Accelerated offshore wind site characterization enabled by integrated ultra-high resolution 3D geophysical and hydrographic surveys

Introduction

Before the construction of an offshore wind farm (OWF) geophysical and geotechnical site characterisation surveys are undertaken. One of the main aims of these surveys is to enable an integrated interpretation to characterise the structure and properties of key soil units, identify hazards and enable reliable and safe foundation or anchoring systems to be selected and designed appropriately. However, these geophysical & geotechnical site characterization surveys can take multiple years because of both structural and technical reasons. One reason is that prior to final investment decision project funding is limited & expenditure on site characterization must be carefully managed. A key technical reason is that geophysical data is required to both plan and derisk geotechnical surveys.

A sequential and iterative survey strategy is sub-optimal and ultimately unsustainable with the growing scale of offshore wind developments, ambition to develop projects rapidly, and need to reduce the levelized cost of energy. Also, many seismic surveys that are undertaken are 2D and multiple surveys may be undertaken with increasingly fine line spacing as the project progresses. Nevertheless, even after this kind of multiyear campaign there can be uncertainty about the spatial variability of key subsurface units and properties, as well as lack of flexibility in the placement of infrastructure such as wind turbine generators (WTG). Such uncertainties – and the need to mitigate risk – contribute to conservatism and over-engineering of structures such as WTG foundations e.g. using more steel than is necessary.

Moving from 2D to 3D seismic methods reduces subsurface risk and uncertainty but it must be both necessary and cost-effective (see e.g. Catterall et al. 2025). Using a case study from a recent project in Northern Europe we show that an integrated geophysical and hydrographic survey incorporating ultra high resolution (UHR) 3D seismic data – utilizing advanced processing and imaging methods - to characterize the seabed & shallow subsurface is a viable way to both optimize the OW site characterization process and reduce the overall duration & cost. This survey strategy will decrease the number of geophysical surveys undertaken, whilst honouring site complexity and subsurface heterogeneity across at spatial scales ranging from meters to hundreds of square kilometres (see McKay et al. 2025).

Typical survey objectives, geophysical methods and practicalities

Typical geophysical site characterization survey objectives are usefully understood with reference to the quantitative ground model (QGM) that is a part of the overall collation of all available site information; see for example OSIG (2022). There are three main components of the QGM: the overall *framework* that defines the major soil units of interest, the *properties* of each soil unit, and *hazards* such as subsurface boulders.

One common survey objective is to be able to detect and locate small hazardous objects such as seabed and subsurface boulders smaller than 1 m, whilst another is to define the main soil units that can include thin, dense, high strength soil units such as glacial tills. Both present a construction risk and affect the choice of foundation type which can adversely affect development costs. Given the typical areal extent is of order 100 km^2 and the depth of interest for an OWF is 100 m below the seabed, then these kinds of objectives highlight one of the challenges: cost-effective site characterization across large spatial scales whilst ensuring resolution at the sub-meter scale.

An integrated seismic survey for an OWF includes all geophysical measurements necessary to characterize the static properties of both the seabed and shallow subsurface, as well as provide data to identify cultural objects that may be hazardous (e.g. unexploded ordnance) and/or have cultural significance (e.g. shipwrecks). The geophysical sensors used, and purpose are outlined in *Table 1*.

Sensor	Purpose
Sparker Sources/ UHR Streamers	3D Imaging of the subsurface at meter/sub-meter scale
Multibeam echo sounder (MBES)	Bathymetric mapping of sea-bed depth, morphology & features
Side scan sonar (SSS)	Mapping of seabed objects & features
Sub bottom profiler (SBP)	Near-surface 2D imaging at sub-meter scale
Magnetometer (MAG)	Detection & mapping of ferrous objects

Table 1 *Geophysical and hydrographic sensors and an outline of the main purpose of each. Note that the spatial and temporal frequency also encompasses that of Extremely High-Resolution seismic data e.g. with sub- milli-second temporal sampling and sub-meter spatial resolution; see Hill et al. (2024).*

Case study: new insights from the seabed to subsurface

We outline a case example from a first of a kind project where an integrated hydrographic and geophysical survey incorporating UHR 3D seismic data was undertaken i.e. all geophysical sensors outlined in *Table 1* were acquired simultaneously in a single-pass fashion.

The 3D survey was designed to both map and image in detail the seabed and subsurface soil units in ultra-high resolution across the full site ~100 square kilometres i.e. to investigate all three aspects of the QGM outlined earlier. One of the key aims was to enable micro-siting of WTGs as the subsurface was known to be complex. The complexity and geological setting required the identification of subsurface boulders. Thus, the detailed nature of the survey included objectives such as identification of 30 cm objects on the seabed (e.g. using SSS) and small (~1-2 m) hazardous subsurface objects such as boulders.

Careful survey design and planning was required to ensure that both the technical and operational objectives could be met overall, as well as individually for each geophysical sensor. Our survey design incorporated the use of 10 UHR streamers, 130 m long, spaced 12.5 m apart and four wide-tow sparker sources. The group interval of each 48-channel streamer was 1.5625 m for the first 12 channels and 3.125 for the remaining 36 channels in the mid/tail streamer sections; the temporal sampling interval was 0.125 ms. The design enabled an efficient line-plan with the vessel sail-line spacing being 62.5 m whilst the 3D seismic imaging to be undertaken with a horizontal spacing of 1.5 m and vertical resolution of about 0.25 m. Efficiency and robust execution were key considerations to ensure that the survey duration was kept to a minimum especially given that for practical reasons (e.g. to minimize disruption to fishing activities) the survey was undertaken towards the end of the summer season i.e. early autumn.

The interpreted survey data deliverables have generated new insights for the project development team that are both important and valuable in terms of both foundation design and installation. Here we highlight two main examples to show the potential of this kind of integrated approach in terms of interpretation outcomes.

Example 1

The first example highlights a comprehensive use of the subsurface velocity model to investigate soil stiffness both qualitatively and quantitatively. This is not common in OWF site characterization. Usually, time-based seismic imaging methods are employed in OWF and whilst this often is sufficient from a structural imaging perspective the underlying velocity models are smooth and do not necessarily honour the interface between stratigraphic or geotechnical soil units. With more advanced depth-based imaging methods (see for example Limonta et al. 2025a) high-resolution velocity models that are conformal with geological structure and soil-units, and consistent with geotechnical parameters, can be derived. For example, Figure 1 shows an example from a depth-imaging workflow where the major change in subsurface velocity occurs at the sediment/bedrock interface. More subtle soil-property changes in the overlying sediment - that do not necessarily generate strong seismic reflections - are captured in some areas as subtle changes in velocity. These subtle changes correlate well with the limited geotechnical sampling that has been undertaken and are interpreted to be sediment stiffness variation in chaotic soft mud units affected by Neogene icesheets pushing, compressing and dewatering the sediments. Therefore, the seismic velocity itself may be used to map regions of stiffer sediments to delineate areas suitable for foundation installation. In addition, a well-estimated seismic velocity model is a key component in QGM construction as this provides crucial low-frequency control on the variability of soil-properties. As also shown in Figure 2 the small strain shear modulus - an important parameter in foundation design – that can be estimated from the seismic data and could be used to characterize the variability of this important geotechnical property within soil units across the site in 3D.

Case Example 2

The second example demonstrates that that even with an efficient 3D acquisition design then it is possible to detect small (~ 1-2 m) subsurface objects. For boulder detection the seismic data were imaged using a diffraction imaging workflow where diffractions are separated from the dominant reflection events pre-migration, and then the 3D diffraction data are migrated to locate the feature in 3D space that caused the diffraction (Limonta et al., 2025b). Figure 2 shows detection and delineation of potential boulders both within a soil-unit (blue arrow in Figure 2) and at the boundary of stratigraphic units defined by a strong reflection event that is effectively removed by the diffraction imaging process (yellow arrows in Figure 2). When investigated in detail we find the diffracted energy from these point-features to be largely confined to a single imaging bin after migration: we conclude therefore that the feature must have a spatial extent that is no greater than about 1.5 m. This is quite remarkable given the scale of the survey.

Conclusions

A single-pass integrated site survey incorporating full coverage UHR3D seismic data enables all soil units to be delineated, soil properties estimated & hazardous objects identified. Geotechnical surveys can be designed & optimized to investigate all soil units whilst the seismic data provides information about variability of soil properties within soil units of interest.

An integrated 3D survey acquired early in the site characterization process eliminates the need for multiple geophysical surveys - such as separate 2D seismic surveys with increasingly fine line-spacing - to move from reconnaissance to detailed surveys and thus can shorten the overall timeline for site characterization considerably. In addition, full site coverage in 3D, together with rapid turnaround of interpretative products, can enable geotechnical sampling and testing to be targeted and optimized.

A site characterization strategy that incorporates an integrated UHR3D survey should enable optimal investigation of OWF sites with a concomitant reduction of both time and cost.

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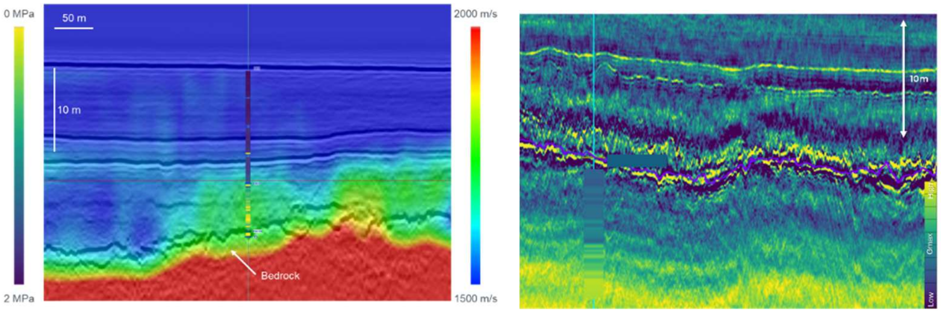

Figure 1 *Interval velocity model (Vp) after depth velocity model building together with overlain Cone Resistance from one CPT location (left); small strain shear modulus (Gmax) estimated from elastic inversion of the 3D UHR data with borehole Gmax shown on same color scale and range (right).*

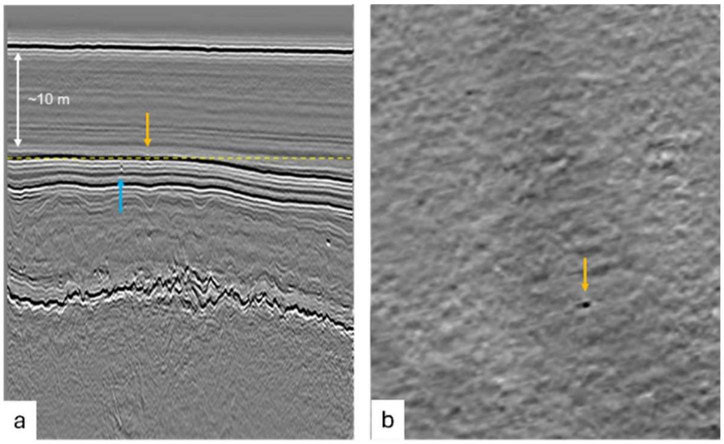

Figure 2 *3D UHR Inline full-stack section (a) and diffraction image time slices (b).*

References

Catterall, V., Arlott, L., Clarke, L., Cottee, J., Morris, J. [2025]. Drivers for acquiring 3D UHRS data across offshore windfarms. Proceedings of the 5th ISFOG 2025, ISBN 978-2-85782-758-0.

Hill, A.W., Nicol, G., and Cook, M.R. [2024] A proposed standard seismic frequency nomenclature for geophysical site investigation surveys in the offshore energy sector. First Break, **42**(11), 37-41

Limonta, L., Caselitz, B., Ruiz, R. and Kjølhamar, B. [2025a] 3D UHRS Depth Velocity Model Building for Offshore Wind Farm Site Characterization, 6th EAGE GET Conference

Limonta, L., Roche, C. and Kjølhamar, B. [2025b] 3D UHRS Diffraction Imaging for Point Contact Detection in Offshore Wind Site Surveys, 6th EAGE GET Conference

McKay, A., Limonta, L., Ruiz, R., Caselitz, B., Kjølhamar, B., Roche, C., O'Doherty, E., and Harrison, T. [2025] Accelerating offshore wind site characterization with integrated 3D UHR geophysical and hydrographic surveys. First Break, **43**(10), 63-69

OSIG Renewables Guidance Notes [2022] Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments. ISBN 0 906940 59 1

Ruiz, R. and Limonta, L. [2025] Pre-stack 3D Ultra High-Resolution Seismic inversion for shear modulus prediction. 6th EAGE GET Conference