodes in the water. In this instance, the MLSS consisted of 3 racks of electrodes at nominal depths of 0.72, 0.82 and 1.12 m, with 160, 120 and 80 tips respectively. While the MLSS setup provided significant improvements to the bandwidth of the emitted wavefield compared to a traditional, single rack sparker source, the rack dimensions of up to 1.8m in length in the inline direction resulted in strong array effects due to the non-discrete origin of the wavefield. The effect of this array footprint on the emitted wavefield is the introduction of directivity, whereby the source wavelet recorded in the seismic data varies with take-off angle. No near field or calibration hydrophone recordings were acquired during acquisition, so to ensure that directivity was honoured through source wavelet processing, a data driven directional designature approach was utilised to perform bubble pulse attenuation and zero-phase conversion with respect to take-angle in the linear Radon domain. Compensation for the directivity variation produces a more stable and AVO-compliant result when compared to a vertical incidence implementation (see Figure 1).

One of the major challenges in the processing of UHRS data is that of static corrections. These manifest as timing shifts between traces and are caused by the surface motions of the seawater as well as the acquisition instrumentation in the water. While these motions and associated shifts are present in all marine seismic data (e.g. lower frequency, oil and gas seismic), the profound impact in UHRS data is caused by the magnitude of the static shifts in relation to the wavelength of the ultra-high resolution targets that the survey has been designed to image. To compensate for these static shifts and minimise their misalignment effects on AVO analysis, we solve using a multi-dimensional approach addressing the static based upon which side of the wavefield the static is created. Firstly, we address the source-side static (or “heave”) - which is caused by the relative movement of the source between adjacent shots – by performing a rolling average, cross correlation analysis of adjacent traces within the common channel domain, and following this, we address the receiver-side static (or “heave”) – caused by the relative movement of hydrophones along the streamer – using a similar, cross correlation methodology but this time applied within the CMP domain.

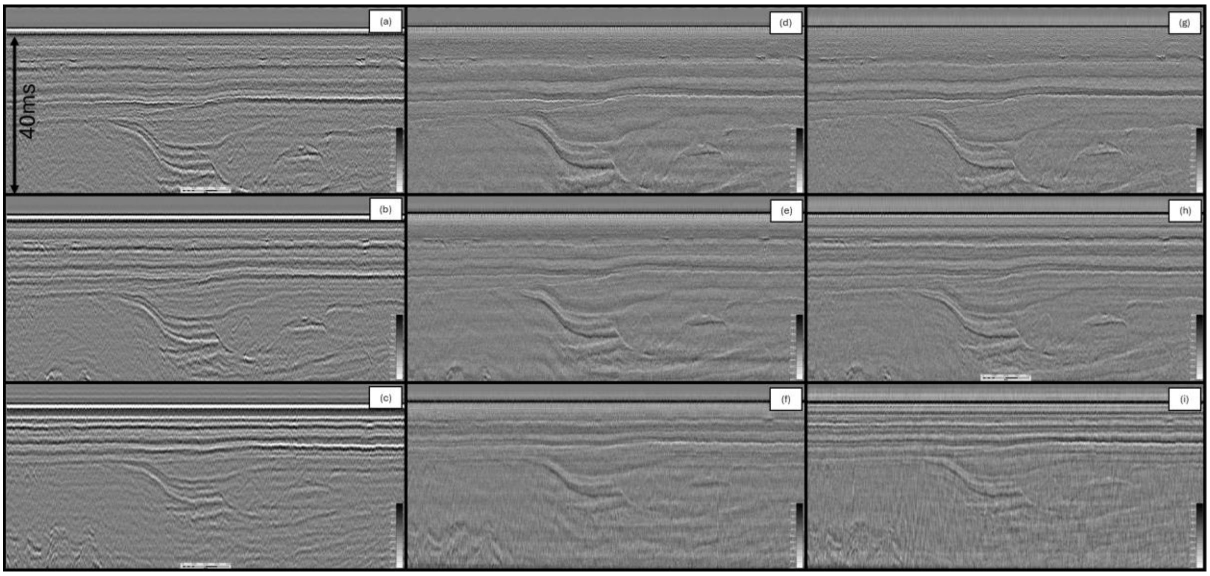

Figure 1 *Example designature results (debubble and zero-phase conversion) on a near, mid and far channel demonstrating directivity effects. Panels a), b) and c) are input near, mid and far channel respectively, d), e) and f) are after application of directional designature, and g), h) and i) are after application of vertical incidence designature (for comparison purposes).*

The final key step in the processing sequence to create AVO compliant, pre-stack gathers for elastic inversion is to image the data to collapse diffractions and closer position reflectors to their true subsurface positions. While pre-stack migration of seismic data has been the default in the oil and gas industry for circa 30 years (Jones, 2014) , it is still common for UHRS data to be migrated in the post-stack domain. Clearly this is insufficient for elastic inversion, a prerequisite for which is the generation of full offset (or angle) gathers, from which AVO trends can be analysed. To meet this requirement, the UHRS data were imaged using a Kirchhoff pre-stack time migration algorithm, which back-propagates the seismic wavefield using the integral form of the wave equation.

AVO Quality Control

To ensure the final processed data adhered to the requirements for elastic inversion, careful QC and analysis was undertaken throughout processing to monitor AVO trends using methods commonly utilised in the oil and gas exploration industry (Araman et al., 2014). Among these, the most valuable attributes for robust and efficient QC across the full 5000 km 2D survey were the intercept-gradient and associated AVO fit product (see Figure 2), and cross correlation analysis of angle stacks to provide correlation coefficient, time shift and phase coefficient statistics.

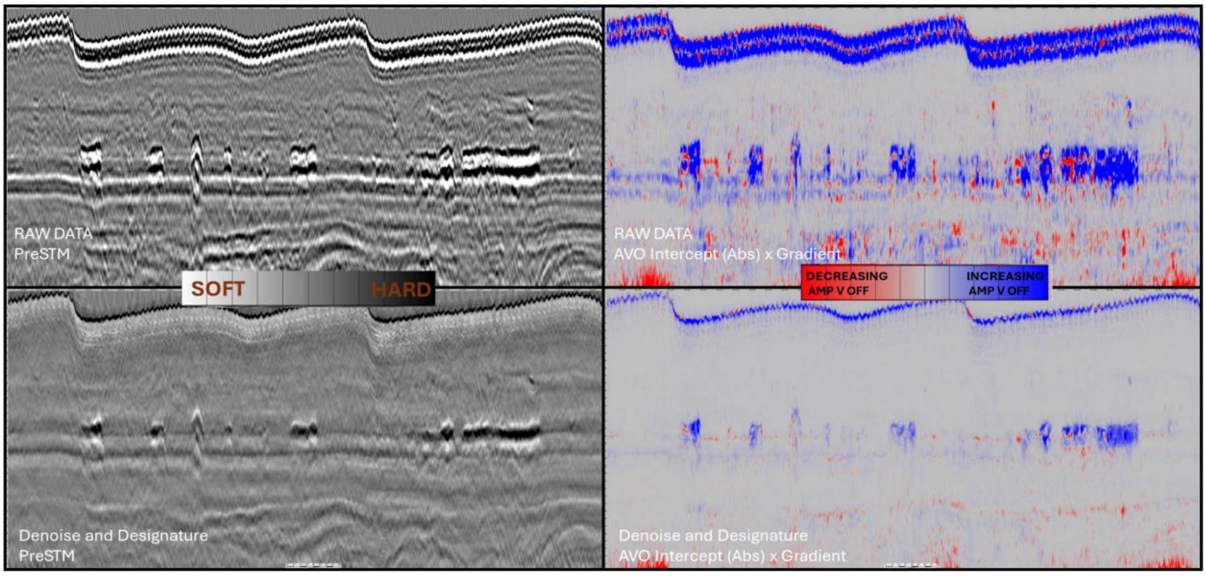

Figure 2 *Example AVO QC displaying the seismic before and after deghost and designature processing and the corresponding AVO fit (intercept * gradient) highlighting AVO anomalies indicative of organic layers.*

Quantitative Interpretation

The final processed UHRS data fed into a simultaneous AVO inversion algorithm which directly inverts partial stacks for bulk modulus, shear modulus and density (Karkov, et al., 2022). Inputs to the inversion are statistical wavelets derived from 5 degree angle stacks (which contain the characteristic frequency and phase content), and a low-frequency model for each property to be inverted. The spectral amplitude content is directly extracted from the seismic data, while the wavelet phase is estimated through analysis of the seabed reflection and constrained to be constant for all frequencies (in this case, estimated as zero-phase). Stability in the frequency spectrum across the survey enables the estimation of wavelets from survey wide target intervals, and these are then scaled per-angle stack through seismic inversion tests. The low-frequency model for each elastic parameter is based on all available geotechnical data, extrapolated along key seismic interpretations and guided by seismic velocities. The results presented in this abstract are solely relative, as the absolute results are currently a work in progress.

Cone Penetration Test (CPT) predictions rely on non-Gaussian probability density functions (PDFs) using Gaussian kernel-density estimation. PDFs specific to characteristic CPT data levels and soil types are established from the inverted elastic properties. Subsequently, the PDFs are applied to the full seismic volume elastic property inversion results to determine full seismic volume synthetic CPTs.

The inversion trial at NWZ-CPT-1033 compares the relative inversion results with elastic properties derived from the individual CPT (see Figure 3); Panel 2 shows absolute values of elastic parameters calculated from the CPT measurements. Panel 3, 4 and 5 shows bulk modulus, shear modulus and density respectively – the seismic inversion is plotted in blue, while the detrended elastic parameter from the CPT is plotted in red. The coloured panels 6, 7 and 8 show a mini section 30 meters to each side of the CPT along the seismic line, with a plot of the CPT in the middle. The right most panels show input stacked seismic, synthetic seismic modelled from inversion and the residual (which is the difference between the input and synthetic seismic). Based on these results and other initial trials, the observations are promising when considering the seismic inversion and geotechnical ground truth data. Namely:

1. The overall dynamics of the inversion results follow what is seen from the geotechnical data. For example, the events closer to seabed are shown to be similarly high in dynamics whereas the events 15 metres below sea floor (mbsf) are less pronounced both from the inversion viewpoint and also in the ground truth geotechnical data.

2. Events correlate well between the seismic inversion and the geotechnical data. Many events - especially the stronger reflections - have a high correlation.
3. The seabed is well defined; some side lobe effects are observed on bulk modulus and density – this may be affected by the phase of the seismic or wavelet.
4. An organic matter layer is very well defined both in bulk modulus and density, and with minimal side lobe effect. This is a very good indication that the AVO information is present in the seismic data and that it can be extracted from the seismic inversion.
5. Presence of side lobes is low, indicating a consistent phase between seismic and the wavelet. Other wave equations for the seismic modelling might change the results.
6. The residual seismic (energy which is not modelled by the inversion) is random in nature and uncorrelated to the input seismic. *f-k* filtering was performed and tested during inversion in order to minimise seismic residuals, and while harsher *f-k* filter tests had less residual energy, no improvements to the inversion results were observed. The current *f-k* filter level is set with the trade-off to maximise SNR and to minimise risk of filtering primary seismic energy.

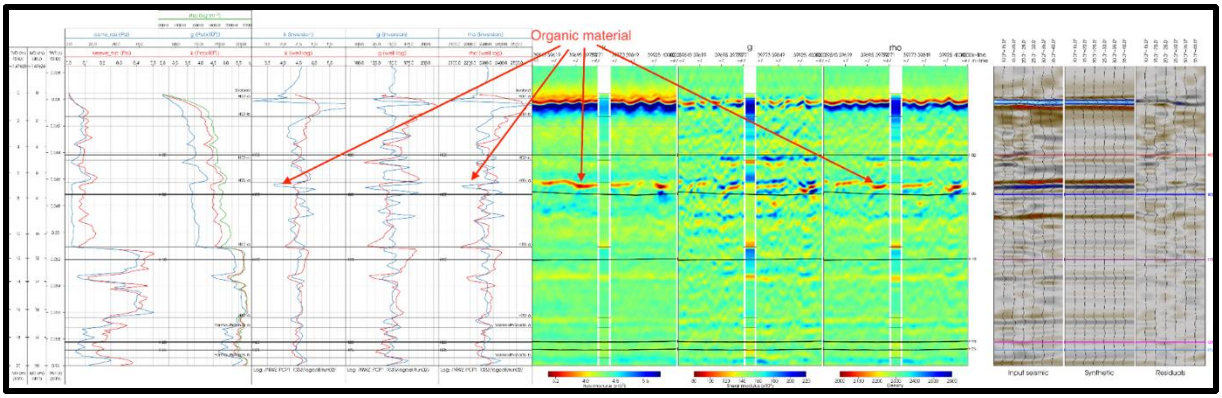

Figure 3 *Elastic inversion results (Bulk-, Shear modulus and density) compared to elastic properties calculated from CPT measurement from PCPT-1033, calculation based on regional model.*

Conclusions

Pre-stack, AVO compliant processing of UHRS data has been demonstrated to result in the reliable prediction of elastic properties of the subsurface at the NWWFZ windfarm site. Careful processing and QC of the pre-stack data was required to ensure that the directionality and offset varying effects often encountered in UHRS data were compensated for, resulting in a dataset where seismic inversion could enable a quantitative interpretation of the subsurface to feed into the multi-disciplinary IGM. While the processes detailed within this paper highlight key stages where AVO compliance was ensured, it is noted that all seismic processing stages have the potential to enhance or corrupt amplitude variance, and thus AVO compliant processing requires careful parameterisation and QC throughout. Other processing stages which can have a significant impact on AVO compliance and the success of elastic inversion are noise attenuation, multiple attenuation and velocity model building.

Acknowledgements

The authors would like to express our thanks to the Netherlands Enterprise Agency for permission to share the data within this paper, as well as all partners involved in the multi-disciplinary Integrated Ground Model work; Arup, British Geological Survey, Cathie, Inosys, RockWave and SolidGround.

References

1. Yilmaz, O. [2001] Seismic Data Analysis
2. Jones, I. [2014] Tutorial: migration imaging conditions
3. Araman, A., Paternoster, B. [2014] Seismic quality monitoring during processing
4. Karkov, K.H., Dalgaard, E., Diaz, A.T., Duarte, H., Hansen, H.J., Hviid, S., Høegh van Gilse, N.C., Krogh, L., Kuppens, S., Salaün, G., Correia, F. [2022] Case Study: Avo Inversion and Processing of Ultra-High Resolution Seismic for a Windfarm Application