High-Resolution Depth Velocity Modeling for Offshore Wind Farm Site Characterization

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Summary

The acquisition and processing of 3D Ultra High-Resolution Seismic (3D UHRS) data are crucial for detailed near-surface imaging, especially for wind farm site characterization. These surveys provide enhanced resolution of shallow subsurface features and are key to obtain a high-resolution velocity model in the overburden. Traditional velocity analysis often lacks the resolution required to obtain accurate geological layer properties for site characterization, such as compressional velocity (Vp).
This study introduces a novel application of depth velocity model building and imaging for site survey characterization. Tools from the oil and gas industry were adapted to process data with extremely high spatial and temporal resolution in unconsolidated geological settings. The proposed depth velocity model workflow produced a detailed model, resolving features as small as 20 meters laterally and a few meters vertically.
The methodology involved Kirchhoff Pre-Stack Depth Migration (KPSDM) and 3D depth reflection tomographic updates, with iterative velocity analysis performed in defined Model Building Units (MBUs). This approach allowed for accurate positioning of reflectors and captured critical subsurface details which can help deriving a more accurate ground model.

Introduction

The acquisition and processing of 3D Ultra High-Resolution Seismic (3D UHRS) data is increasingly utilized for detailed near-surface imaging in the context of wind farm site characterization. These surveys are designed to enhance the resolution of shallow subsurface features. They necessitate specialized processing workflows tailored to their unique data characteristics (Limonta et al., 2023). Customization is required not only for standard pre-processing steps such as denoising and demultiple but also for the crucial phase of Velocity Model Building (VMB). Traditionally, site survey characterization involves acquiring sparse 2D lines or small 3D volumes and conducting relatively simple velocity analysis using semblance-based picking. This approach primarily aims to flatten CMP gathers in the time domain and improve stacking response, typically yielding RMS velocities that offer a low-resolution approximation of subsurface velocity variations. Such analysis often lack detailed information such as true interval compressional velocity (Vp). The goal of seismic survey acquisition and processing extends beyond achieving a well-focused subsurface image for the extraction of key subsurface properties. Among these, Vp is particularly significant for quantitative interpretation (QI) and estimation of soil properties such as Uniaxial Compressive Strength (UCS) (Lindh and Lemenkova, 2022). This abstract explores the application of depth velocity model building and imaging in site survey characterization. We demonstrate that tools originally developed for the oil and gas industry can be adapted to process data with high spatial and temporal resolution in unconsolidated geological settings. The discussion focuses on Kirchhoff Pre-Stack Depth Migration (KPSDM) and 3D depth tomographic updates for data acquired using a 3D survey layout. Prior to presenting the results of depth velocity model building and imaging, we summarize the differences between migration techniques and the methodology used for velocity derivation.

Imaging and Velocity Model Building: Time vs. Depth

Kirchhoff migration is the most common technique for seismic imaging, performed either pre-stack or post-stack. This abstract focuses on the more advanced pre-stack migration, implemented in either the time domain (KPSTM) or depth domain (KPSDM). Seismic migrations aim at positioning subsurface reflectors at their true locations. The distinction between time and depth migration lies in the complexity of the velocity model and the accuracy of the output image. Time migration (KPSTM) assumes smoothly varying velocities and employs a 1D velocity approximation to calculate travel times. This method is effective for simple geological structures but cannot handle complex velocity variations, necessitating smoothed velocities to avoid artifacts. In contrast, depth migration (KPSDM) accounts for lateral and vertical velocity variations, requiring a detailed velocity model and corresponding 3D travel time computation. KPSDM provides more accurate imaging, making it essential for areas with larger velocity variations. 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 typically performed in the common mid-point (CMP) domain using semblance plots to flatten gathers, yielding a best-fit velocity parameter that is disconnected from true subsurface properties. In KPSDM, velocity analysis is iterative, performed in the common reflection point (CRP) domain by calculating depth differences (dZ) to refine the velocity model through tomographic updates. This process, executed in Model Building Units (MBUs), begins with the shallowest layers, with each iteration improving ray path accuracy and progressively refining deeper layers.

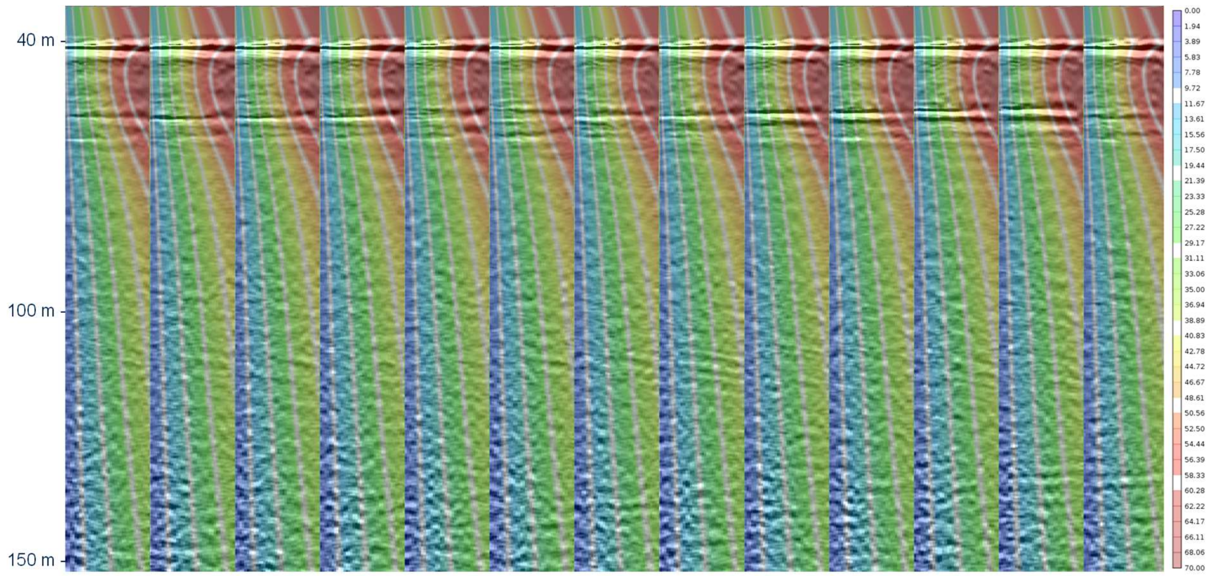

Figure 1 Depth migrated CRP gathers with final velocity model. Angle of Incidence in degrees is overlayed on the gathers

Depth Velocity Model Building

For this study, the 3D UHRS data were acquired with a nominal lateral resolution of 1.56 x 1.56 meters and vertical sampling of 0.25 milliseconds, yielding a Nyquist frequency of 2 kHz. The acquisition utilized wide-tow sparker sources (Widmaier et al., 2019) emitting energy starting from 150 Hz. The 150-meter streamer length ensured reflection angles of up to 35 degrees angle of incidence (AOI) were recorded for most of the trace length, down to approximately 90 meters below the seabed. While the maximum 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 meters grid with a vertical step of 25 centimeters and a maximum depth of 180 meters. Velocity analysis was performed by picking residual moveout every 4 CRP in inline and crossline directions. To minimize the influence of potential anisotropy, gathers were muted above 35 degrees. The VMB process was systematically divided into two Model Building Units (MBUs). The first MBU focused on the shallow section, ranging from 0 to approximately 20 meters below the seabed. This region includes the H50 horizon, as annotated in Figure 2, where numerous sediment-filled channels erode into a more consolidated geological layer. The velocity updates derived from this shallow section were subsequently used to re-migrate the data in depth, thereby improving ray tracing for the following iterations.

The second MBU concentrated on the deeper section, extending from approximately 20 to 140 meters below the seabed. This section encompasses the tunnel valley and its underlying layers, capturing the velocity variations within and at the base of the valley. By addressing these two distinct sections, the velocity model building process was able to account for significant lateral velocity variations within the

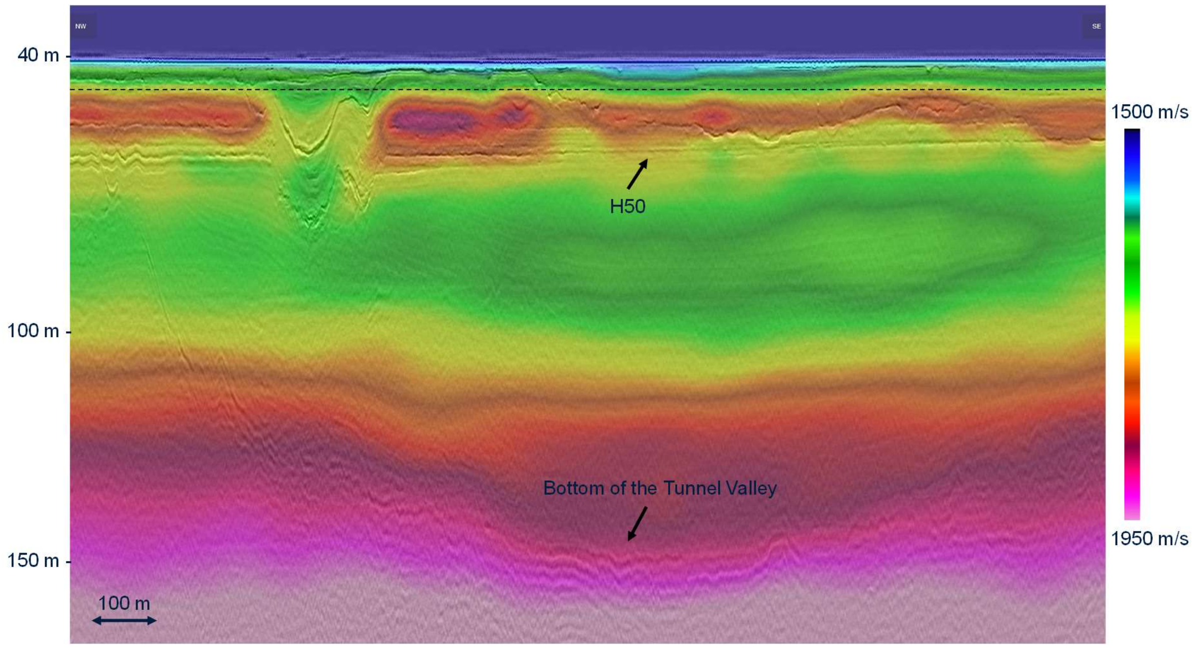

Figure 2 Inline display of final interval velocity model overlayed to depth migrated full stack. The dotted line is representing the depth slice shown in on Figure 3

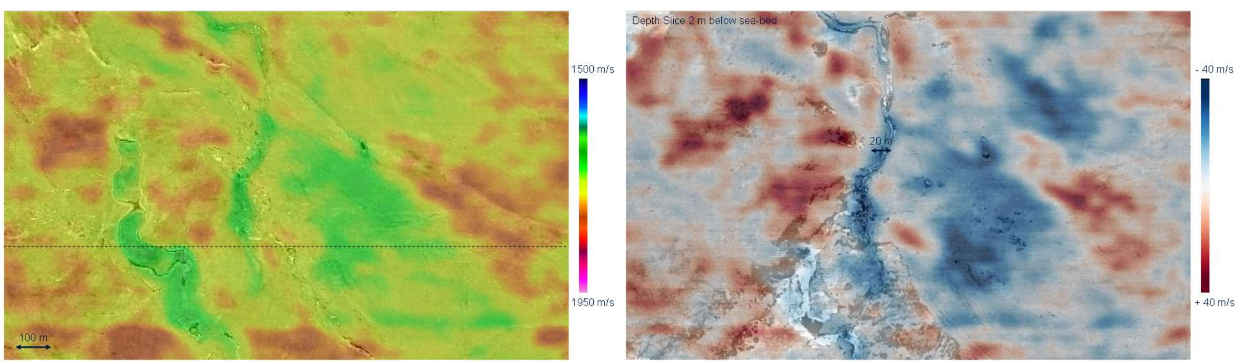

Figure 3 Left: Depth slice 48 m (~ 6 m below sea bottom) of final interval velocity model overlayed to depth migrated full stack. The dotted line is representing the Inline shown in Figure 2. **Right:** Depth slice 43 m (~ 2 m below sea bottom) of difference between input and final velocity model overlayed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

first 20 meters of the subsurface, as illustrated in Figures 2 and 3. Variations of up to 200 m/s were observed across the main channel, causing structural vertical 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 channels of various size, ranging from 20 to 200 meters wide. 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.

Conclusion

This study demonstrates the successful application of a depth velocity model building (VMB) workflow to 3D UHRS data, resulting in 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 critical subsurface details, including rapid velocity variations and geological features within the first 20 meters below the seabed, which are crucial for geotechnical design and site characterization.

Capturing this very shallow subsurface complexity plays a critical role in the subsequent quality and reliability of the imaging workflows, interpretation efforts and beyond.

An accurate velocity model is essential for supporting quantitative interpretation (QI). The interval compressional velocity field derived through this workflow provides indirect low-frequency information (below 10 Hz), which is not directly recorded in sparker data. This low-frequency content is vital for elastic or acoustic inversion, further enhancing the geophysical understanding of the subsurface.

These findings also pave the way for exploring 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.

This depth VMB study demonstrates that 3D UHRS data can provide a robust foundation for offshore wind farm development. The ability to accurately characterize the shallow subsurface ensures safer, more efficient foundation planning, contributing to the overall success of renewable energy projects.

Acknowledgements

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