Depth Velocity Model Building and Imaging for 3D UHRS site characterization surveys

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Summary

This study presents a workflow for building depth velocity models (VMB) using 3D Ultra-High-Resolution Seismic (UHRS) data, focusing on offshore wind farm site characterization. Traditional velocity analysis for site surveys relies on simple RMS velocities, which fail to capture detailed subsurface properties. The methodology, adapted from the oil and gas sector, employs Pre-Stack Kirchhoff Depth Migration (KPSDM) and 3D depth tomographic updates to deliver precise imaging in complex geological settings.

The workflow was applied to 3D UHRS data from the North Sea, achieving a lateral resolution of 3.125 x 3.125 m and vertical precision of 0.125 ms. It involved extensive preprocessing and iterative velocity updates across shallow and deeper subsurface sections, resolving key features like sediment-filled channels and tunnel valleys. The process revealed rapid velocity variations, enhancing the accuracy of subsurface reflector positioning crucial for geotechnical design.

The study highlights the importance of accurate velocity models for reliable seismic imaging and quantitative interpretation (QI). It demonstrates that 3D UHRS data can robustly characterize shallow subsurface features, supporting safer and more efficient foundation planning for renewable energy projects. The findings suggest potential advancements using Full Waveform Inversion (FWI) to further integrate geophysical and geotechnical workflows.

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Introduction

Acquisition and processing of 3D Extremely High-Resolution Seismic (3D UHRS) is rapidly becoming the method of choice for detailed near-surface imaging, particularly in wind farm site characterization. These surveys are tailored to maximize the resolution of shallow subsurface features and require highly specialized processing workflows that address their unique data characteristics (Limonta et al., 2023). The need for customization extends beyond standard pre-processing steps like denoising and demultiple to encompass the critical phase of Velocity Model Building (VMB).

The standard practice in site survey characterization is to acquire sparse 2D lines (or small 3D volumes) and perform relatively simple velocity analysis using semblance-based picking, which aims mainly to flatten CMP gathers in the time domain and improve the stacking response. This type of velocity analysis typically requires a RMS velocity, providing only a low-resolution approximation of velocity variations in the subsurface which typically lacks meaningful information about true layer or interval properties, such as compressional velocity (Vp).
The objective of seismic survey acquisition and processing extends beyond obtaining a clear subsurface image to include the extraction of key subsurface properties. Among these, Vp is particularly important for quantitative interpretation (QI) and soil property estimation.

In this abstract, we explore the application of depth velocity model building and imaging in site survey characterization. We demonstrate that tools developed for the oil and gas industry can be adapted for processing data with extremely high lateral and temporal resolution in unconsolidated geological settings. The discussion focuses on Pre-Stack Kirchhoff Depth Migration (KPSDM) and 3D depth tomographic updates for data acquired using a 3D survey layout.
Before discussing the results of depth velocity model building and imaging, we summarize the distinctions between migration techniques and the methodology used for velocity derivation.

Imaging and Velocity Model Building: Time vs. Depth

The most common technique for seismic imaging is Kirchhoff migration, performed either pre-stack or post-stack. This abstract focuses on the more advanced pre-stack migration, implemented in the time domain (KPSTM) or depth domain (KPSDM).

Seismic migration positions subsurface reflectors at their true locations. The difference between time and depth migration lies in the velocity model complexity and image accuracy. Time migration (KPSTM) assumes smoothly varying velocities and uses a 1D velocity approximation to calculate travel times. This method is effective for simple geological structures but cannot handle complex velocity variations, requiring smoothed velocities to avoid artifacts.

Depth migration (KPSDM), by contrast, accounts for lateral and vertical velocity variations, requiring a detailed velocity model. While computationally intensive, it provides more accurate imaging, making it essential for complex geological features.

Time migration is faster and suited for simpler environments, while depth migration is critical for precise imaging in complex settings. KPSTM results can be stretched into depth, but the images remain less accurate due to fundamental differences in the migration process.

Velocity analysis differs significantly between time and depth migration. In KPSTM, it is performed in the CMP domain using semblance plots to flatten gathers, yielding RMS velocities that approximate subsurface properties. In KPSDM, velocity analysis is iterative, performed in the CRP domain by calculating depth differences (dZ) to refine the velocity model through tomographic updates. The process, executed in Model Building Units (MBUs), begins with the shallowest layers, with each iteration improving ray path accuracy and progressively refining deeper layers.

Depth VMB

This section analyses 3D UHRS data acquired in the North Sea, designed with a lateral resolution of 3.125 x 3.125 m and vertical sampling of 0.125 ms, yielding a Nyquist frequency of 4 kHz. The acquisition utilized wide-tow sparker sources (Widmaier et al., 2019) emitting energy starting from 150 Hz. The 150 m streamer length ensured reflection angles above 35 degrees angle of incidence (AOI) for most of the trace length, down to approximately 90 m below the seabed. While the AOI decreases with depth, it remains sufficient for accurate moveout correction in deeper layers, as illustrated in Figure 1.

The input data for velocity analysis underwent extensive pre-processing, including denoising, deghosting, designature, sea state statics correction (redatumed to MSL), water velocity corrections, and demultiple processing, as described by Limonta et al. (2024). Due to the lack of borehole information in the area, the initial velocity model was derived from a simple 1D gradient function. The absence of Vp logs made it challenging to estimate anisotropy; as a result, an isotropic media approximation was chosen for depth migration and velocity analysis.

The data was depth-migrated using the initial velocity model on a 3.125 x 3.125 m grid with a vertical step of 25 cm and a maximum depth of 180 m. Velocity analysis was performed by picking residual moveout every 4 x 4 CRP grid in inline and crossline directions. To minimize the influence of potential anisotropy, gathers were muted above 35 degrees.

The velocity model building process was divided into two Model Building Units (MBUs):

1. Shallow Section (0–20 m below seabed): This region includes the H50 horizon (annotated on figure 2), where numerous sediment-filled channels erode into a more consolidated geological layer. The velocity updates from this section were used to re-migrate the data in depth, improving ray tracing for subsequent iterations.
2. Deeper Section (20–140 m below seabed): This includes the tunnel valley and its underlying layers, capturing velocity variations within and at the base of the valley.

Figures 2 and 3 illustrate the final depth velocity model, highlighting significant lateral velocity variations within the first 20 m of the subsurface. Variations of up to 200 m/s were observed across the main channel, causing structural shifts of several meters. Correctly positioning reflectors in depth is critical for geotechnical design and ensures reliable interpretation of subsurface conditions.

Figure 3 shows the velocity variations just a few meters below the seabed, where tomography resolved small-scale features, such as 20 m wide channels. These results demonstrate the high lateral resolution achievable with this workflow.

Figure 1 presents representative CRP gathers after depth migration using the final velocity model. The flatness of the gathers, even at high angles, confirms the accuracy of the velocity updates.

Conclusions

This work demonstrates the successful application of a depth velocity model building (VMB) workflow to 3D UHRS data, enabling the creation of an accurate, high-resolution velocity model with vertical precision in the order of a few meters and lateral resolution of tens of meters. The methodology effectively captured important subsurface details, including rapid velocity variations and complex geological features within the first 20 meters below the seabed, crucial for geotechnical design and site characterization.

An accurate velocity model is vital not only for producing reliable seismic images but also for supporting quantitative interpretation (QI). The interval compressional velocity field derived through this workflow provides indirect low-frequency information (below 10 Hertz), which is not directly recorded in sparker data. This low-frequency content is essential for elastic or acoustic inversion, to further enhance the geophysical understanding of the subsurface.
The results emphasize the complexity of the very shallow subsurface, with rapid velocity changes and small-scale geological features playing a critical role in imaging and interpretation. These findings lay the foundation to explore more advanced velocity model building techniques, such as Full Waveform Inversion (FWI), to further enhance subsurface characterization and enable seamless integration with geotechnical workflows from the outset.

By leveraging this workflow, the study demonstrates that 3D UHRS data can provide a robust foundation for offshore wind farm development, enabling reliable soil property estimation and reducing uncertainties in site design. The ability to accurately characterize the shallow subsurface ensures safer, more efficient foundation planning, contributing to the overall success of renewable energy projects.

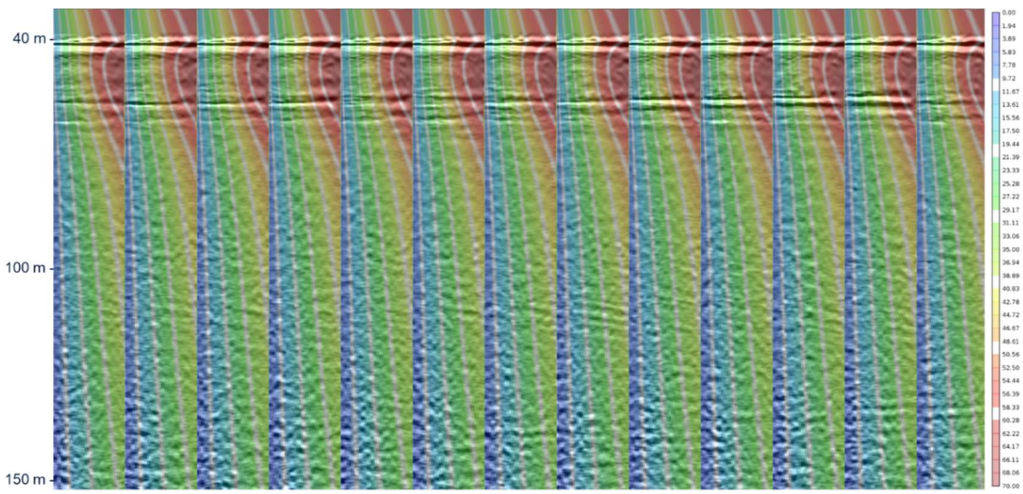

Figure 1 *Depth migrated CRP gathers with final velocity model. Angle of Incidence in degrees is overlay to the gathers.*

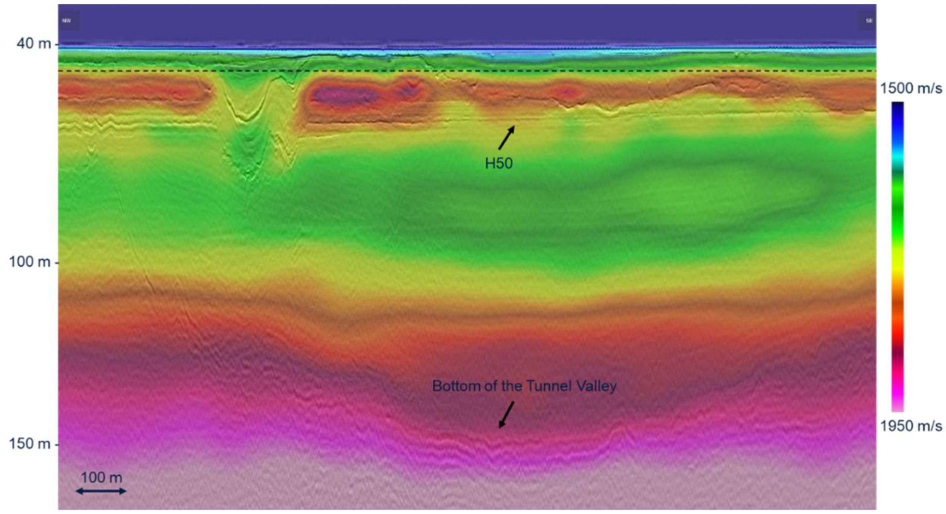

Figure 2 *Inline display of final interval velocity model overlayed to depth migrated full stack. The dotted line is representing the depth slice shown in on Figure 3*

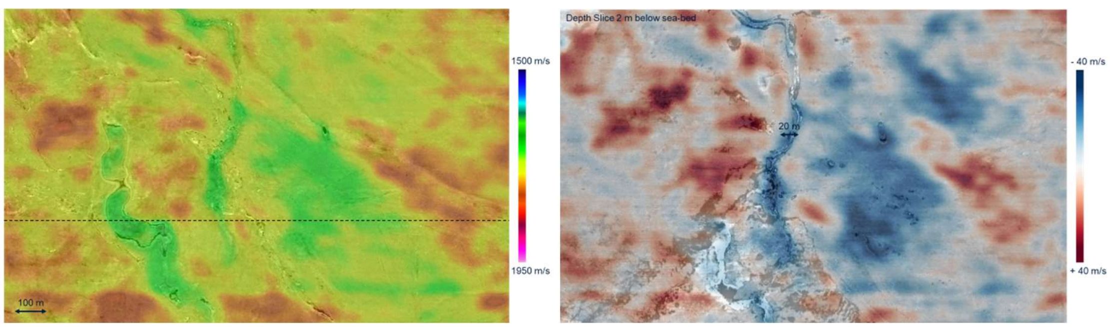

Figure 3 Left*: Depth slice 48 m (~ 6 m below sea bottom) of final interval velocity model overlayed to depth migrated full stack. The dotted line is representing the Inline shown in on Figure 2.* ***Right:*** *Depth slice 43 m (~ 2 m below sea bottom) of difference between input and final velocity model overlayed to depth migrated full stack. Very small channels of about 20 m wide are captured by the velocity*

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