# High-Frequency Full Waveform Inversion for Enhanced 3D Ultra-High-Resolution Seismic Velocity Model Building

## Introduction

3D Ultra-High-Resolution Seismic (3D UHRS) surveys are increasingly employed for offshore wind-farm site characterisation, where accurate near-surface imaging is vital for foundation design and for reducing geotechnical uncertainty. These datasets require advanced processing workflows that move beyond conventional time-domain methods, critically incorporating velocity-model building (VMB) and depth imaging tailored to the distinct characteristics of ultra-high-resolution data (Limonta *et al*., 2024). Traditionally, site surveys have relied on sparse 2D lines or small 3D volumes, applying basic time-domain velocity analyses, typically semblance-based picking, to flatten common-midpoint (CMP) gathers and improve stacking response. While this approach yields RMS velocities, these values only approximate subsurface velocity variations and do not provide accurate interval compressional velocity (Vp) information, nor do they capture detailed soil property variations essential for engineering purposes. To overcome these limitations, TGS implemented a comprehensive 3D depth-domain velocity-model building workflow, combining Kirchhoff Pre-Stack Depth Migration (KPSDM), 3D tomographic inversion, and Dynamic Matching Full Waveform Inversion (DMFWI) (Huang *et al*., 2023) with frequencies up to 600 Hz. Interval compressional velocity (Vp) is particularly significant for quantitative interpretation (QI) and for estimating soil parameters such as uniaxial compressive strength (UCS) (Lindh and Lemenkova, 2022). We further emphasise the importance of validating seismic velocity models by direct comparison with geotechnical measurements, such as Seismic Cone Penetration Test (SCPT) results, to ensure both their accuracy and reliability.

## Data and Geological Context

For this study, the 3D UHRS data was acquired in autumn 2024 in the Irish Sea with a nominal lateral resolution of 1.56 × 1.56 m and a vertical sampling of 0.25 ms, yielding a Nyquist frequency of 2 kHz. The acquisition utilized four sparker sources arranged in a wide-tow configuration (Widmaier *et al*., 2019) emitting energy starting from 150 Hz, with a shot interval of 250 ms. The 150 m streamer length ensured that reflection angles up to 35° angle of incidence (AOI) were recorded for most of the trace length. Although the maximum AOI decreases with depth, it remains sufficient for accurate moveout correction in deeper layers, 40-50 m below seabed.

The original scope of the project was to perform a Kirchhoff Pre-Stack Time Migration (KPSTM) by deriving a suitable time migration velocity model, with the main objective of flattening the time-domain image gathers. The geological setting of the area is characterized by soft clay units overlying hard bedrock. The initial motivation for acquiring the full 3D UHRS survey was to map the bedrock accurately and provide input for foundation design where the bedrock is used as an anchoring layer.In this project, Cone Penetration Test (CPT) data were available, and cone resistance (a measure of soil stiffness) was compared directly with the seismic velocity model derived for time migration. Even after the initial time-domain VMB, a clear correlation was observed between cone resistance and velocity increase, particularly in the layer immediately above the bedrock. The velocity model also indicated significant lateral variability, suggesting the presence of chaotic soft-clay units influenced by Neogene ice-sheet processes, including pushing, compression, and dewatering.

The observed increase in strength and stiffness within this layer is of significant importance to the project for non-rock bearing foundation options. It is important to note that this stiffness increase was not clearly identified from the KPSTM image. The chaotic nature of the layer prevented the mapping of a consistent seismic reflector, and the time-domain velocity model was therefore used to guide the first round of interpretation. Based on these findings, it was decided to perform a more sophisticated depth velocity-model building (VMB) using advanced algorithms. A more accurate velocity model and subsequent depth migration (KPSDM) improve the depth positioning, the imaging of complex structures, and amplitude-versus-offset (AVO) response. Furthermore, the higher resolution in the velocity model enhances the low-frequency background model used in the quantitative interpretation workflow, providing more accurate seismic inversion results.

## Depth Velocity Model Building

The input data for velocity analysis underwent extensive pre-processing, including denoising, deghosting, designature, sea-state statics correction (re-datumed to mean sea level, MSL), water-velocity correction, and demultiple, as described by Limonta *et al*. (2024).With limited shallow borehole data and sonic logs above bedrock, the depth VMB workflow started with the final KPSTM model as input. Below bedrock, velocities were replaced by kriging sonic log values and a preliminary interpretation from KPSTM data. The absence of check-shots made it challenging to estimate anisotropy; therefore, an isotropic medium approximation was adopted for both depth migration and velocity analysis. The data were pre-stack depth migrated using the initial velocity model on a 3.125 × 3.125 m grid, with a vertical sampling step of 0.2 m and a maximum depth of 180 m.

Velocity analysis was first performed using 3D reflection tomography across the full area of approximately 90 km², followed by reflection-based FWI up to 600 Hz applied to two selected test areas of about 3 km² each. In this abstract, we focus primarily on the two areas where FWI was performed.

3D tomography was carried out by picking residual moveout for each Common Reflection Point gather (CRP). To minimize the influence of possible anisotropy, the gathers were muted above 36° AOI. Due to the characteristics of the site, the tomography was performed over the entire section rather than within discrete model-building units, with a total of two iterations of migration, picking and tomographic inversion applied.

Acoustic DMFWI followed the 3D tomography stage. Shot gathers after demultiple and re-datuming to MSL were used as input to the process (see Figure 1). Shots spaced approximately 10 × 10 m were selected for each iteration, and several inversion stages were run on different frequency bands, with maximum frequencies starting from 200 Hz and progressing up to 600 Hz. Good agreement between observed and modelled data was achieved at lower frequencies, indicating a reliable starting model, and this good match persisted as the frequency increased as shown in Figure 1. No specific data muting was applied to the FWI input gathers. The inversion primarily focused on reflected energy, as the relatively deep-water depth (~50 m) and limited offset prevented adequate recording of critical refraction events. This aspect could be further optimized in future survey designs if FWI becomes an operational component of site characterization workflows.

## Final Results

The results from the depth VMB show a significant improvement in the resolution of the velocity model. The velocity model after the final tomography (prior to FWI) was used to guide the interpretation of stiffer clay layers that were not practically interpretable in the migrated seismic stacks, enabling better discrimination between soil units. Although FWI was only applied to subsets of the survey, the benefits in increased resolution are obvious when compared to the depth tomography results. As shown in Figure 2, iceberg scour marks and geological features less than 10 m wide are mapped in the velocity model, achieving a vertical resolution of under one meter. At one location, SCPT data were also available. As part of the SCPT measurements, shear-wave velocity (Vs) was measured at one-meter intervals. Figure 3 presents the interpolated and scaled Vs log, which present a similar trend to the P-wave velocity (Vp) extracted from the FWI results. Ratio between Vp/Vs conversion has been kept constant for this comparison.

The log display clearly shows that the tomography-derived velocity (red) and the FWI velocity (green) closely follow the SCPT profile (black), while the initial time-processing velocity (blue) deviates significantly. It is also noteworthy that the vertical resolution of the FWI-derived velocity exceeds that of the actual log sampling, revealing sub-meter sensitivity. The velocity overlay on the seismic image demonstrates excellent geological conformity, confirming that the FWI model captures true stratigraphic variations useful when used for interpretation.

## Conclusion

This study demonstrates a novel application of Full Waveform Inversion (FWI) up to 600 Hz on 3D Ultra-High-Resolution Seismic (UHRS) data, representing a step change in near-surface imaging for offshore wind-farm site characterization. The integration of depth velocity-model building provided a detailed and geologically consistent velocity field that significantly improves both structural imaging and quantitative interpretation.

The depth-domain velocity model allowed for enhanced interpretation of stiffer clay layers that were not clearly expressed in the seismic image, improving discrimination of soil units and time-to-depth conversion accuracy. The strong correlation between the inverted P-wave velocity (Vp) and geotechnical measurements, including SCPT-derived shear-wave velocity (Vs) and cone resistance, validates the seismic model and confirms its relevance for engineering design.

The increased vertical resolution achieved through high-frequency (600 Hz) FWI also enhances the low-frequency background model required for quantitative inversion, enabling more reliable soil-property prediction. Overall, this workflow highlights the growing capability of UHRS data to bridge the gap between geophysical-and geotechnical measurements, using seismic data not only as input for soil unitization but also for extracting key soil parameters relevant to offshore foundation design.

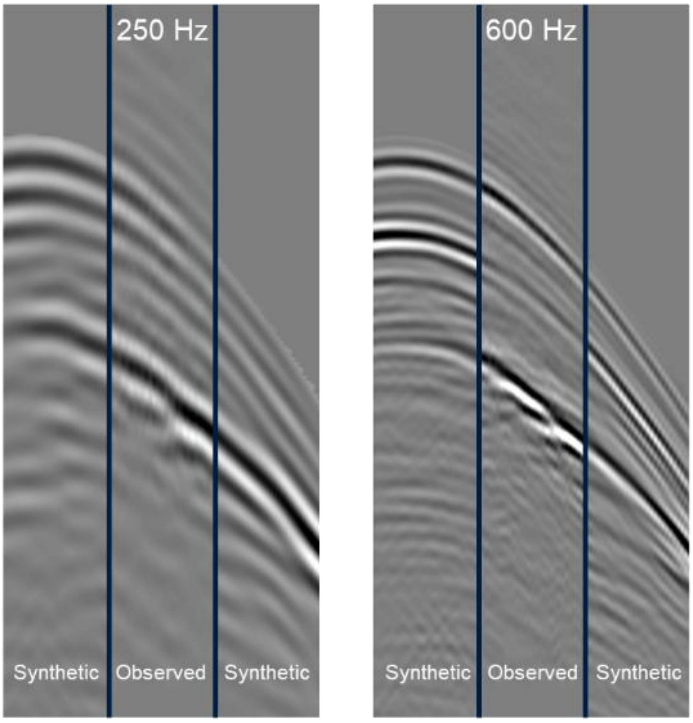

***Figure 1*** *FWI QC - Interleaved shot comparison; the shot is modelled/filtered at 250Hz (left) and 600Hz (right) maximum frequency. In this display the modelling was performed using the final model output FWI.*

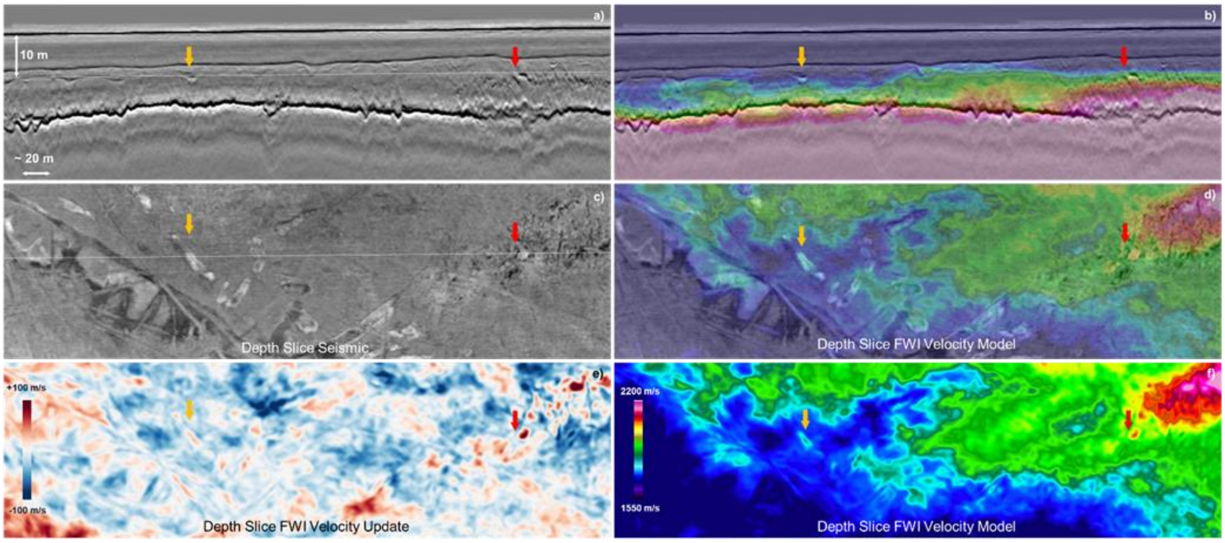

***Figure 2*** *FWI results over the test area. Image* ***a***, ***b***, ***c*** *and* ***d*** *are showing an inline and depth slice with and without stack overlay. The orange arrow is pointing a small iceberg scour mark, around 10m wide and less then 1m thick which is filled with harder sediment then surrounded clay layers. Red arrow is indicating a chaotic weathered-rock section subject to dewatering and increase in*

*stiffness and Vp. Velocity update* ***e*** *shows the complexity of the geology and velocity model. Image* ***f*** *is showing the velocity model without stack overlay*

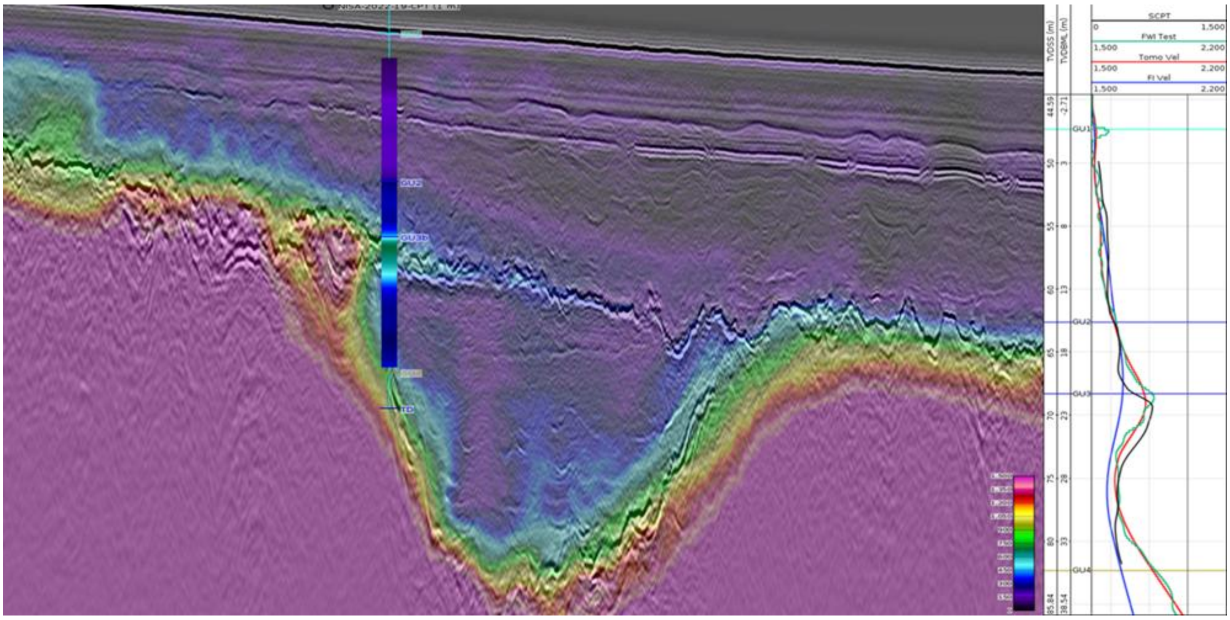

***Figure 3*** *Final depth migrated stack overlay by FWI velocity. The log profile is derived from SCPT Vs data, and it is showing the good correlation between FWI (green), Tomography (red), calibrated Vs (black). The blue curve shows the time VMB velocity.*

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