Introduction

To meet the global targets for wind power deployment by 2030—estimated to require over 2,000 GW of total installed capacity to stay on track for net-zero emissions by 2050 (IEA, 2023)—the industry must rapidly scale up the development of wind farms in a cost-effective and timely manner. A critical factor in achieving this is a robust understanding of subsurface conditions, including geotechnical parameters and design-relevant behaviors.

A key enabler in this process is the quantitative joint interpretation of ultra-high-resolution seismic (UHRS) data and geotechnical investigations, which can significantly enhance subsurface mapping accuracy and reduce uncertainties. This, in turn, supports better decision-making throughout the project lifecycle.

In this presentation, we will examine three recent and diverse offshore wind projects, illustrating the role of integrated ground modeling in various project phases:

- Early-phase projects with sparse, low-quality data
- Mid-to-late-stage developments characterized by dense, high-quality datasets

Each case presents unique challenges and opportunities, shaped by data availability, project maturity, and decision timelines.

We will demonstrate how effective, quantitative ground modeling can support:

- Early and mid-stage design and planning of geotechnical campaigns
- Later-stage design processes, including robust uncertainty analysis and risk mitigation

Method

Pre-stack seismic inversion is a well-stablished technique (Karkov et al., 2022, Hansen et al., 2024) for deriving subsurface elastic property estimates from seismic reflection data. These estimates can be translated into geotechnical and soil parameters essential for quantitative ground modeling and engineering design. This presentation delves into the core elements of the inversion workflow—including wave equation assumptions, wavelet estimation, and prior model construction—and examines how each is influenced by the quality and resolution of UHRS data.

We also address key validation strategies such as well-to-seismic ties and synthetic modeling, which help assess the reliability and limitations of downhole geophysical data and reduce inversion uncertainty. Furthermore, we explore methods for uncertainty quantification, emphasizing the need to understand and account for data limitations to produce robust and interpretable ground models.

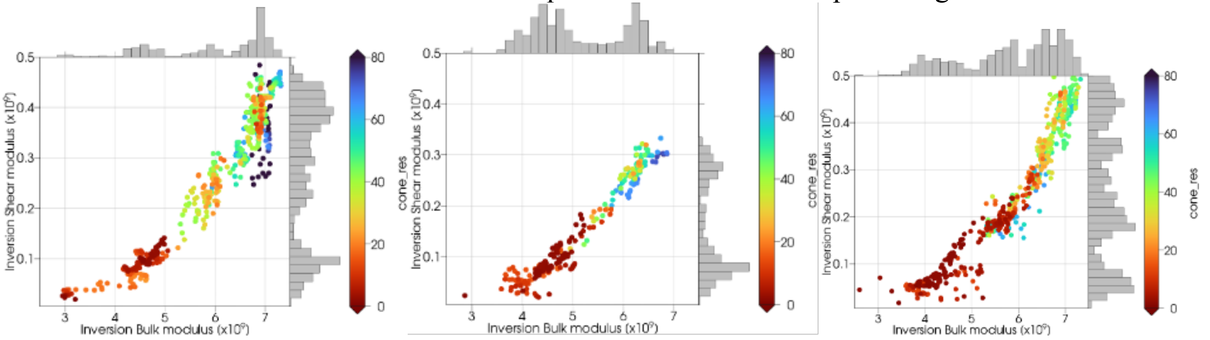

Figure 1 *Cross-plot analysis from three selected CPT locations. Cross-plot analysis is the basis of the definition of the non-Gaussian probability density functions used for classifying the soil units. The cross-plots display the inverted bulk modulus on the x-axis and the inversion shear modulus on the y-axis color-coded with the measured cone resistance. The entire CPT measured interval at the locations is shown.*

CPT prediction – dense and high-quality data case

CPT property prediction is carried out within a Bayesian framework, enabling a fully probabilistic interpretation of the results. This method inherently addresses the ambiguity arising from the fact that different soil types can exhibit similar elastic responses. In such cases—often due to overlapping mineral compositions or elevated noise levels in the seismic data—the model appropriately reflects uncertainty by assigning comparable probabilities to multiple plausible soil types.

This CPT prediction method uses absolute elastic property estimates from seismic inversion as input to derive geotechnical parameters. The approach leverages non-Gaussian probability density functions (PDFs), constructed via Gaussian kernel density estimation, to capture the complex, data-driven relationships between elastic and geotechnical properties.

These PDFs are defined from polygons in elastic property cross-plot space that enclose representative inversion data points corresponding to specific CPT parameters (as shown in Figure 1). The polygons are carefully delineated to distinguish between soil types that display distinct elastic signatures in the seismic domain.

By applying these PDFs to the inversion results, the method computes the likelihood of encountering each soil type (e.g., Type A, Type B, etc.) at any given location. Each classified soil type is then assigned characteristic geotechnical properties, which, when combined with the associated probabilities, yield a predicted CPT profile.

This global approach ensures consistency across the site, as the same PDFs and soil property definitions are applied uniformly to all seismic traces, allowing elastic attributes from AVO data to be systematically translated into CPT-relevant outputs.

Uncertainty quantification – dense and high-quality data case

Multiple factors contribute to the overall uncertainty in CPT prediction, including:

- Variability and limitations in geotechnical input data
- Uncertainty in seismic data quality and inversion outputs
- Interpretation of seismostratigraphic units and integration with geotechnical datasets
- Challenges in interpreting soil behavior due to the inherent complexity of physical soil properties

With access to a large CPT dataset, we can perform robust statistical analyses to accurately quantify these sources of uncertainty, with a focus on maintaining unbiased estimates.

Uncertainty quantification is based on the deviation between measured and predicted geotechnical parameters—such as cone resistance (q_c), sleeve friction (f_s), bulk modulus (K), and small-strain shear modulus (Gmax)—at surveyed locations. Predictions are generated using a leave-one-out cross-validation method, where each CPT point is predicted without using its own data. This ensures all predictions are effectively treated as blind tests, allowing for the derivation of truly independent error estimates.

Using this method and following the DNV-RP-C207 (DNV, 2021) guideline, uncertainty bounds (A to E lines) were established (see Figure 2), providing a clear and standardized framework for assessing prediction reliability across the site.

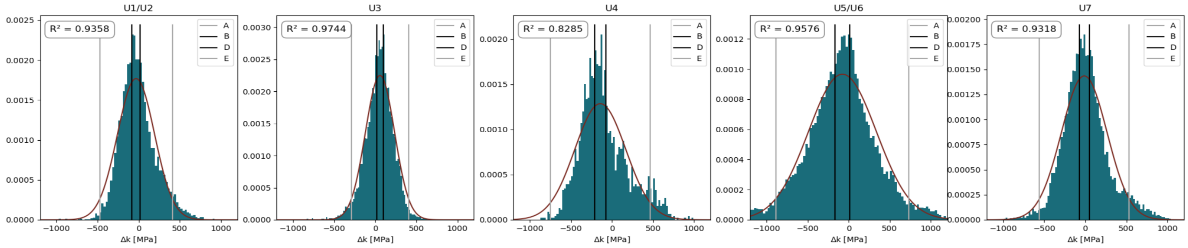

Figure 2 *Distribution of the unbiased error on bulk modulus for different geotechnical soil units. In green we see the distribution plotted with the red curve representing the Gauss curve describing the distribution. The A, B, D and E intervals are plotted on top of at each interval and each property*

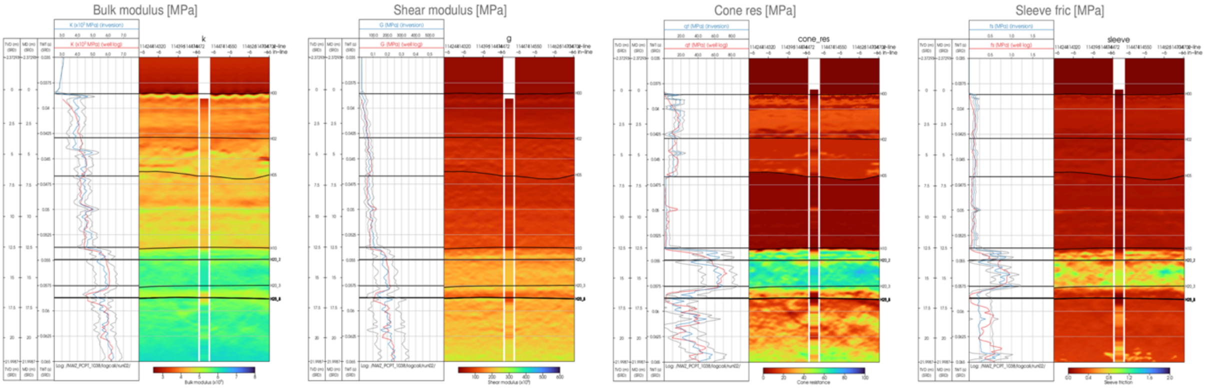

Figure 3 *Bulk modulus, shear modulus, cone resistance and sleeve friction. Blue curve is the predicted parameter, and the red curve is the measured. Grey curves represent the prediction interval (A and E bounds). Right part of each plot is a cross section along the seismic line with the CPT in the centre.*

Conclusions

Accurate and phase-adaptive subsurface characterization is essential to accelerate offshore wind development and meet global energy targets. By integrating UHR seismic data with geotechnical information through quantitative inversion and ground modeling, we can improve early-phase planning and deliver robust late-stage designs. Addressing data quality, validation, and uncertainty at each stage enables more efficient, cost-effective, and de-risked offshore wind farm development.

Acknowledgements (Optional)

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. This abstract is part of the WINDFARM research project funded by EUDP (reference 640232-511623).

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