Title:
3D Ultra-High-Resolution Depth Velocity Model Building and Full Waveform Inversion for Offshore Wind Site Characterization

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Introduction

3D Ultra-High-Resolution Seismic (3D UHRS) surveys are increasingly used for offshore wind-farm site characterization, where accurate near-surface imaging is essential for foundation design and the reduction of geotechnical uncertainty. These datasets demand specialized processing workflows that extend beyond conventional time processing, critically incorporating velocity-model building (VMB) and imaging.

Traditional 2D site surveys rely on sparse lines and time-domain velocity analysis to flatten CMP gathers, producing RMS velocities that don't measure accurately soil variations. To advance beyond this limitation, we applied a full 3D depth-domain VMB workflow combining Kirchhoff Pre-Stack Depth Migration (KPSDM), 3D tomography, and Dynamic Matching Full Waveform Inversion (FWI) (Huang *et al.*, 2023) up to 600 Hz to resolve sub-10 m wide geologic features in unconsolidated sediments.

Data and Geological Context

The 3D UHRS survey was acquired in 2024 in the Irish Sea across approximately 92 km², using wide-tow dual-sparker sources (Widmaier et al., 2019) and ten streamers spaced 12.5 m apart, with a mixed group interval of 1.56 and 3.125 m for respectively the near-mid and mid-far channels. The nominal acquisition grid was 1.56 × 1.56 m, and traces were vertically sampled every 0.25 ms, providing a maximum bandwidth of up to 2 kHz. The area is dominated by soft-mud units overlying hard bedrock. The survey's original goal was to delineate the bedrock surface for foundation anchoring, but early results from the KPSTM migration revealed laterally variable stiff-mud units above the bedrock that were not clearly visible on the stacked image yet appeared as localized "high-velocity" anomalies in the KPSTM velocity field. From a geological point of view, the ice sheet thickening may have compressed muds over bedrock anticlines, stiffening elevated areas while protecting synclines—producing a patchy stiffness landscape. Available Cone Penetration Test (CPT) data showed a strong correlation between cone resistance and higher seismic velocities, motivating a detailed depth-domain analysis. Identifying these stiffer horizons is critical for optimizing foundation design and reducing construction cost, potentially changing the design from the original bedrock-anchoring plan.

Depth Velocity Model Building

The input gathers underwent extensive preprocessing; denoising, deghosting, designature, sea-state statics correction (redatumed to mean sea level), water-velocity correction and demultiple (Limonta *et al.*, 2024). The initial time-domain velocity model was refined through iterative 3D tomography over the full ~92 km² area, followed by acoustic FWI on two 3 km² test zones. Tomographic updates were derived from residual-moveout picking on CRPs; gathers above 36° AoI were muted to minimize anisotropy effects. FWI used shot gathers every ~10 × 10 m, progressing from 200 Hz to 600 Hz. Good agreement between observed and modeled data confirmed the validity of the starting model and its stability across the frequency range. Because of the ~50 m water depth and limited offsets, the inversion primarily utilized reflected energy.

Results

Depth-domain VMB significantly enhanced the resolution and geological consistency of the velocity model. The tomographic field enabled discrimination of stiffer mud layers that lacked clear seismic reflectivity, while FWI further sharpened small-scale features Figure 1 shows a patchy stiffness landscape in chaotic Quaternary mud unit with zones of high and low velocity. Vp around the bottom of an iceberg scour mark (<10 m wide) filled with harder material is accurately resolved, achieving sub-meter vertical resolution. At one location, Seismic CPT (SCPT) data were available for validation. Figure 2 shows the strong correlation between FWI-derived Vp (green), tomography Vp (red), and SCPT-calibrated Vs (black). The time-domain velocity curve (blue) diverges significantly, confirming the improvement achieved by the depth-domain workflow. The FWI

velocities exhibit finer vertical detail than the log spacing (1m log sampling), demonstrating sub-meter sensitivity, and excellent geological conformity with the seismic stratigraphy.

Conclusion

This study demonstrates a novel application of FWI up to 600 Hz on 3D UHRS data, representing a major step forward in near-surface imaging for offshore wind. The integrated depth-VMB workflow (KPSDM + tomography + FWI) produces a high-resolution, geologically consistent velocity field that improves time-to-depth conversion and provides quantitative insight into soil stiffness. The strong correlation between seismic and geotechnical parameters (Vp–Vs–qc) validates the methodology and underscores its engineering relevance. The increased resolution achieved through high-frequency FWI also enhances the low-frequency background model used in quantitative inversion, enabling more reliable soil-property prediction. Overall, this approach demonstrates how 3D UHRS seismic data can be leveraged not only for imaging but also for quantitative extraction of soil properties, bridging geophysical and geotechnical site characterization for offshore-wind development.
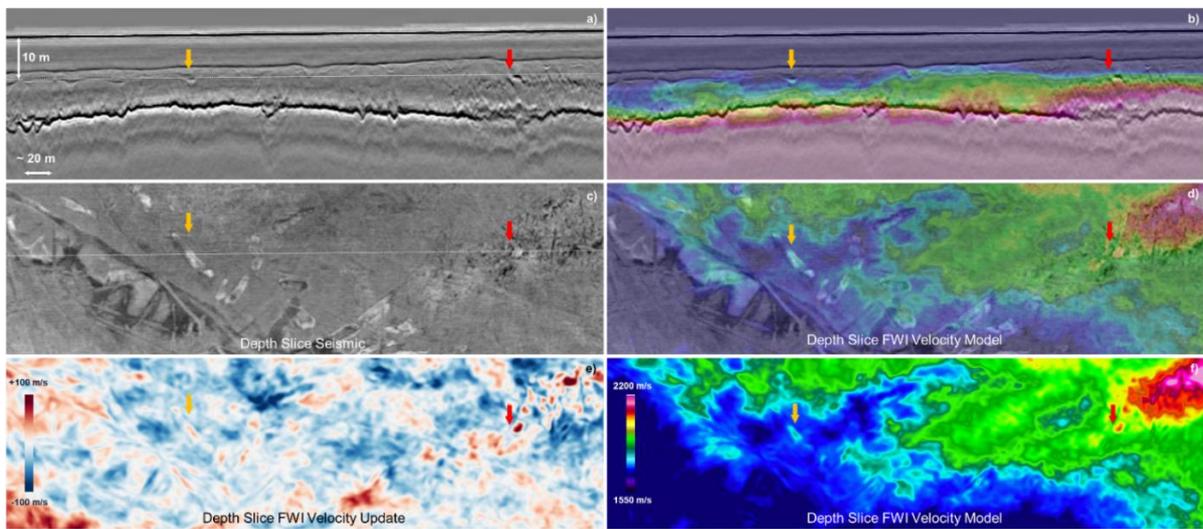

Figure 1 FWI results over the test area. The orange arrow is pointing a small iceberg scour mark, around 10m wide and less then 1m thick which is filled with harder sediment then surrounded mud layers. Red arrow is indicating a chaotic weathered-rock section subject to de-watering and increase in stiffness and Vp. Velocity update "e)" shows the complexity of the geology and velocity model
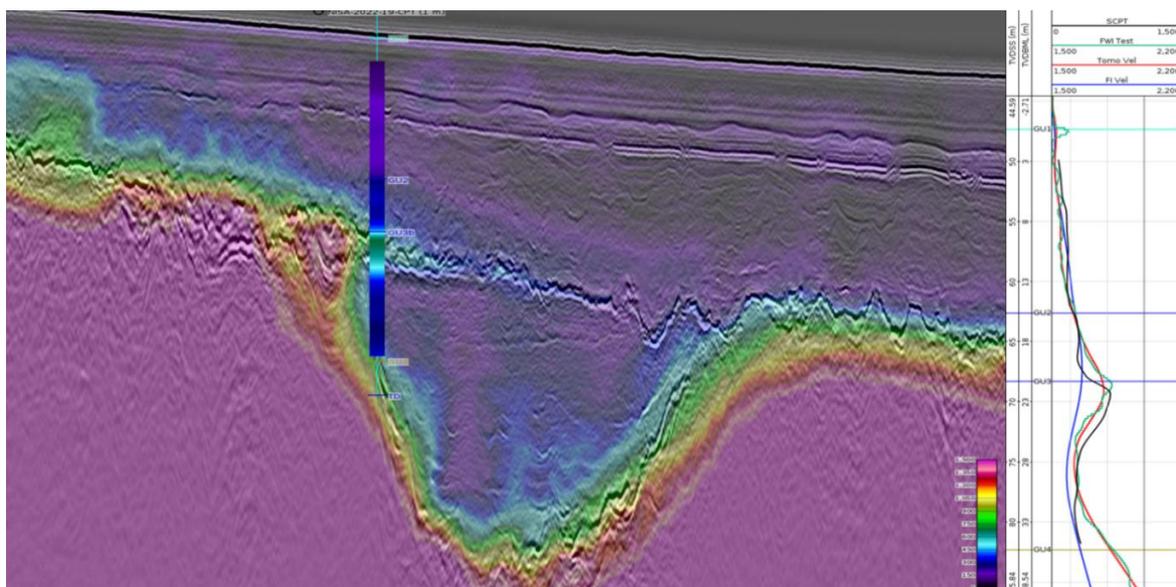

Figure 2 Final depth migrated stack overlay by FWI velocity. The log profile is derived from SCPT Vs data, and it is showing the good correlation between FWI (green curve), Tomography (red curve), calibrated Vs (black curve). The blue curves show the time VMB velocity

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