

CASE STUDY: AVO INVERSION AND PROCESSING OF ULTRA-HIGH RESOLUTION SEISMIC FOR A WINDFARM APPLICATION

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Summary

The development of offshore windfarms has increased worldwide. A thorough understanding of the subsurface geotechnical conditions for foundation design and installation is still more important as turbines are getting larger and available sites are further from the coast at deeper water. Ultra-high resolution seismic (UHRS) data is key in the process of developing a qualitative integrated ground model. To exploit the full potential of the UHRS data applying AVO inversion for a quantitative interpretation of geotechnical properties is a promising procedure to get an improved understanding of the geotechnical ground conditions.

A field case is demonstrated to show how improved seismic processing in the pre-stack domain of UHRS together with simultaneous AVO inversion can aid in forming a quantitative ground model. Based on the UHRS inversion results we present a method to predict geotechnical CPT parameters like cone resistance, sleeve friction and porewater pressure. These results are key to the geotechnical engineer, as they can aid foundation design and installation calculations. The results will also help to make a more informed geotechnical field campaign planning.

Case study: AVO inversion and processing of ultra-high resolution seismic for a windfarm application

Introduction

The development of offshore windfarms has increased worldwide. A thorough understanding of the subsurface geotechnical conditions for foundation design and installation is still more important as turbines are getting larger and available sites are further from the coast at deeper water. Ultra-high resolution seismic (UHRS) data is key in the process of developing a qualitative integrated ground model, and seismic post-stack procedures have previously been presented (Vardy, 2015) to obtain quantitative parameters. In recent years, UHRS data quality in the pre-stack domain have been through a great evolution (Duarte et al., 2017) allowing for pre-stack methods to be explored. To exploit the full potential of the UHRS data applying AVO inversion for a quantitative interpretation of geotechnical properties is a promising procedure to get an improved understanding of the geotechnical ground conditions. Seismic AVO inversion has been an effective procedure for quantitative interpretation in the oil and gas industry for several years (Buland et al., 2008).

A field case is demonstrated to show how improved seismic processing in the pre-stack domain of UHRS together with simultaneous AVO inversion can aid in forming a quantitative ground model. Based on the UHRS inversion results we present a method to predict geotechnical CPT parameters like cone resistance, sleeve friction and porewater pressure. These results are key to the geotechnical engineer, as they can aid foundation design and installation calculations. The results will also help to make a more informed geotechnical field campaign planning.

UHRS processing

The amplitude response varying with angle in UHRS data is strongly affected by phenomena related to source and receiver positions such as heave motion and ghost reflections. What is particular to UHRS, when compared to lower resolution spreads, is the magnitude of these phenomena relative to its fundamental wavelet duration and shape. Small decimetre perturbations in the water surface will noticeably impact the data, and most UHRS surveys are carried out in significant wave heights (sH) of 1.5 m. This cannot be emphasized enough, if one considers the fact that the geotechnical parameters to be inverted are frequently sampled every 5 cm.

The processing workflow for this case study follows a conventional set of procedures, such as source signaturred deconvolution, receiver deghosting, pre-stack demultiple, velocity analysis and pre-stack Kirchhoff Time Migration. The key innovations tailored to quantitative use are in in-house developed techniques to reduce the seismic data to a floating processing datum that determines the static corrections decomposed into various components such as mean array depth, mean cable slant, source heave relative to mean array depth, receiver heave relative to mean cable slant.

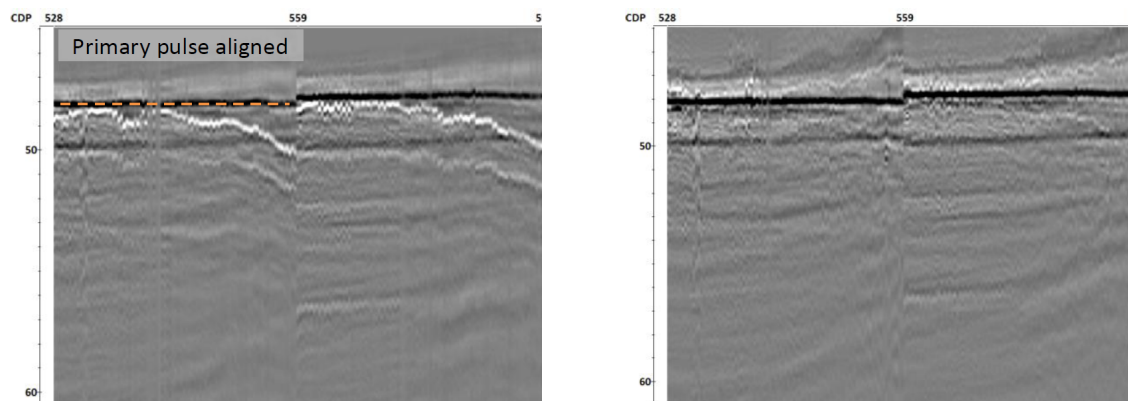


Figure 1 CDP gathers NMO corrected with a single velocity. Left – gathers with static corrections to a common floating datum. Right – gathers with corrections and after subtraction of the receiver ghost.

Being able to resolve the various components of motion and datum reduction is absolutely necessary in order to determine reliable stacking velocities, predict and attenuate source and receiver ghost reflections as well as free surface multiples. Furthermore, imaging with pre-stack processes such as Kirchhoff Time Migration can only be achieved reliably if the altitude components of the floating datum corrections are estimated to within $\frac{1}{4}$ of the desired wavelength to be migrated.

The CDP gathers shown in Figure 1 are NMO corrected with a single sound velocity. The distinctive receiver ghost reflection of the slanted streamer (deeper at the tail) undulates fractions of a millisecond, and significantly disturbs the primary reflections (Figure 1, left). Knowledge of the various motion components allowed for the prediction, modelling and subtraction of the ghost significantly improving the recovery of the primary amplitudes in the pre-stack gathers (Figure 1, right).

Another illustration of the importance of determining the datum reduction is the imaging uplift, both in amplitude and in resolution of small sub-ms sized targets after pre-stack Kirchhoff Time Migration. Figure 2 shows the differences between Kirchhoff Time Migration run post stack (left) and pre-stack (right). The ability to image and preserve the frequency content of the small targets (blue arrow) is mostly dependent on the accurate estimate of the source and receiver altitudes. Poor velocities may over or under migrate a reflection, whereas poor altitudes in UHRS will smear and degrade the stack, potentially by several octaves.

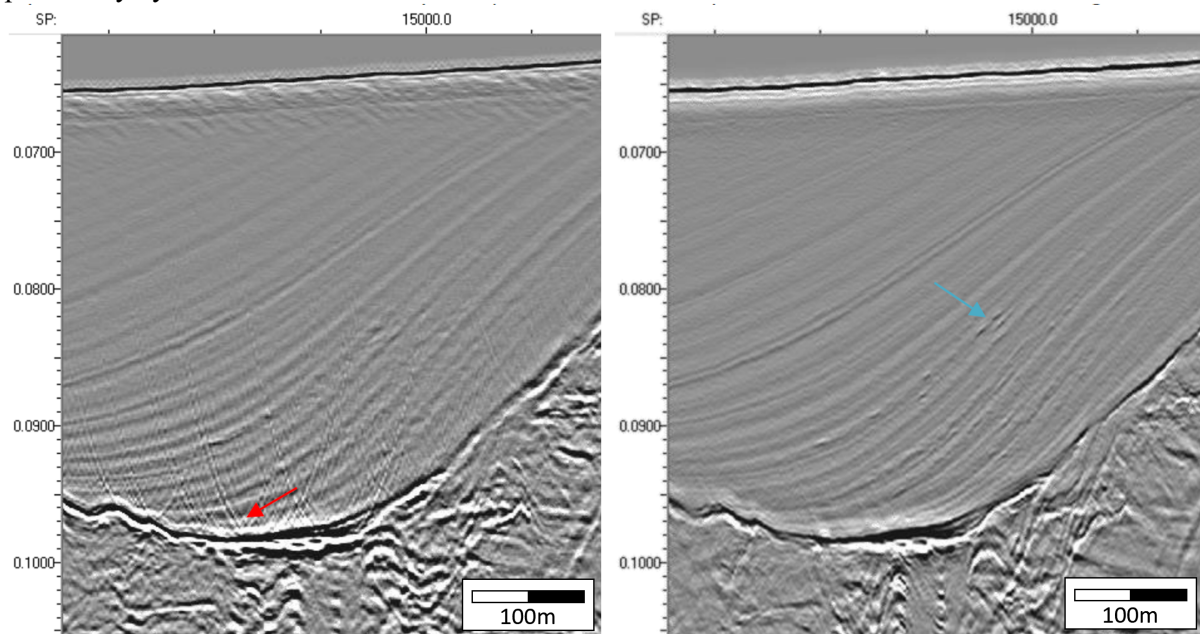


Figure 2 Stacked sections with Kirchhoff Time Migration applied post-stack (left) and pre-stack (right). Red arrow points to migration artifacts due to strong amplitude variations in the stack. Blue arrow points to improved imaging of small targets after pre-stack migration with source and receiver altitudes estimated to within $\frac{1}{4}$ of the frequencies of interest.

UHRS AVO inversion

The seismic inversion scheme used is a simultaneous AVO inversion algorithm, which inverts partial stacks directly for bulk modulus, shear modulus and density. Input to the simultaneous AVO inversion is a wavelet for each partial stack, which carries the characteristic phase and frequency content of that partial stack, and a low-frequency model for each property to be inverted for. The seismic gathers were stacked into angle bands of 5 degrees prior to the inversion.

The wavelets used for the inversion are statistical wavelets based on the seismic data only. The spectral amplitude content is derived directly from the seismic data, whereas the phase of the wavelet is estimated using the seabed reflection and constrained to be constant for all frequencies. Here, the phase

is estimated to be zero. The scaling of the wavelet was estimated based on seismic inversion tests. A wavelet characteristic for each angle stack was used. The frequency spectrum of the seismic data across all the lines was observed to be very similar, hence the wavelets were calculated from all lines in a target interval. The low-frequency model for each elastic parameter is based on all the available logs, extrapolated along key seismic interpretations, and guided by the seismic velocities.

The CPT prediction is based on non-Gaussian probability density functions (PDFs) using Gaussian kernel-density estimation. The probability density functions specific for characteristic CPT data levels and soil types are established from the elastic property inversion results extracted at co-located geotechnical stations color coded with CPT measurements and soil identification data. The PDFs are subsequently applied to the full seismic volume elastic property inversion results to arrive at full seismic volume CPT probabilities. From the interpreted logs and log reports, the subsurface under study, is seen to primarily be a sand-till system. Hence, to a first order, differentiation between till and sandy soils is performed. The CPT/sand-till probabilities are transformed to actual CPT parameter values by applying a computed linear relation based on log data.

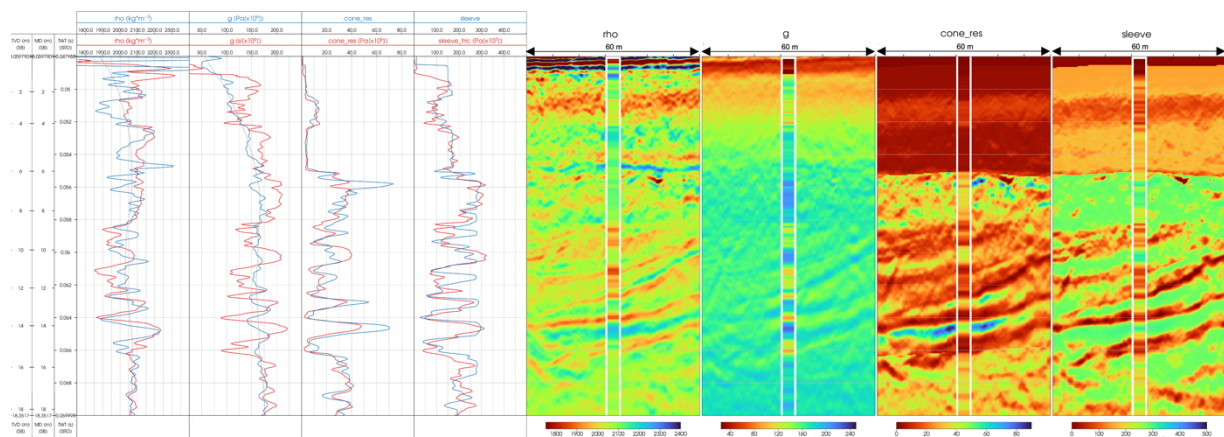


Figure 3 Inversion and CPT prediction results at a geotechnical location. To the left a 1D representation of the results with blue curves showing inversion results and red curves as measured geotechnical data, and grey curves being the applied background model. From left to right: Density, shear modulus, cone resistance and sleeve friction. The panels to the right show the inversion result along the seismic line centered around the geotechnical location with the geotechnical data inserted.

Results

Evaluation of the UHRS seismic inversion results at a geotechnical location (Figure 3) demonstrates that two independent measurements with completely different physics can be correlated, as they relate to the same subsurface. Looking at the general behaviour of the elastic inversion results, there is a good correlation between seismic derived parameters and CPT logged parameters from 0.25-1 meter below seabed down to the first seabed multiple. From the inversion results, geological features and their elastic properties can readily be identified and extracted. From the elastic CPT prediction, geotechnical properties can be extracted throughout the seismic volume. For instance, in Figure 4 the mean value of elastic predicted friction ratio in an interval between 0.042 and 0.044 seconds is shown. This map provides clear information about the spatial variability of the soil and the geotechnical ground conditions.

Conclusions

It has been demonstrated that it is possible to obtain a quantitative understanding of the subsurface based on UHRS data. 3D volumes of geotechnical properties like shear modulus, cone resistance, sleeve friction, porewater pressure and friction ratio have been generated with the purpose of an improved planning of wind turbine locations and foundations.

Processing of UHRS data in preparation for quantitative inversion requires a method to estimate mean array depth, mean cable slant, source heave relative to mean array depth, receiver heave relative to mean cable slant. The reason being that sensor motion due to sea states is disproportionately larger than a typical UHRS wavelet. Knowledge of trace-by-trace parameters to reduce the data to a floating seismic datum allows for the reliable receiver deghosting, velocity analysis and pre-stack migration, irrespective of the sea conditions during survey.

From seismic AVO inversion of UHRS data, elastic parameters like bulk modulus, shear modulus and density can be obtained. Key steps in this process are generation of low-frequency models, and wavelet estimation, which both are based on geotechnical ground measurements. The CPT prediction results resolve CPT parameters within the seismic bandwidth and can be used to delineate spatial variations for specific CPT parameters of interest. A key step in obtaining elastic predicted geotechnical properties is the generation of the non-Gaussian PDFs which are based on the seismic inverted elastic parameters together with the available geotechnical data.

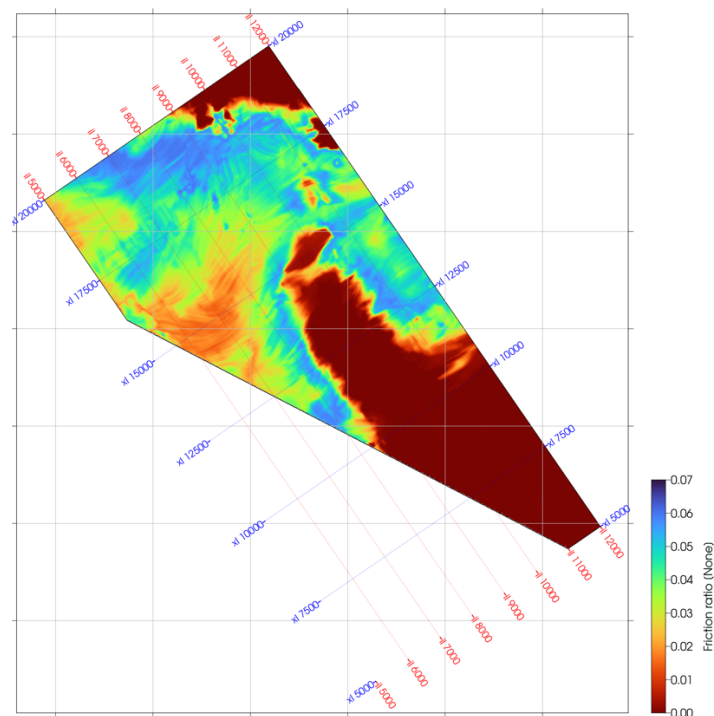


Figure 4 Map view of mean value of elastic predicted friction ratio in an interval between 0.042 and 0.044 seconds.

Overall, the example shown here, evaluating the UHRS inversion results against the geotechnical data, it can be seen, that two completely independent measurements can be correlated and integrated. The results give a spatial quantitative understanding of the geotechnical ground conditions which can be used for foundation design within offshore windfarms.

References

Buland, A., O. Kolbjørnsen, R. Hauge, Ø. Skjæveland and K. Duffaut, [2008] Bayesian lithology and fluid prediction from seismic prestack data. *Geophysics*, **73**, C13-C21

Duarte H., N. Wardell and O. Monrigo [2017] Advanced processing for UHR3D shallow marine seismic surveys. *Near Surface Geophysics*, **15(4)**, 347-358

Vardy, M., [2015] Deriving shallow-water sediment properties using post-stack acoustic impedance inversion. *Near Surface Geophysics*, **13(2)**, 143-154