Accelerating offshore wind site characterisation with integrated 3D UHR geophysical and hydrographic surveys

Allan McKay[1]*, Luca Limonta[1], Roberto Ruiz[1], Bertrand Caselitz[1], Bent Kjølhamar[1], Christine Roche[1], Enda O'Doherty[2] and Toby Harrison[3] outline how use of an integrated 3D survey is a viable way to both improve the offshore wind site characterisation process and reduce the overall duration and cost.

Introduction

Prior to the construction of an offshore wind farm (OWF) geophysical and geotechnical site characterisation surveys are undertaken. One of the main purposes is to enable an integrated interpretation to characterise the structure and properties of key soil units, identify hazards – be they of natural or cultural origin – and enable reliable and safe foundation or anchoring systems to be selected and designed appropriately.

However, these site characterisation surveys can take multiple years as a sequential and iterative site characterisation survey strategy is often employed because of both structural and technical reasons. One key structural reason is that prior to contract award and/or a final investment decision project funding is limited and expenditure on site characterisation must be carefully managed. So initial survey scopes are usually limited to reconnaissance. A key technical reason is that interpreted geophysical data is required to both plan and derisk geotechnical surveys and guide the foundation design, i.e. determine where the subsurface needs to be investigated to ensure all soil units are sufficiently well sampled and tested both to enable robust characterisation, and to ensure safety of e.g. geotechnical operations.

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 overall levelised cost of energy. In addition, many seismic surveys that are undertaken are 2D, and as the site characterisation phase progresses then multiple surveys may be undertaken with increasingly fine line spacing. Nevertheless, even after a multiyear campaign there can be both 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 – can contribute to conservatism and over-engineering of structures such as WTG foundations e.g. using more steel than is necessary. Clearly, conservatism in engineering design is a cost driver, and has led to the development of modern design methods that are tailored to the specific case of OW; see for example Zdravković et al. (2020). This kind of development of engineering design methods needs to be matched by geophysical methods.

Moving from 2D to 3D seismic methods reduces subsurface risk and uncertainty but it must be both necessary and cost-effective. The most obvious factor driving necessity is geological complexity, but it is by no means the only factor; see for example Caterall et al. (2025). In addition, prediction of geotechnical parameters (e.g. Klinkvort et al. 2024) and/or soil properties such as small strain shear modulus (e.g. Ruiz et al. 2025) using seismic data has progressed rapidly (see for example the review of Michel et al. 2025, and references therein). These kind of developments offer ways to ensure that the soil information in the seismic data is fully utilised, and to strike an optimal balance between e.g. soil properties inferred across the full subsurface volume of interest using seismic data and soil properties determined at discrete locations by geotechnical sampling and testing. However, most of this predictive work has been done using 2D seismic data that may not have been designed, acquired or processed with quantitative interpretation in mind. In addition, without 3D data methods to interpolate parameters and/or incorporate auxiliary parameters spatially such as geo-statistics and kriging must be employed. To realise the full potential 3D seismic data is necessary.

A key step in ensuring that geophysical surveys are cost effective was our development of an integrated geophysical and hydrographic survey incorporating 3D Ultra High Resolution (UHR) seismic data – using advanced processing and imaging methods – to characterise the seabed and shallow subsurface. This innovative survey approach was proven in a recent project in Northern Europe and is the subject of the brief case study described in this paper. A similar approach has been then employed on further projects. In addition, building on the idea that prediction of soil properties is key to enabling site characterisation survey activities to be optimised, we outline briefly examples that show progress. Finally, we will outline how use of an integrated 3D survey is a

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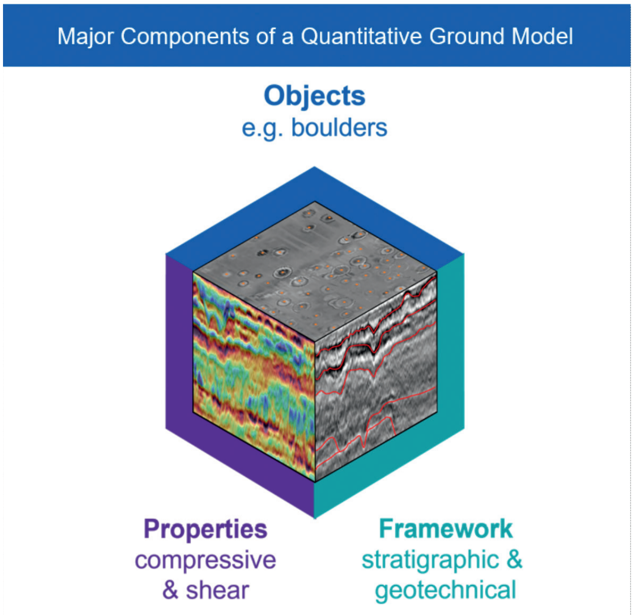

Figure 1 The three main components of a quantitative ground model.

viable way to both improve the OW site characterisation process and reduce the overall duration and cost.

Typical survey objectives, geophysical methods and practicalities

Typical geophysical site characterisation survey objectives are usefully discussed 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 major components of the QGM as shown in Figure 1: the overall framework that defines the major soil units of interest, the properties of each soil unit, and hazards such as subsurface boulders. The areal extent and depth of interest for a QGM for an industrial scale windfarm is of order 100 km^2 and 100 m below the seabed respectively. The scale highlights one of the challenges: cost-effective site characterisation across large spatial scales whilst ensuring resolution at the sub-metre scale. For example, in former glaciated margins 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. 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.

An integrated 3D UHR seismic survey includes all geophysical measurements necessary to characterise 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.

To ensure the survey is cost effective, and can be performed in a single-pass fashion where all data are acquired simultaneously, necessitates using a capable survey vessel that has sufficient space to accommodate all the required equipment and can remain at sea for extended periods of time without recovering all sensors during inevitable periods of poor weather, or for regular port-calls. A sketch of the sensors and how they can be deployed from the vessel is shown in Figure 2.

Careful line planning is needed as part of the survey design and planning process. Whilst the sub-bottom profiler and magnetometer are usually constrained to the vessel and side scan sonar tracks, complete seabed and subsurface data coverage over the defined survey area(s) is usually needed for 3DUHR, MBES and SSS. The swath coverage that can be achieved is constrained by both the survey area conditions (e.g. water depth and sea-conditions) as well as the survey goals (e.g. resolution requirements).

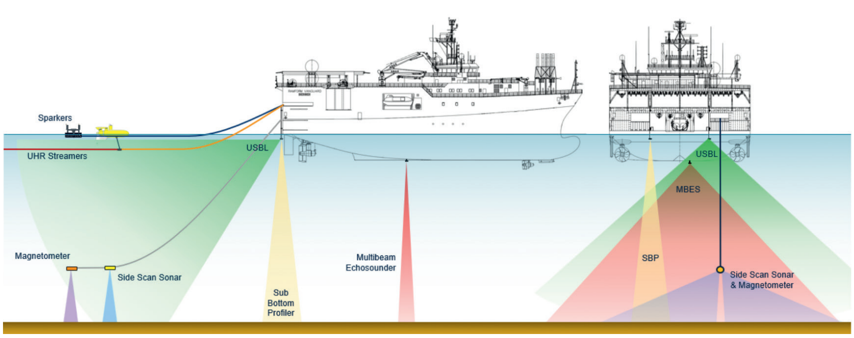

Figure 2 Sketch showing various geophysical sensor platforms deployed.

Sensor	Purpose
Sparker Sources/ UHR Streamers	3D Imaging of the subsurface at meter/sub-metre scale
Multibeam Echo Sounder (MBES)	Bathymetric mapping of sea-bed depth, morphology and features
Side Scan Sonar (SSS)	Mapping of seabed objects and features
Sub Bottom Profiler (SBP)	Near-surface 2D imaging at sub-meter scale
Magnetometer (MAG)	Detection and mapping of ferrous objects

Table 1 Geophysical and hydrographic sensors deployed in an integrated 3D UHR survey and outline of the main purpose of each. Note that the spatial and temporal frequency of UHR encompasses that of Extremely High-Resolution seismic data e.g. with temporal sampling rates of a fraction of milli-second and sub-metre spatial resolution; see Hill et al. (2024).

As outlined in Widmaier et al. 2023 utilisation of multiple wide-tow sources and streamers enables the sail-line efficiency, near-offset coverage, sampling and resolution of UHR 3D seismic acquisition to be optimised especially in the shallow waters (e.g. 15-60 m) typical for bottom fixed offshore wind. Furthermore, Caselitz et al. 2025 demonstrate that whilst the typical processing and imaging workflows are based on high resolution exploration and production 3D seismic methods, special attention to the processing of UHR data before migration and imaging is required to maximise bandwidth (e.g. with both inversion and machine learning-based de-ghosting methods) and to remove the effects of sea conditions as the 3D UHR sources and streamers are towed relatively shallow in the water column.

Case study

Here we outline a case example from a first of a kind project where an integrated hydrographic and geophysical survey incorporating 3D UHR seismic data was undertaken. To the best of our knowledge this was the first time that all geophysical sensors such as Multibeam Echo Sounder, Side Scan Sonar, Sub bottom Profiler and Magnetometer were acquired together with full-coverage 3D UHR seismic data in a single-pass fashion.

Survey objectives and design

The survey was designed to both map and image in detail the seabed and subsurface soil units in 3D UHR across the full site of approximately 100 km^2. One of the key aims was to enable micro-siting of WTGs as earlier studies and the geological setting indicated a complex subsurface. The complexity drove one of the technical objectives of being able to identify subsurface boulders that can damage piles during installation. Hence, all three aspects of the QGM outlined previously were being investigated.

Efficiency was a key consideration to ensure that the survey duration was kept to a minimum. In addition, for practical reasons (e.g. to minimise disruption to fishing activities) the survey was undertaken towards the end of the summer season. Therefore, an important consideration was ensuring that the line-plan and survey strategy was realistic and would not generate excessive data infill on a particular geophysical sensor thus compounding weather risk and increasing survey duration.

The detailed nature of the survey included objectives such as identification of 30 cm objects on the seabed and small hazardous subsurface objects such as boulders. In practice that meant that e.g. the vertical resolution of the UHR data needed to be less than 50 cm. Careful survey design and planning was required to ensure that both the technical and operational objectives could be met as a whole, 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 split between 1.5625 and 3.125 m across the first 12 and remaining 36 channels in the mid/tail streamer sections respectively; 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. In addition, to ensure that the line-plan could be satisfied two multi-beam sensors were installed to increase the bathymetric swath coverage. Deployment of a (nadir) gap-filling side scan sonar was evaluated but considered unnecessary, assuming the line-plan could be adhered to.

Rapid and prompt turnaround of survey deliverables was key. Given the scale of the survey and number of sensors deployed the data volumes were significant: several terabytes of raw data were generated each day. Therefore, high bandwidth satellite connectivity was used to ensure that the survey data could be supplied continuously to office-based staff to enable processing and interpretation to continue in parallel with data acquisition.

Survey execution

The survey started mobilisation in early September and completed towards the end of October. Despite being undertaken in early autumn and experiencing inevitable periods of poor weather the vessel remained on site during periods of weather standby with all survey equipment except the sparker sources deployed in safe standby mode e.g. streamers deployed deep. This enabled operations to begin quickly as the weather improved and was possible because the survey vessel was designed for long endurance surveys, as are the technical solutions designed and employed to enable safe standby mode.

As is to be expected in any first of a kind project there were challenges, with valuable learnings. Indeed, there were sleepless nights for all key personnel on the project team but close collaboration across the full project team – vessel and office-based staff - ensured that all remained focused on the desired outcome: a safe and successful survey. In line with the saying that 'the proof is in the eating of the pudding' the survey completed successfully with all key Health, Safety and Environmental performance indicators being met.

Data and results: new insights from the seabed to subsurface

Interpretation of the data is ongoing but there is no doubt that 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. In addition, the data offers new insights of wider project stakeholder and cultural interest such as added information about potential wrecks. Here we highlight three main examples, based on each element of the QGM introduced earlier, to show the potential of this kind of an integrated approach in terms of interpretation outcomes with a focus on the 3D UHR seismic data and the quantitative integration of geotechnical data.

The first example illustrates the potential of 3D UHR seismic data to go beyond structural imaging and map more detailed and subtle changes in soil properties such as soil-stiffness that are significant for both WTG foundation design and installation. One of the subsurface challenges is that reconnaissance geotechnical testing showed a marked stiffness change in chaotic glaciomarine/glaciolacustrine sediments overlying the bedrock. However, the spatial extent of the stiffness change is uncertain: it does not generate strong, spatially continuous and easily interpretable reflections. Nevertheless, having access to 3D UHR seismic data enables the extraction of many different seismic attributes across

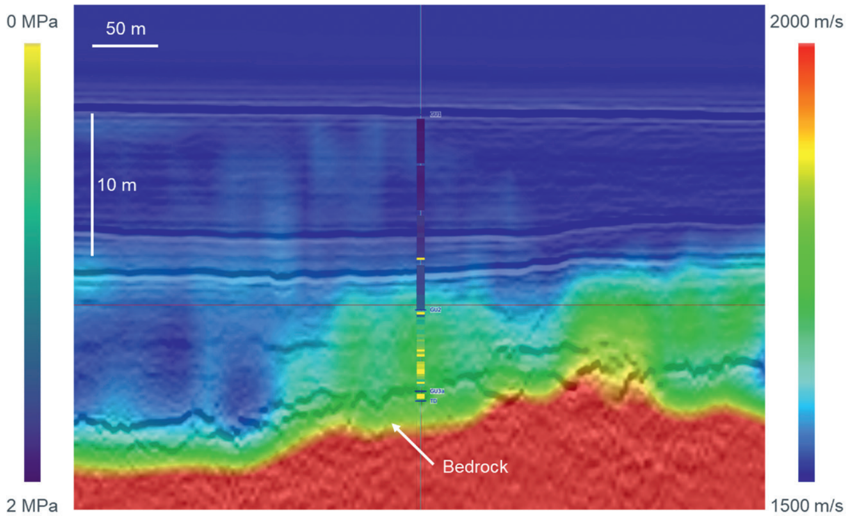

Figure 3 Final interval velocity (Vp) after depth VMB compared to cone resistance at one CPT location.

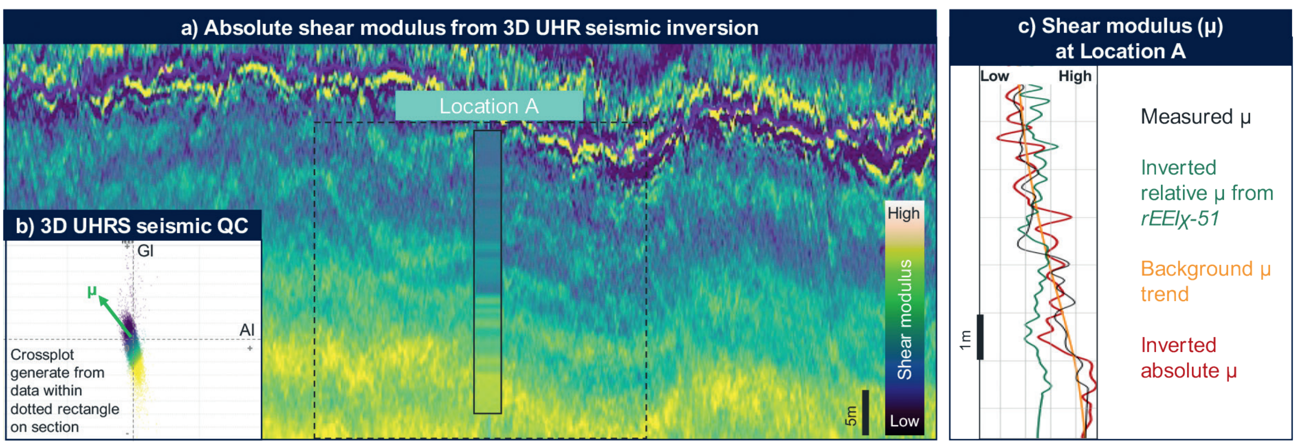

Figure 4 (a) absolute shear modulus line across location A, derived from seismic rEEIχ-51 and background model from seismic velocities; (b) seismic cross-plot in the AI-GI space coloured by rEEIχ-51; (c) match at geotechnical location A for inverted shear modulus.

the site, and changes in seismic velocity – a fundamental and key attribute of seismic imaging – appear to be correlated with the stiffness change. This correlation motivated further analysis.

Whilst time-based seismic imaging methods have mainly been employed in offshore wind, and are often sufficient from a structural imaging perspective to highlight major features of interest, the associated velocity models are smooth and do not necessarily honour the interface between soil units. With more advanced depth-based imaging methods, high-resolution velocity models that are conformal with geological structure and soil-units, and consistent with geotechnical parameters, can be derived. Figure 3 shows an example from a pre-stack Kirchoff based depth-imaging workflow where a tomographic velocity modelling approach was used; see Limonta et al. (2025a) for more details. The example shows that while a major change in subsurface velocity occurs at the sediment/bedrock interface more subtle soil-property changes in some areas in the overlying sediment - the chaotic units of interest – are captured as changes in velocity. These subtle changes in velocity clearly vary spatially and correlate well with an important change in soil-stiffness, as can be seen by the correspondence with the overlain CPT cone resistance in Figure 3: both are positively correlated.

The second example goes beyond observation of soil property changes via qualitative comparison of geophysical and geotechnical data and into the realm of quantitative soil property prediction. In Figure 4 we show the prediction of the small strain shear modulus that is a fundamental measure of a soil's stiffness. The prediction used pre-stack inversion of the 3D UHR data for Acoustic and Gradient Impedance as part of the relative Extended Elastic Impedance method (see Went 2025, and references therein). The low frequency model – to transform from relative to absolute quantities – was estimated using a parametric transform between compressional wave velocity and shear modulus derived from the limited set of geotechnical measurements available and applied to the seismic velocities. As shown in Figure 4 (C) the predicated and measured shear modulus at the geotechnical testing location match well, highlighting the robustness of the proposed workflow; see Ruiz et al. (2025) for more details.

The third example highlights the reduction of subsurface uncertainty because of access to multiple geophysical datasets and moving from only interpretation of 2D profiles to 3D data volumes. As noted earlier one of the key aims was to enable micro-siting of WTGs and this drove one of the aims of being

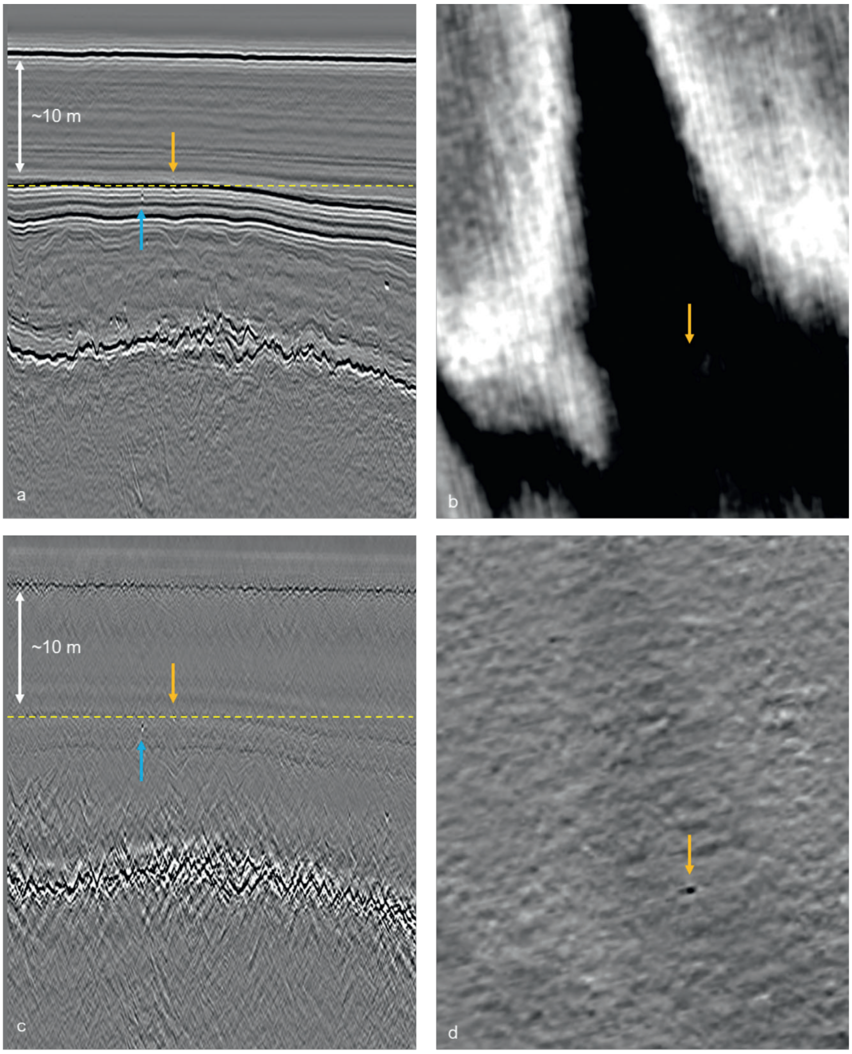

Figure 5 3D UHR Inline Section (a,c) and time slices (b,d). The top images show Full stack; the bottom images are the diffraction imaging volumes. Point contacts are shown by the arrows. Note how a potential point contact is obscured by a strong reflection event but is clearly observed in the diffraction volume.

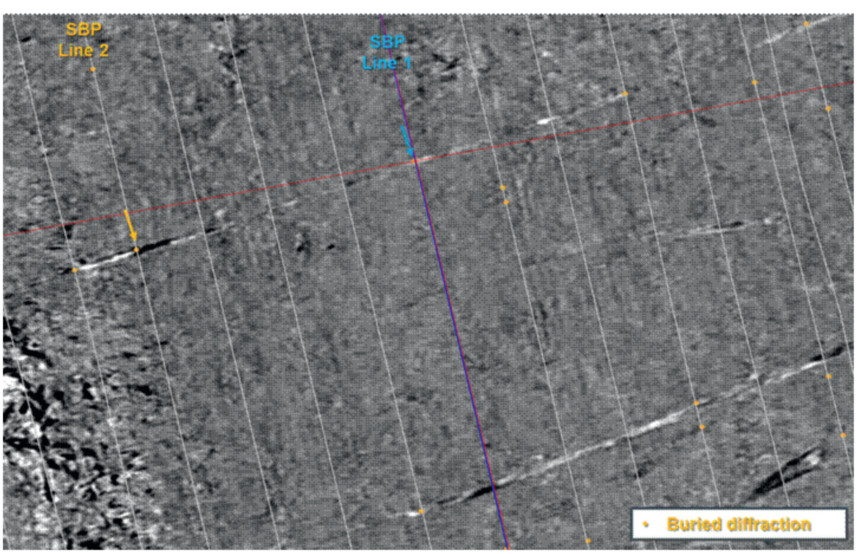

Figure 6 Time slice through the 3D UHR volume with 2D SBP lines (grey/purple lines) overlain. Orange dots show point contacts from only SBP interpretation: note how the orange dots correlate with the obvious linear features interpreted to be iceberg scour marks.

able to identify subsurface boulders. Despite the efficiency of the survey, it was possible to detect and isolate small subsurface features at depth. To do so, the 3D 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; see Figure 5 that shows detection and isolation of potential boulders about 1.5 m in size, and Limonta et al. (2025b) for more details. One of the key learnings is that while there are undoubtably subsurface boulders present

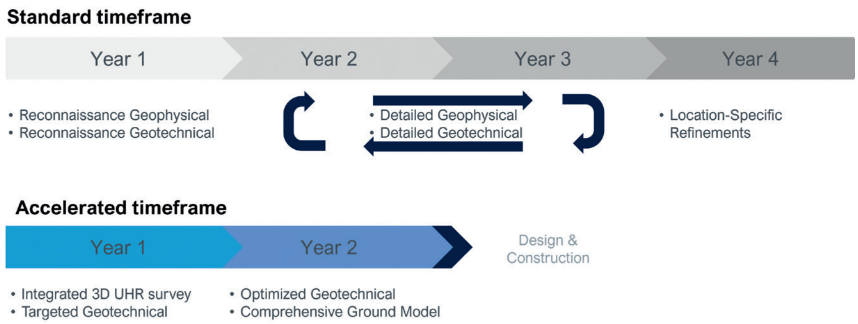

Figure 7 Time reduction potential for a survey strategy that utilises at its core an integrated 3D geophysical survey.

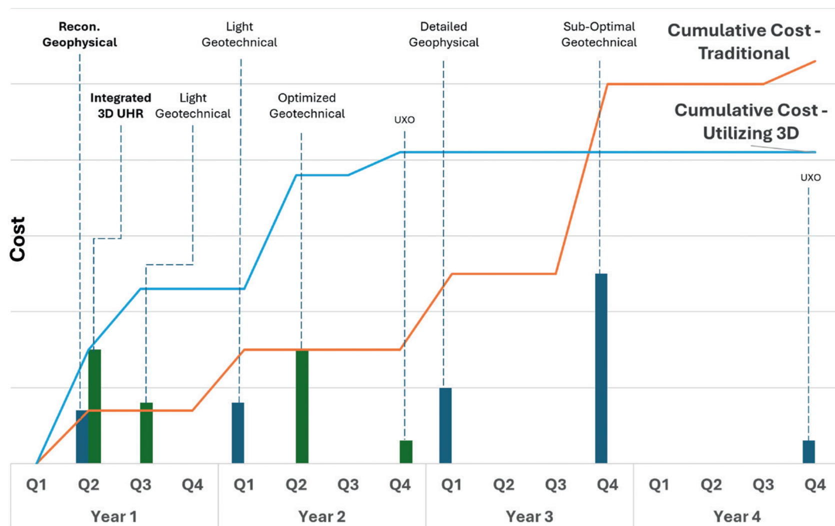

Figure 8 Cumulative cost reduction potential for a survey strategy that utilises at its core an integrated 3D UHR geophysical survey.

there are fewer than might have been expected had the sparse and limited insight from 2D data been all that is available to the team. As illustrated in Figure 6 numerous potential boulders were found initially via interpretation of the 2D SBP data. However, when the SBP data are interpreted together with the 3D UHR seismic data it is clear that the source of the majority of these anomalies is strong linear features that are interpreted to be iceberg plough marks created by icebergs scraping along the former muddy paleo seabed.

Time and cost savings with an integrated 3D UHR Survey

An integrated 3D survey acquired early in the site characterisation process negates the need for multiple geophysical surveys to move from reconnaissance to detailed surveys. Thus, as illustrated in Figure 7, adoption of an integrated 3D UHR survey from an early stage in the offshore site characterisation process can shorten the overall timeline for site characterisation considerably. In addition, by utilising high-bandwidth satellite connectivity relevant survey data can be supplied continuously to office-based staff to enable processing and interpretation to proceed in parallel with data acquisition. This shortens the time between data acquisition and interpretation and therefore the complementary geotechnical site characterisation survey can proceed concurrently, or back-to-back with the geophysical survey. In contrast, a traditional site characterisation survey strategy usually allows at least a few months to elapse between geophysical and geotechnical surveys, and this may mean that the geotechnical survey can only be executed the following year which is clearly inefficient.

There are numerous different ways that a time-reduction of site characterisation activities can translate to a reduction in the cumulative cost of the site characterisation work or be considered in terms of overall value to an offshore wind project (e.g. quicker route to electricity generation if site characterisation is on the critical path of the project). Ultimately analysis needs to be undertaken on project basis with a view of controlling factors and constraints, such as site complexity and the regulatory environment, to ensure it is robust. However, an illustrative comparison can be made if we consider the potential optimisation of geotechnical sampling and testing with a view to reducing the overall survey scope, even if the reduction in overall geophysical survey costs – due to fewer surveys being performed – are marginal. This has a clear cost impact for any project as geotechnical sampling and testing is necessary, and accounts for greater than half of the seabed and subsurface site characterisation budget; see for example the overview of windfarm costs in the UK compiled by BVG Associates (2025) on behalf of various UK governmental and trade bodies. Also, geotechnical survey activities could account for up to about 80% of the site characterisation cost if separate geophysical and hydrographic surveys are forgone. This kind of comparison is shown in Figure 8 and it is clear that while more may be spent in the earlier phase of site characterisation (see the cumulative costs in Year 1 on Figure 8) the overall cumulative cost could be lower with optimisation of the detailed geotechnical survey.

Summary and outlook

A single pass integrated geophysical and hydrographic site characterisation survey incorporating full coverage 3D UHR seismic data enables seabed and subsurface soil units to be delineated, soil properties estimated and hazardous objects identified. Incorporation of such an integrated 3D survey into the site characterisation survey strategy during the offshore wind project's development phase should at the very least enable a decrease in the number of geophysical surveys that need to be undertaken to characterise the static properties of a site. However, as the case example outlines, high quality UHR 3D data and a limited sample of geotechnical data enable key soil properties to be estimated. These kinds of methods will enable optimisation of geotechnical sampling and testing surveys, with the QGM being a key decision tool in this respect e.g. being used to help decide where sampling and testing could be done on a given site with a complete 3D view of subsurface soil unit and property variability. As outlined these efficiency gains could translate to a reduction of the cumulative cost of site characterisation even if the cost of an integrated 3D survey is greater than the cost of an early phase reconnaissance survey.

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