Improving 3D Site Characterization Velocity Models with High-Frequency FWI

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Summary

3D Ultra-High-Resolution Seismic (3D UHRS) surveys are increasingly critical to offshore wind-farm site characterization, where accurate imaging and a quantitative understanding of the shallow subsurface are essential for foundation design, geotechnical risk mitigation, and cost-effective project execution. While UHRS acquisition technology provides dense spatial sampling and broadband frequency content, conventional time-domain processing and velocity analysis often fail to fully exploit the information content of these datasets, particularly in geologically complex near-surface environments dominated by strong lateral heterogeneity and rapid vertical velocity variations.

In this study, we present an integrated 3D depth-domain velocity-model building (VMB) workflow that combines Kirchhoff Pre-Stack Depth Migration (KPSDM), large-scale 3D reflection tomography, and high-frequency Dynamic Matching Full Waveform Inversion (DMFWI) applied at frequencies up to 600 Hz. The workflow is applied to a large 3D UHRS dataset acquired in the Irish Sea and is specifically tailored to address the challenges of shallow-water acquisition, limited offsets, and sparse borehole control. Particular emphasis is placed on validating seismic-derived velocity models through direct comparison with independent geotechnical measurements, including Seismic Cone Penetration Test (SCPT) data.

The results demonstrate a significant improvement in velocity-model resolution, depth positioning accuracy, and geological consistency compared to conventional time-domain approaches. The final FWI velocity model resolves sub-meter vertical variations and laterally heterogeneous features such as iceberg scour infills, stiffened clay horizons, and weathered or dewatered zones above bedrock. Strong agreement between inverted P-wave velocity (Vp) and SCPT-derived shear-wave velocity (Vs) confirms the quantitative reliability of the workflow. These findings highlight the growing potential of high-frequency FWI to transform UHRS seismic data from a primarily imaging-focused tool into a robust quantitative input for offshore wind-farm foundation engineering.

Introduction

Offshore wind-farm developments require detailed and reliable characterization of the shallow subsurface to support foundation design and to manage geotechnical risk effectively. The increasing scale of offshore wind projects has placed growing emphasis on understanding near-surface geological complexity at spatial scales directly relevant to foundation behavior. In this context, 3D Ultra-High-Resolution Seismic (UHRS) data have emerged as a key geophysical dataset, providing dense spatial sampling and broadband frequency content optimized for near-surface imaging (Limonta *et al*., 2024).

Despite these advances in acquisition technology, processing and interpretation workflows have often remained rooted in conventional time-domain approaches. Velocity analysis is commonly performed using semblance-based picking to derive RMS velocities that flatten common-midpoint (CMP) gathers and improve stack response. While adequate for producing interpretable seismic images, this approach provides only approximate velocity information and does not yield reliable interval P-wave velocities (Vp). As a result, subtle but geotechnically significant features, such as localized sediment stiffening, partial cementation, or dewatering effects, may not be adequately resolved.

Accurate interval velocity information is increasingly recognized as a critical input for quantitative interpretation and for linking seismic observations to geotechnical properties such as stiffness, shear strength, and uniaxial compressive strength (UCS) (Lindh and Lemenkova, 2022). Furthermore, reliable velocity models underpin accurate time-to-depth conversion, amplitude-versus-offset (AVO) analysis, and seismic inversion workflows. These requirements motivate the transition from time-domain velocity analysis to depth-domain velocity-model building approaches that are better suited to handling the complexity of near-surface geological environments.

Full Waveform Inversion (FWI) has long been recognized as a powerful tool for recovering high-resolution velocity models. Recent advances in 3D acquisition, computational efficiency, and inversion algorithms, such as Dynamic Matching FWI (Huang *et al*., 2023), have enabled the extension of FWI to the ultra-high-frequency seismic. This study explores the application of high-frequency (up to 600 Hz) FWI to 3D UHRS data and evaluates its value for offshore wind-farm site investigations through direct comparison with independent geotechnical measurements.

Site Conditions and Geological Framework

The 3D UHRS dataset used in this study was acquired in the Irish Sea during autumn 2024. The survey geometry

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provides a nominal lateral resolution of 1.56 × 1.56 m and a vertical sampling interval of 0.25 ms, corresponding to a Nyquist frequency of 2 kHz. These acquisition parameters enable high-frequency signal content essential for resolving fine-scale geological features in the shallow subsurface. The acquisition employed four sparker sources arranged in a wide-tow configuration (Widmaier *et al.*, 2019), emitting energy from approximately 150 Hz, with a shot interval of 250 ms. A 150 m streamer length allowed the recording of reflection angles up to approximately 35° angle of incidence (AOI) over most of the survey area. Although maximum AOI decreases with depth, it remains sufficient for moveout analysis and reflection-based velocity updates down to approximately 40–50 m below seabed.

Geologically, the study area is characterized by a succession of soft clay-dominated sediments overlying a hard and irregular bedrock surface (Figure 1). The sedimentary sequence exhibits strong lateral heterogeneity associated with Neogene glacial processes, including ice-sheet loading, pushing, compaction, and subsequent dewatering. These processes have produced a highly heterogeneous near-surface environment with localized zones of increased stiffness embedded within otherwise soft clay units.

The initial objective of the survey was to map bedrock geometry accurately and to provide reliable input for foundation design, particularly where bedrock serves as the anchoring horizon. Cone Penetration Test (CPT) and SCPT data were available at selected locations, enabling direct comparison between geotechnical measurements and seismic-derived velocities. Even at the time-domain processing stage, a correlation between increased cone resistance and elevated seismic velocity was observed, particularly in the interval immediately above bedrock. However, the chaotic internal structure of this interval prevented the identification of continuous reflectors in time-migrated images, limiting the interpretational value of amplitude-based seismic products alone.

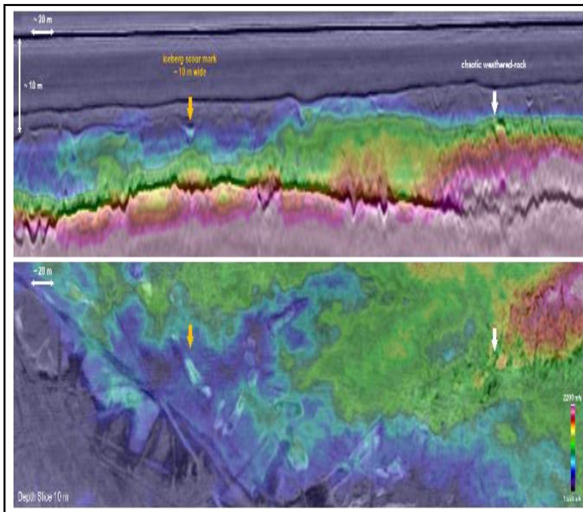

Figure 1: Inline (top) and depth slice (bottom) of FWI model overlaid to seismic. The orange arrow is pointing a small iceberg scour mark, around 10m wide and less then 1m thick which is filled with harder sediment then surrounded clay layers. Red arrow is indicating a chaotic weathered-rock section subject to dewatering and increase in stiffness and Vp.

Depth Velocity Model Building workflow

All data used for velocity analysis underwent extensive pre-processing, including denoising, deghosting, designature, sea-state statics correction (re-datumed to mean sea level), water-velocity correction, and demultiple, following the workflow described by Limonta *et al*. (2024). Due to limited shallow borehole data and sonic logs above bedrock, the final Kirchhoff Pre-Stack Time Migration (KPSTM) velocity model was used as the initial input for depth-domain processing. Below the bedrock interface, velocities were replaced using kriged sonic log values and preliminary geological interpretation.

The absence of check-shot data complicated anisotropy estimation; therefore, an isotropic medium assumption was adopted for both depth migration and velocity analysis. An initial Kirchhoff Pre-Stack Depth Migration (KPSDM) was performed on a 3.125 × 3.125 m grid with a vertical sampling interval of 0.2 m and a maximum imaging depth of 180 m.

Velocity updates were first obtained through 3D reflection tomography applied across the full survey area of approximately 90 km². Residual moveout was picked on Common Reflection Point (CRP) gathers, with muting applied above 36° AOI to reduce sensitivity to potential anisotropy effects. Two full iterations of migration, picking, and tomographic inversion were performed over the entire section, producing a smooth yet geologically plausible velocity model that served as a robust starting point for FWI.

Following the large-scale 3D reflection tomography, we applied acoustic Dynamic Matching Full Waveform Inversion (DMFWI) to two targeted test areas (~3 km² each) to further increase velocity resolution and sharpen geological contrasts that remain below the resolving power of reflection-tomography updates alone.

FWI used shot gathers after demultiple and re-datuming to mean sea level (MSL) as input. Because the UHRS acquisition is characterized by limited offsets, with reflection angles generally up to ~35° AOI for most coverage, and because the site is in ~50 m water depth, the dataset contains limited clear critical refraction energy.

Consequently, the FWI updates were primarily driven by reflected energy rather than refractions.

Despite these constraints, the UHRS data provide high spatial sampling and strong high-frequency content (sparker energy starting around 150 Hz), which supports a reflection-based inversion strategy in the shallow section, especially when the starting model is already stabilized by depth migration plus tomography.

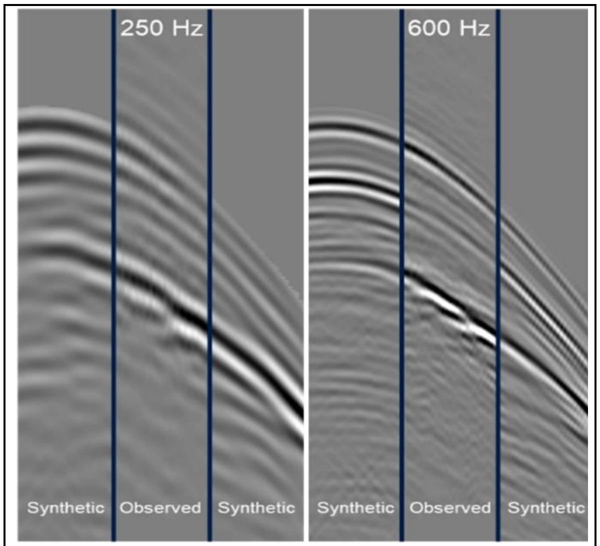

Figure 2: FWI QC - Interleaved shot comparison; the shot is modelled/filtered at 250Hz (left) and 600Hz (right) maximum frequency. In this display the modelling was performed using the final model output FWI

We implemented a multi-scale inversion strategy that progressively increased the maximum inverted frequency from approximately 200 Hz up to 600 Hz, allowing the algorithm to first fit longer-wavelength components before incorporating finer-scale details. Shots were sub-sampled for each stage at roughly 10 × 10 m spacing, balancing computational cost with illumination consistency over the test area.

Importantly, no dedicated muting was applied to the input gathers specifically for FWI in this workflow; instead, the inversion relied on the quality of the preconditioning steps (including demultiple and redatuming) and the stability of the tomographic starting model.

FWI quality control is illustrated using an interleaved shot comparison (Figure 2), where the same shot gather is modeled and band-limited first to 250 Hz and then to 600 Hz using the final FWI output model. The consistency of a good observed-versus-modeled data as the frequency content increases indicates that the workflow achieved a stable high-frequency match and that the inverted model is consistent with the recorded wavefield across the tested bandwidth. In this UHRS setting, where refraction-based constraints are limited, the QC shown on Figure 2 is especially important because it demonstrates that the final model can reproduce reflection-dominated kinematics and wavelet behavior at high frequencies, which is the practical prerequisite for trusting sub-meter-scale velocity variations inferred from the inversion.

Results

The depth-domain VMB workflow produced a clear improvement in model fidelity from the original time-domain velocity field, to the depth-tomography model, and finally to the high-frequency FWI model. Even before FWI, the post-tomography velocity model contributed significantly to interpretation by revealing stiffer clay intervals that were not practically interpretable from the migrated seismic stacks alone, improving the ability to differentiate soil units where reflectivity is weak or chaotic. Applying FWI to the selected test areas yielded a further step-change in resolution compared with tomography-only results, clearly visible when comparing the velocity and the sharpness of small-scale features in the inversion zones.

As shown in Figure 3, the FWI velocity field resolves features narrower than 10 m and vertical structure better than ~1 m, including small geomorphological and near-surface geohazard-type elements that are directly relevant to foundation risk screening. A representative example is the imaging of an iceberg scour mark of about 10 m width and less than 1 m thickness, interpreted as being filled with harder sediment than the surrounding clay layers; the associated localized velocity increase is explicitly highlighted in Figure 3 (orange arrow). Figure 3 also highlights a chaotic weathered-rock section interpreted as being subject to dewatering and increased stiffness and Vp (red arrow), demonstrating that the FWI update is sensitive to mechanical contrasts associated with near-bedrock alteration and/or sediment remobilization processes. The FWI velocity model becomes not only an imaging aid but a high-resolution property volume capable of revealing subtle stiffness heterogeneity that may be poorly expressed by reflectivity alone in chaotic intervals.

Validation against independent geotechnical measurements is central to establishing confidence that the inverted velocity variations correspond to real mechanical contrasts. At one location, SCPT data were available with Vs measured at 1 m intervals. Figure 4 shows the comparison between the FWI-derived velocity (green), the tomography-derived velocity (red), a scaled/interpolated SCPT-derived Vs log (black), and the time-domain VMB velocity (blue). For the displayed comparison, the Vp/Vs ratio is held constant, enabling a consistent trend-based evaluation between the seismic-derived Vp and the SCPT-derived Vs. The overlay demonstrates that both depth-domain approaches (tomography and FWI) track the SCPT profile closely, while the time-domain velocity diverges significantly, emphasizing the improvement delivered by depth-domain VMB in a shallow, laterally heterogeneous setting. A further notable observation is that the FWI velocity exhibits vertical detail finer than the 1 m SCPT sampling, indicating sensitivity to sub-meter velocity variations in the shallow section. Finally, Figure 4 includes the velocity curves displayed together with the migrated stack, allowing visual assessment of geological consistency; the FWI output shows strong conformity between velocity contrasts and stratigraphic changes visible in the seismic image, supporting the interpretation that the inverted velocity field is geologically meaningful and suitable for engineering-focused interpretation.

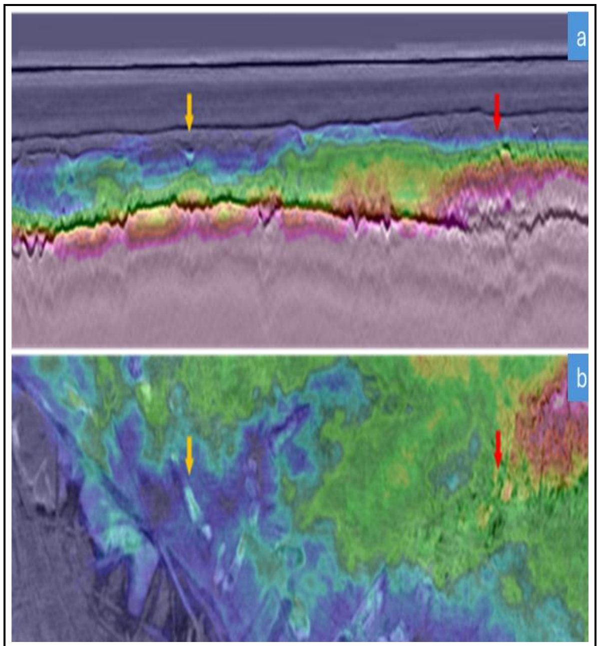

Figure 3: FWI results over the test area. Image are showing the FWI model of an inline (a) and depth slice (b) with stack overlay.

Conclusion

This study demonstrates the successful application of high-frequency (up to 600 Hz) Full Waveform Inversion to 3D Ultra-High-Resolution Seismic data for offshore wind-farm site characterization. By integrating KPSDM, 3D reflection tomography, and Dynamic Matching FWI, the workflow delivers a detailed and geologically consistent velocity model that significantly outperforms conventional time-domain approaches.

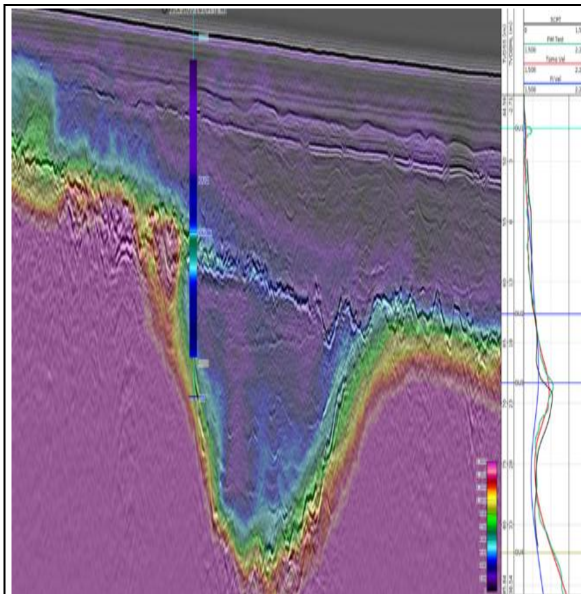

Figure 4: Final depth migrated stack overlay by FWI velocity. The log profile is derived from SCPT Vs data, and it is showing the good correlation between FWI (green), Tomography (red), calibrated Vs (black). The blue curve shows the time VMB velocity.

The final velocity model resolves sub-meter vertical variations and fine-scale lateral heterogeneity, enabling reliable identification of stiffened clay layers, iceberg scours, and weathered bedrock zones. The availability of reliable, high-resolution seismic velocities is particularly critical to improve the stability and geological consistency of low-frequency models for pre-stack seismic inversion workflows. Strong agreement with independent SCPT measurements validates the seismic-derived velocities and confirms their relevance for foundation engineering. Overall, the results highlight the expanding role of 3D UHRS seismic data as a quantitative bridge between geophysical imaging and geotechnical characterization in offshore renewable-energy projects.

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