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3D Ground Model Insights for Offshore Windfarm Development

High resolution (HR) towed streamer 3D seismic for oil and gas exploration is capable of efficiently yielding high-resolution near-surface imaging. Yet, much higher frequency shallow images are often sought by windfarm developers. After comparing the features of HR seismic, ultra-high resolution (UHR) seismic, and UHR acoustic profiling, I summarize the traditional approach when building windfarm ground models. Most workflows acquire a reconnaissance 2D grid of seismic / acoustic data, which is then crudely interpolated to build a reference 3D model, and then various geotechnical data are propagated into that 3D model. Bathymetric data are typically available as a 3D horizon for the seafloor and associated hazards, but the spatial uncertainty in soil properties and stability rapidly increases with increasing depth below the seafloor.

UHR 3D towed streamer seismic can provide remarkably accurate 3D subsurface insights with feature detection <0.5m, and both new acquisition of HR 3D multisensor seismic data and bespoke reprocessing of 3D multisensor seismic data can achieve near-surface image resolution of about 2-3m. I consider different strategies to combine the merits of both HR and UHR 3D towed streamer seismic when building regional ground models in an efficient manner and integrate contemporary views on the role of geosciences throughout the windfarm lifecycle.

Subsurface Insights from Offshore Oil and Gas Exploration to Offshore Windfarms

Terminology: HR versus UHR Seismic and Acoustic Profiling.

Many specialists have different definitions of what HR or UHR is, so **Table 1** defines the terminology used here (rather than the now-outdated ISO definitions). As also illustrated in **Figure 1**, a continuum of subsurface resolution exists from conventional towed streamer 2D / 3D seismic to acoustic profiling with hull mounted or AUV / USV devices. The most significant benefit of seismic methods is the subsurface imaging of geology from seafloor to many km of depth. In general, the kHz frequency source mechanisms used for acoustic profiling have negligible penetration below seafloor. Although the UHR P-Cable seismic solution typically uses sparker or boomer sources capable of emitting useful signal up to about 4 kHz (and recorded with appropriately short sample rate), subsurface features several hundred meters below seafloor will be imaged with peak frequency in the 300-500 Hz range because of natural attenuation effects. Conventional 2D / 3D and HR seismic uses 2 milliseconds sample rate during acquisition, which limits the maximum frequency to 250 Hz.

HR 3D Towed Streamer Developments.

The development of towed streamer 3D seismic acquisition in the 1980s realized a decades-old ambition to gain subsurface insights cost-effectively and rapidly for those exploring for oil and gas in offshore environments. The most notable technology advances from the early-1990s to the mid-2000s were the physical scale of the streamer dimensions being towed by a single vessel: up to 1.5 x 8 km, with best-practice spatial sampling in the common midpoint (CMP) domain of 12.5 x 6.25m (crossline x inline) being common for “High density 3D” (HD3D) surveys (refer also to **Figure 1**).

Multisensor streamers were introduced by PGS in 2007, enabling removal of free-surface “ghost” effects in processing, and broadband imaging in the range of 4-250 Hz where natural high-frequency attenuation effects by the Earth allow. The launch of the first of four Titan-class Ramform vessels in 2013 also enabled multisensor streamer spreads to become even larger for reconnaissance surveys (dimensions up to 1.8 x 10 km).

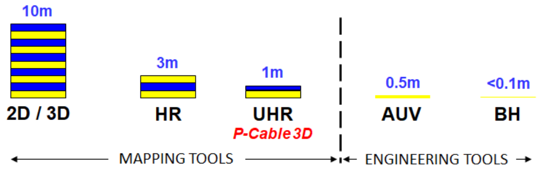
Abbreviation	**Features** 
2D / 3D	Exploration 3D seismic data 3 to 100 Hz images, 8 km+ insights below seafloor
HR	High resolution seismic 3 to 250 Hz images, 8 km+ insights below seafloor
UHR	Ultra-high resolution seismic 6* to 2 kHz images, 2 km+ insights below seafloor
USV (Unmanned surface vehicle) / AUV (Autonomous underwater vehicle: uncommon) / Tow Fish / Hull-mounted (most common) Platforms for Measurement	• Multibeam echosounder (MBES): up to 1 MHz, backscatter data may indicate seafloor lithology changes. • Sidescan sonar (SSS): up to 500 kHz, seafloor reflectivity / characterization and hazard identification of objects on the seafloor. • Sub-bottom profiler (SBP): up to 130 kHz, may have subsurface imaging insights of 10s of meters if seafloor properties are amenable.
BH	Borehole coring and sampling: Cone penetration testing (CPT) and box coring more common and less expensive in this setting

*Table 1: Terminology and comparative features of various seismic and acoustic profiling platforms. The cartoon represents the comparative vertical resolution of thin layers for each method. Refer also to Figure 1. *Low frequency cutoff depends upon source mechanism, recording filters, and source / streamer towing depths.*

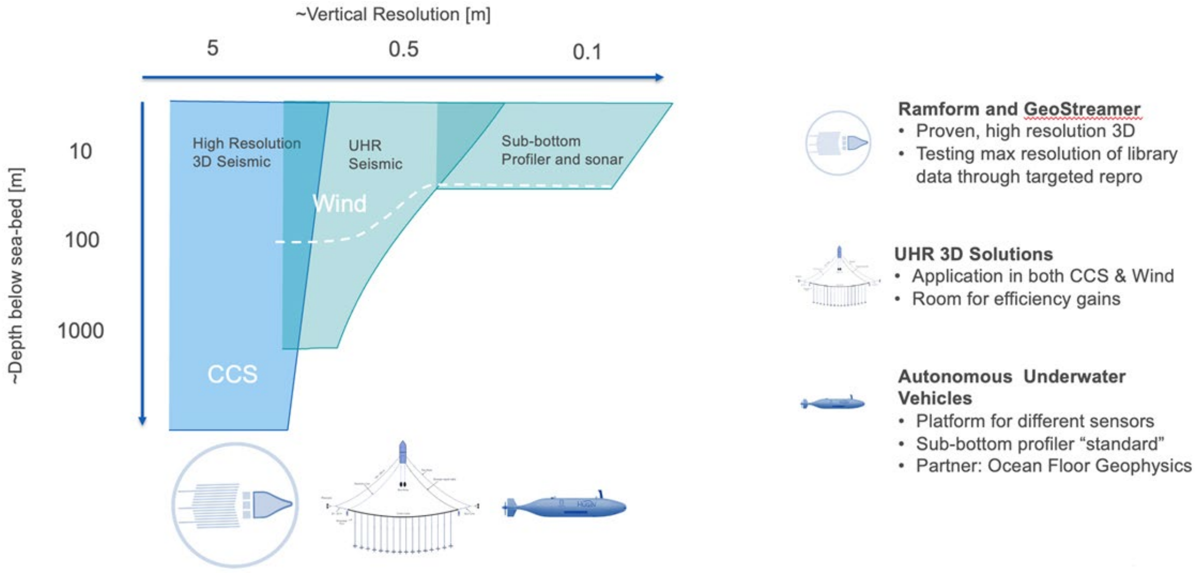


Figure 1: Continuum of resolution achievable from HR towed streamer seismic (applicable to all depths, subsurface images typically in the 0 to 250 Hz range) to UHR acoustic profiling (negligible subsurface insight, ultra-shallow images in the 0 to 1 MHz range). UHR seismic (i.e., P-Cable) extends HR seismic to UHR acoustics with subsurface insights up to a few km below seafloor and subsurface images typically in the 0 to 2 kHz range.

A focus on improved near-surface resolution, most notably in the Barents Sea, accelerated the use of wide-tow multi-source seismic as a component of highly efficient 3D surveys that commonly acquire more than 100 square kilometers of seismic data per day. Up to six sources can be towed from the streamer vessel, distributed laterally over several hundred meters as a strategy to greatly improve the near offset distribution critical to high-resolution near-surface imaging, and enabling best-practice spatial sampling in the CMP domain of about 5 x 6.25m (crossline x inline).

Figure 2 shows shallow depth slices of 410 and 468m depth, respectively, with no evidence of the traditional “crossline acquisition footprint” every few hundred meters at the boundary between each sail line of CMP coverage. Penta-source seismic used 78.75m lateral separation between each source (i.e., outer source separation of about 315m), and 16 long multisensor streamers were towed at 56.25m separation.

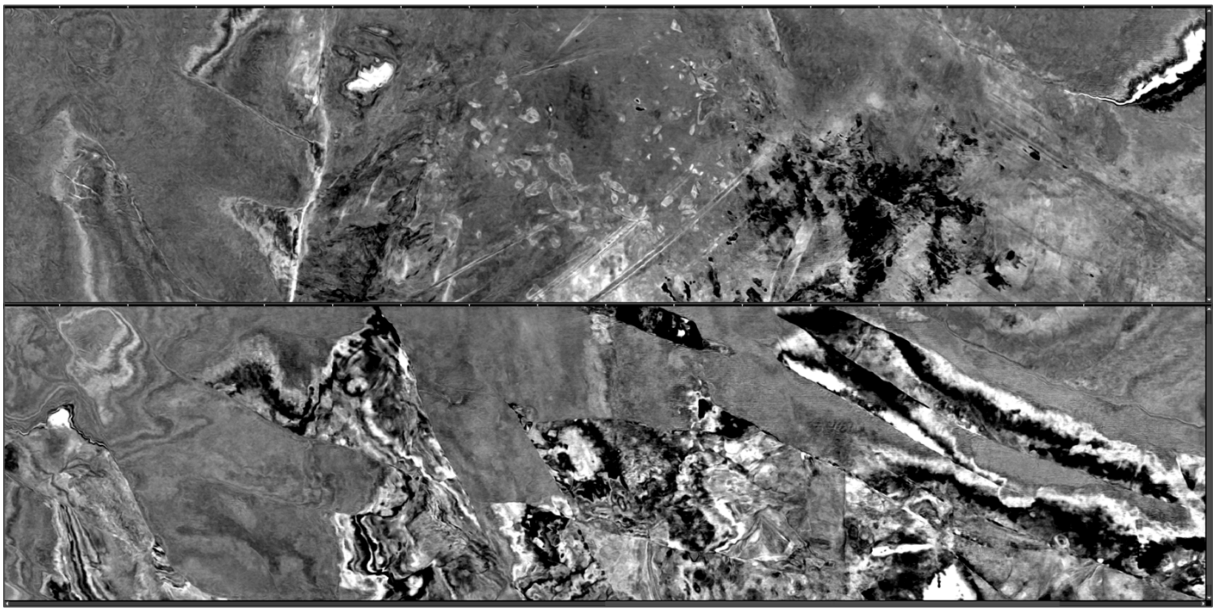


Figure 2: Depth slices at 410m and 468m below MSL in a location with 300-400m water depth, respectively, using CMP bin dimensions of 5.625 x 6.25m (crossline x inline). Image dimensions are 5.3 x 21.9km.

P-Cable UHR 3D Seismic.

UHR 3D towed streamer solutions are available that use sparker or boomer sources and temporal sampling rates of 0.125 to 0.25 milliseconds to record frequencies as high as 4 kHz. The P-Cable system, originally developed by Sverre Planke and Christian Berndt, tows short hydrophone-only streamers (typically 50-100m long) from a cross cable (**Figure 3**) with separation as small as 6.25m. Typical spatial sampling in the CMP domain is between 0.78 and 3.125m.

The P-Cable system is easily transportable, can be mobilized on a suitable vessel of opportunity, and run concurrently with other high-resolution systems (e.g., Multibeam, Sidescan Sonar, SBP, Camera, and Gradiometer/Magnetometer) to provide single pass acquisition of all geophysical data typically required to characterize a windfarm site. Refer also to the BOEM guidelines.

Very close (25m) vessel passes to infrastructure (platforms, wind turbines, etc.) are possible because the overall P-Cable streamer spread is narrow and the paravanes are close to the outermost streamers (refer to **Figure 3**). The compact configuration of trailing equipment is linked to a cross cable that maintains the streamer separation.

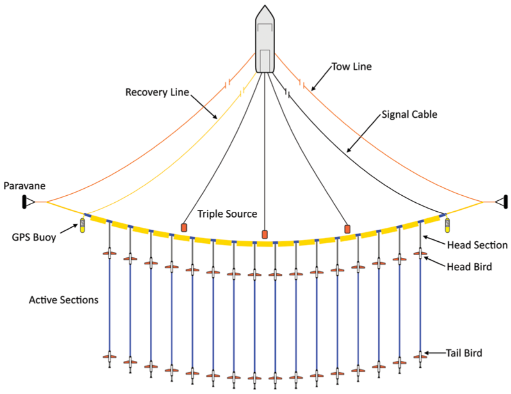


Figure 3: Schematic P-Cable configuration for UHD 3D seismic surveys. Refer also to Figure 5.

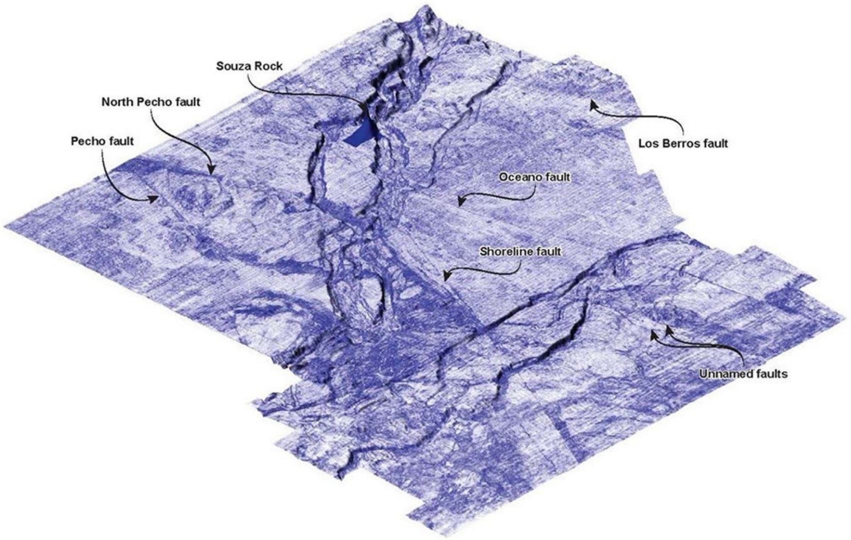


Figure 4: Extracted horizon image (i.e., intra-sedimentary) from a P-Cable UHR3D survey in San Luis Obispo Bay, California, used to assess fault slip rates just offshore from a nuclear power generation facility. The CMP bin size of 3.125 x 3.125m with a sampling interval of 0.25 milliseconds enabled vertical resolution on the order of 0.3m. Several previously unidentified faults were discovered in this well-established geohazard field due to the high resolution of the P-Cable data collected. Data courtesy PG&E.

By comparison to the dimensions of 3D streamer spreads used for oil and gas exploration, the dimensions of a P-Cable spread are small (**Figure 5**), and the daily acquisition rates are correspondingly much less. A pragmatic seismic acquisition strategy is proposed below to cost-effectively build 3D ground models for windfarm development that may cover several hundred square kilometers using a combination of HR and / or UHR seismic data.

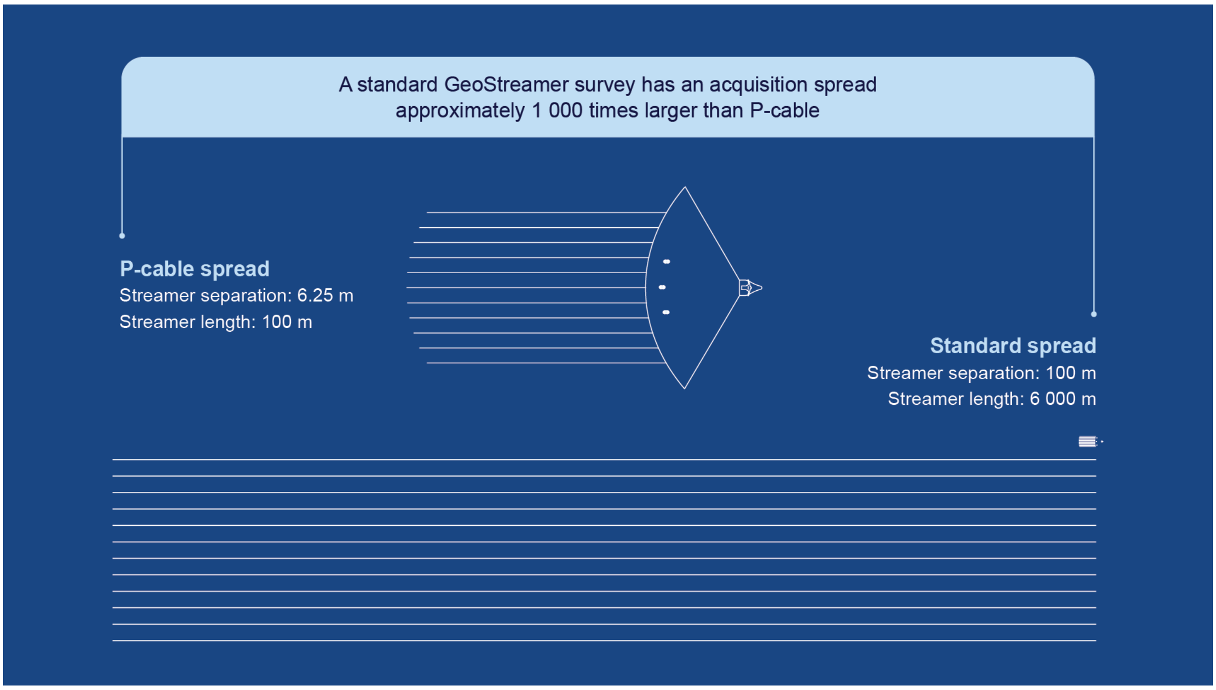


Figure 5: (upper) Example of a UHR 3D P-Cable spread configuration (wide-tow triple source, 11 x 100m streamers towed with 6.25 m streamer separation) recently used for windfarm site characterization; and (lower) shown to scale next to a typical 12 x 6km streamer spread with 100m streamer separation used for oil and gas exploration.

UHR Acoustic Profiling.

The development of offshore windfarms has traditionally only used 2D UHR acoustic profiling to understand the risks associated with ground conditions and associated hazards. Acoustic data has traditionally been acquired from specialist site survey vessels operating single and multi-beam echo-sounders, side scan sonars, sub-bottom profilers and magnetometers. This suite of hull-mounted or towed equipment is commonly known as 'analogue profiling'. USV (unmanned survey vehicles), AUV (autonomous underwater vehicles) and sometimes ROV (remotely operated vehicles) have increasingly also been used to acquire these datasets. Site survey vessels can also acquire 2D short offset multi-channel ultra-high-resolution (UHR) seismic and can carry light geotechnical spreads to ground truth / quantify seafloor and shallow soil properties.

Ground Model Development for Windfarm Planning: A Role for 3D Seismic?

The purpose of a ground model is to create a geophysical summary of the subsurface lithology, develop unitized geotechnical soil parameters, and demonstrate how the parameters change across a specific area of interest. Ground models are traditionally created from a continuous and iterative cycle of data collection, data interpretation, model updates, and revision of a living hazard register used to plan the next iteration until the project decommissioning stage.

Ideally, the useful imaging depths should delineate all relevant faults and fractures, gas pockets and variable pore pressure zones, stratigraphic complexity, and sedimentary compaction effects should be mappable to features extending several hundreds of meters below the seafloor:

- Continuous vertical and horizontal bathymetric resolution at decimeter scale: shallow sub-seafloor (0-5m depth of interest) for inter-array and export cable protection or burial depths.
- Continuous subsurface resolution at decimeter to one-meter vertical and horizontal scale for depths relevant to wind turbine foundations (as deep as 50-100m below seafloor)
  - Intermediate sub-seafloor (5-10m depth of interest) for anchoring and small structure foundations.
  - Deeper sub-seafloor: (10-100m depth of interest) for large structures (e.g., piled foundations).
- Continuous subsurface resolution at one-meter to five-meter vertical and horizontal scale for depths relevant to project lifecycle changes in site stability: 100-500m depth of interest.

The distribution, thickness, and geotechnical properties of soil units within the 'shallow' subsurface can laterally vary significantly over a few hundred meters (i.e., between each wind turbine foundation). Unfortunately, most acoustic site investigations involve the acquisition of a grid of 2D lines of acoustic and seismic profiling of the near-surface sediments, and only bathymetry and seafloor hazards are mapped in 3D. The placement of foundations along each 2D traverse may present an unacceptable engineering risk unless ground-truthed with geotechnical boreholes at every proposed turbine location. This very intensive expense is mandatory in some jurisdictions.

Spatial uncertainty and risk are therefore high in a ground model based on 2D traverses. Furthermore, conversion from two-way travel time to vertical units of depth are, at best, only valid along each 2D traverse (refer also to **Figure 6**), compromised by poor signal-to-noise ratio (SNR) of single-channel acoustic measurements, and typically recorded with very limited offset ranges.

The available geophysical data are used to spatially constrain geotechnical measurements; whether physical cores or the use of cone penetration testing (CPT) to test *in situ* soil strength at discrete locations, and CPT dissipation testing to monitor the dissipation of shallow pore pressure over the time interval where soil penetration is temporarily halted. CPT measurements include high-resolution vertically sampled cone-tip resistance (RES) and sleeve resistance (FRES) which are indicative of the soil properties like density, shear wave velocity, Young's modulus, soil stiffness, etc. Where appropriate offset (i.e., reflection angle) measurements are recorded, inversion of acoustic and elastic seismic attributes may be calibrated to Young's modulus and shear modulus estimates derived by CPT measurements for the derivation of synthetic CPTs at key locations.

A coarsely interpolated 3D depth model, built from 2D grids of acoustic and available seismic data is used in conjunction with available velocity data measured on core samples to spatially map (i.e., propagate) geotechnical data in 3D (CPT and associated RES and FRES data, and any information pertaining to soil stratification).

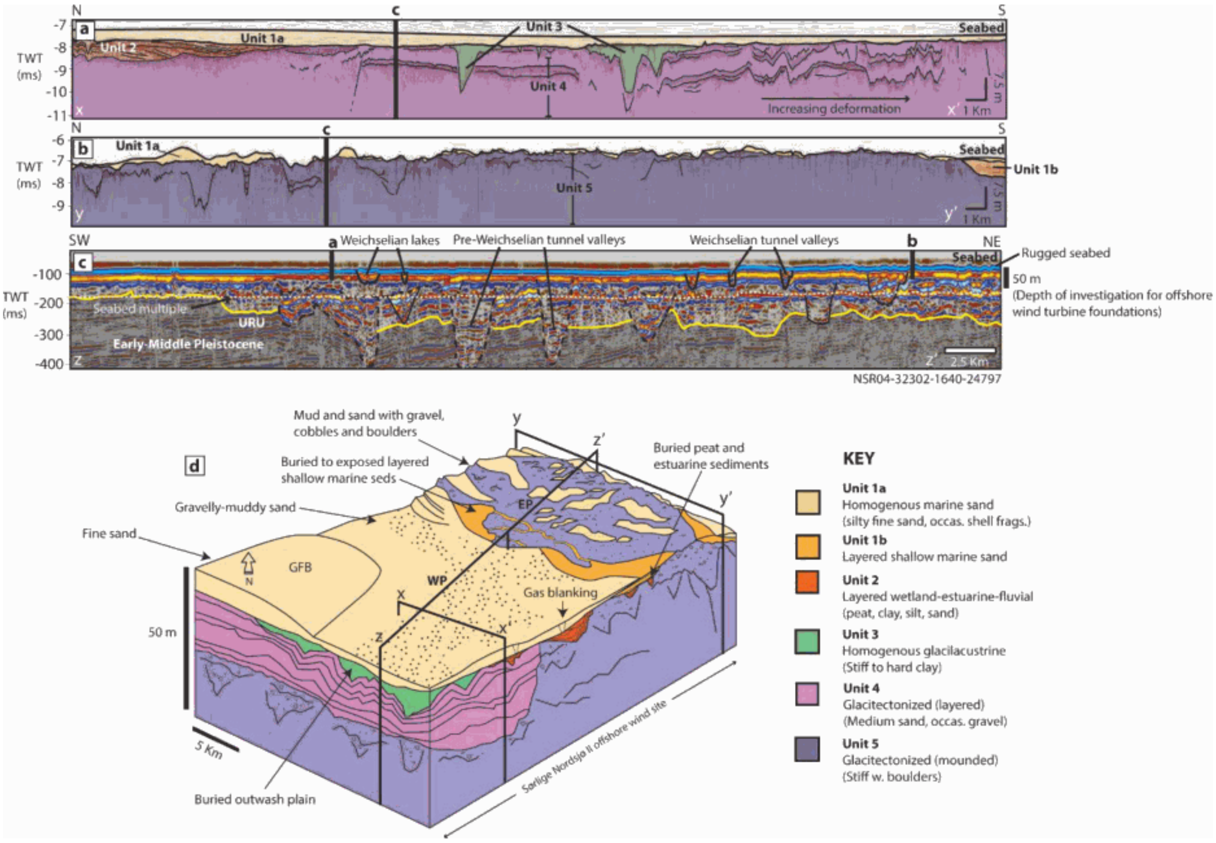


Figure 6: Example Sub-Bottom Profile (SBP) profiles (a: X-X') and (b: Y-Y'); a 2D Multi-Channel Seismic (MCS) line showing deeper stratigraphy (c: Z-Z'); and conceptual geological model showing key geological units from a study in the Norwegian North Sea (d). Most 3D model features are speculative and are interred from the sparse 2D SBP and MCS data rather than being interpolated or imaged with 3D seismic migration operators. Note the significant difference in vertical scale between the SBP (7-11 ms) and MCS (0-400 ms) sections. From Petrie et al. (2022), Figure 2.

Reasons to Consider UHR 3D Data

Subsurface insights from 3D (HR and UHR) seismic provide an understanding of the regional context of depositional systems and place all local features into an understandable context. Mapping of the 3D geomorphology of features commonly associated with turbine foundation risks (e.g., channel systems, vertical and lateral heterogeneity of tunnel valley systems, shallow subsurface boulders) is possible, as is delineation of faulting and pockmarks that affect seafloor bathymetry and stability). The geometry connecting deeper and shallow stratigraphy is clearly interpretable, and drilling and coring hazards related to gas chimneys and shallow gas accumulations (safety) are precisely represented.

A variety of interpretation methodologies have emerged to exploit the UHR frequency content and spatial sampling of P-Cable data. The full UHR 3D coverage afforded by P-Cable seismic data means that geophysical and geotechnical measurements would be coincident in space rather than being interpolated or extrapolated from 2D seismic profiles several hundreds of meters away, allowing better calibration and more robust quantitative interpretation of sub-surface properties between geotechnical sampling sites.

Approaches based on inversion and machine learning combined with diffraction imaging methods have proven to be especially valuable in settings with extensive paleo-glacial deposits and for precisely mapping the spatial distribution of near-surface boulders ("boulder mapping"). Such methods benefit from dense 3D sampling of scattered shallow seismic wavefields. Geotechnical campaigns can also be guided so that sampling is focused in areas where properties are likely to vary the most.

A challenge for future windfarm projects, is how contiguous 3D UHR seismic coverage can be cost-effectively acquired early during ground model development. This is like the challenges faced by the oil and gas industry three decades ago. If such data were available for windfarm developers, a large-scale 3D ground model would enable the estimation of subsurface attributes and the mapping of geophysical and geotechnical data with uniform resolution, risk, and confidence throughout the entire model dimensions. Economic issues are considered below.

Repurposing HD3D Seismic Data for Near Surface Ambitions.

Figure 7 shows the uplift in spatial and vertical resolution possible when multisensor streamer data is reprocessed using Separated Wavefield Imaging (SWIM). Surface multiple illumination in the near surface is substantially better than primary reflection illumination, but traditional seismic processing and imaging attempts to remove all multiple wavefield energy as early as possible. In contrast, SWIM is applied to shot gathers immediately after multisensor wavefield separation, thereby exploiting the full wavefield during a finite difference implementation of pre-stack depth migration (PSDM). Wide-tow multi-source seismic and SHAZ (shallow hazard) imaging is a natural fit.

Resolution and interpretability can be further enhanced through RGB blending of different frequency slices from spectral decomposition (**Figure 8**).

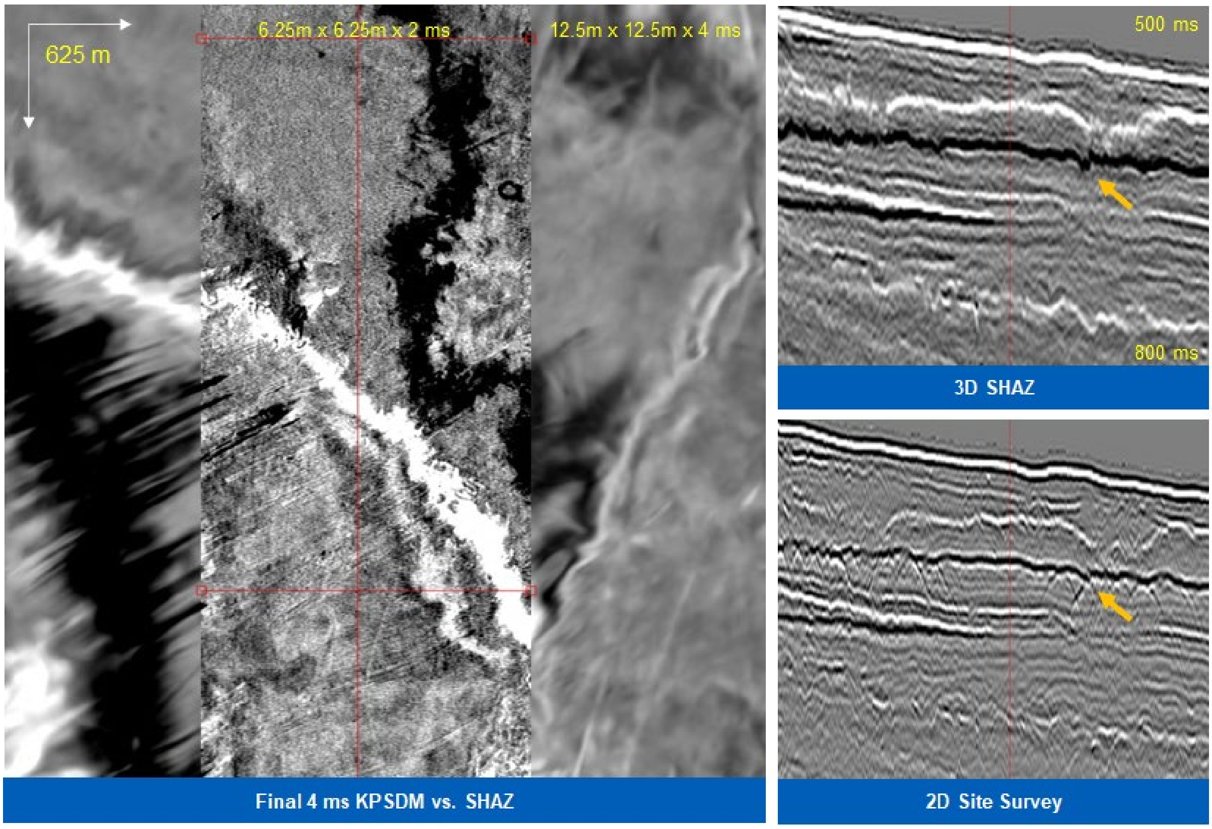


Figure 7: SWIM reprocessing superimposed on a 3D multisensor (GeoStreamer) dataset (left). The comparison of vertical sections on the right shows that a reprocessed SHAZ (shallow hazard) 3D seismic volume can meet or exceed the vertical and spatial resolution of traditional 2D site survey images, with the benefit of being 3D. Refer also to Figure 8.

The Economics of Windfarm Concessions: Building a Case for 3D HR and UHR Seismic

A policy by the International Energy Agency (IEA) describes the economics of windfarm ‘concessions’: Domestic and international companies are invited to bid for relatively large-scale potential projects (100-200MW). Successful bidders are selected according to the price per kWh of wind electricity proposed and the share of domestic components utilized in the windfarm. The wind concession lasts for 25 years, and the bid price is guaranteed as a feed-in tariff for the first 30,000 full load hours achieved (for a 100 MW project, this amounts to approximately 3

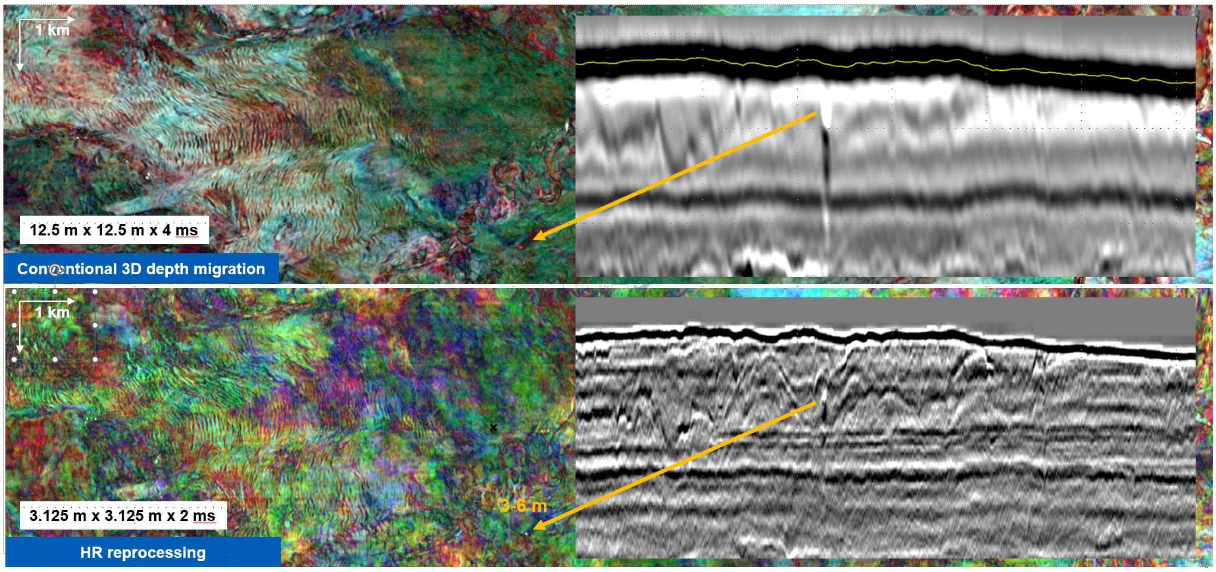


Figure 8: Legacy 3D seismic data with an extracted horizon from 30 ms below seafloor and displayed with RGB blending of different frequencies after spectral decomposition. The upper row is with traditional processing applied and the lower row is after HR reprocessing. Note the buried boulder is detectable as a localized discrete feature on the vertical HR image but is less resolved on the legacy image.

billion kWh). Depending on the site's wind resource, this could cover about 10-15 years. After 30,000 full load hours, the project owner will receive the average local feed-in-tariff on the power market at that time.

No two concessions will be identical so they should have individual plans. Any windfarm development will begin with a desktop study that collates and evaluates all information relevant to the project, allowing a cost-effective preliminary assessment to be made. An integrated assessment of engineering considerations will also be required.

Consistent with the seismic acquisition and reprocessing considerations introduced above, several cost considerations can correspondingly be factored into any desktop study used during windfarm planning. Examples can include the following:

- Is suitable 3D multisensor data available to reprocess into a useful HR interpretation product?
- Would a project scale 3D HR dataset mitigate known shallow structural and stratigraphic heterogeneities that present high risk to project planning?
- If new 3D HR seismic is recommended, is there any synergy with other stakeholder requirements (e.g., shallow oil and gas exploration or CCS) that could dilute the shared cost?
- Would reconnaissance acquisition in the first project year of 2D UHR seismic data be optimal in terms of the project timeline, license terms and survey logistics (vessel availability, environmental permitting, stakeholder consultations, weather windows, engineering flexibility, etc.)?
- Does the subsurface risk in the concession justify the acquisition of 3D UHR seismic data?

Overall, a holistic approach is proposed rather than being locked into a traditional lump-sum EPIC (engineering, procurement, installation, and commissioning) mindset.

An Efficient Hybrid HR-UHR Strategy for Building Regional Ground Models?

The following sections provide different strategies to incorporate HR or UHR 3D seismic data into windfarm planning; also summarized in **Table 2.**

Project-scale HR 3D acquisition: High-graded processing and imaging

Acquisition of new HR 3D seismic data over an entire windfarm project area with wide-tow multi-source seismic and densely towed multisensor streamers can yield a best-practice broadband 3D seismic dataset, including a high-resolution 3D velocity model, and the platform to pursue inversion of elastic seismic attributes for the estimation of geotechnical properties. If completed prior to any infrastructure development, the reference 3D data will be contiguous and unaffected by infrastucture holes. Spatial resolution of about 2m should be possible at the seafloor and the near surface with temporal frequencies up to 250Hz being possible with 2 ms sample rate in acquisition. If there are no ‘conventional’ oil and gas targets at larger depths, streamer lengths could be cost-effectively reduced to 2 or 3km to focus upon imaging the upper 1-2km of sediments, and acquisition of over 100 square kilometers of 3D data per day should be feasible in most settings. High-end near-surface imaging technologies such as SWIM (Separated Wavefield Imaging: refer also to **Figure 7**) can exploit the broadband multisensor data to yield high-resolution near-surface images and interpretation products for geohazard characterization. If additional offsets are required for high-end velocity model building solutions such as FWI (Full Waveform Inversion), one or two long “streamer tails” can be towed without compromising acquisition efficiency.

Where available, it may also be possible to re-process existing multisensor 3D seismic data for better near surface delineation, enhanced 3D velocity model building, and extended 3D coverage.

New or reprocessed 3D HR data may be integrated with any UHR data in various ways. UHR seismic data are deficient in low-frequency signal by comparison to HR multisensor data because hydrophone-only UHR streamers are affected by receiver ghost effects. Multisensor (GeoStreamer) data is rich in low-frequency signal and can be used to extend the frequency bandwidth of (blended) UHR seismic data, providing a better platform for the inversion of elastic seismic attributes. Spatially coincident HR seismic data with long offset information can facilitate high-resolution velocity model building with FWI, which in turn would benefit UHR processing. A regional high-resolution 3D velocity model would be significantly beneficial for aforementioned reasons.

Project-scale HR 3D Acquisition: Platform to Design Bespoke UHR 2D / 3D Acquisition.

A project-scale 3D HR seismic volume could be used to either directly plan wind turbine locations or plan cost-effective 2D / 3D UHR P-Cable surveys. These UHR P-Cable surveys may either be 2D grids or grids of 3D swaths (“Corridor 3D coverage” as in **Figure 9**). A swath is two or more adjacent sail lines of P-Cable data acquired with contiguous CMP coverage so that a 3D migration operator benefits from the availability of a crossline aperture. A 3D near-surface image will be available to delineate “out of the plane” features more accurately on 2D transects.

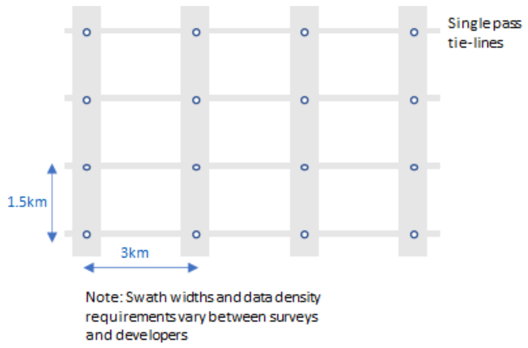


Figure 9: ‘Corridor 3D coverage’ of UHR 3D P-Cable data based upon anticipated wind turbine locations. Interpolation of geophysical and geotechnical data between each 3D swath will have significantly less risk if spatially coincident high-quality regional 3D seismic data is available.

Uniform 2D / 3D UHR Acquisition: Complemented Where Appropriate with 3D UHR Seismic Data.

Alternatively, UHR P-Cable data may be acquired in the traditional manner wherein a 2D grid of lines is acquired to intersect the nominal wind turbine locations, and additional P-Cable data (3D swaths or small 3D surveys) are added later in a piecemeal manner. As noted earlier, such an approach assumes that out-of-the-plane geobodies and spatial variations in soil properties can be robustly interpolated between (sparse) 2D lines and can be detected before unstable foundation issues arise.

Method	Comments
Project-scale HR 3D acquisition: High-graded processing or reprocessing	Uniform spatial subsurface acoustic and elastic insights throughout entire project area
Project-scale HR 3D acquisition: Platform to design bespoke UHR 2D / 3D acquisition	Informed planning and acquisition of UHR seismic to high-grade of HR seismic insights throughout entire project area
Uniform 2D / 3D UHR acquisition: Can be complemented with 3D UHR data	Lower cost UHR seismic acquisition with assumption to 3D spatial variations in subsurface properties are benign

Table 2: Options to use 3D HR and UHR seismic to augment ground models.

Integrated Strategies Over the Windfarm Lifecycle

A recent publication in Earth Science, Systems and Society examines the role of geosciences in addressing challenges to the integration of offshore wind into the natural environment and the wider energy system throughout the windfarm lifecycle.

The authors note in the section titled "Advanced Three Dimensional Geological Ground Models" that, "*We advocate the integration of geological and geotechnical approaches to develop three dimensional ground models that will permit bespoke design of turbine foundations. This is particularly important as future developments in offshore wind are focused on very large ("XXL") turbines (>8 m wide foundations). A site-specific approach is feasible because of the vertical resolution of the geophysical data. However, adoption of geophysical techniques in oil and gas industry could further reduce installation costs and decrease the risk of failure. The wider use of three-dimensional geophysical data collection, and use of high-resolution techniques such as three-dimensional Ultra-High Resolution (UHR) surveys and P-Cable, will provide high resolution and improved spatial control. Adoption of P-cable techniques could be particularly attractive to improve site lifecycle management because geophysical data can be (re)collected during windfarm operations, and thereby support decommissioning and repowering plans. A further innovation in future ground models will be development of dynamic bathymetry, and sediment mobility layers, to integrate the substrate architecture and erodibility with seabed hydrodynamics. Improved modelling of sediment suspension and scour would assist the modelling of habitat creation and modification provided by hard surface creation to increase seabed biodiversity*."

Collectively, there is considerable scope for a broader and holistic view of how to collaborate between the many relevant disciplines more effectively.

"*To integrate offshore wind into the environment in an efficient and sustainable way, geosciences are needed to provide spatial assessment of substrate heterogeneity, and to predict future changes in sediment mobility. Geoscientific understanding is a key component to the development of multi-functional systems and structures, such that marine space users, and uses, are combined to be synergistic and avoid conflict. Unlocking increased flexibility for the integration of offshore wind into the energy system and reducing issues of intermittency can be improved by commissioning more energy storage capacity using geo-assets, such as abandoned mine shafts or decommissioned oil and gas fields, which requires significant contribution from the geosciences. Furthermore, geosciences and geoscientists, are integral to the whole lifecycle management of offshore windfarms, from initial site evaluation, foundation, and layout design, through installation, and operations and maintenance, to lifetime extension, repowering and decommissioning strategies. Therefore, it is essential that the skills and training of geoscientists are focused on meeting these challenges*."

Summary

Cost-effective 3D seismic data acquired as a complement to other geophysical and geotechnical data can substantially improve the spatial understanding of soil properties for ground models. Ultra-high-resolution (UHR) 3D P-Cable data and innovative imaging / inversion / characterization solutions can detect and locate features smaller than 0.5m in the near surface, be used to calibrate soil properties derived from geotechnical data and extend the benefits traditionally derived from reconnaissance 2D acoustic profiling to unambiguous 3D ground models. 3D UHR insights can be extended to project scale at all relevant depths by first acquiring bespoke high-resolution (HR) 3D seismic data across the windfarm project area with a combination of wide-tow multi-source seismic and dense configurations of multicomponent streamers. Where HR imaging of such (regional) data requires higher resolution insights in specific locations, appropriate UHR data can be acquired where relevant.

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