Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Drivers for acquiring 3D UHRS data across offshore wind farms

V. Catterall*
RWE Renewables, Swindon, UK

L. Arlott, J. Clarke, L. Cottee, J. Morris
RWE Renewables, Swindon, UK

**Vicky.catterall@rwe.com (corresponding author)*

ABSTRACT: Geophysical site surveys are often designed to determine ground risk and reduce uncertainty. However, ground risk is not the only factor to consider, and a wider understanding of other project risks is essential for efficient and cost effective survey selection and design.

Many factors need to be considered when making the decision to recommend the acquisition of 3D rather than 2D ultra-high resolution seismic (UHRS) data. Factors such as geohazard risk, engineering supply chains, permitting and consenting timelines and project financials all need to be considered on a project-by-project basis. In countries with well-established offshore wind industries risks associated with many of these factors are often either lower, or better understood. However, in countries with a nascent offshore wind industry, geophysical site survey strategies need to be planned to account for a whole range of possible future unknown events and minimise uncertainties across a range of factors. The acquisition of 3D UHRS surveys, both in established and newly emerging markets, can provide projects with greater flexibility for engineering decisions, it can reduce repeat surveying, reduce future costs and enable project timelines to be met.

This case study explores the decision to recommend the acquisition of 3D UHRS data across several offshore wind farms with a variety of survey plans finally agreed upon and the factors leading to the decisions are discussed.

Keywords: 3D UHRS; geohazards; risk; timeline;

1 INTRODUCTION

Offshore wind developers require seismic data to support infrastructure design and to de-risk installation. Ultra-High Resolution 3-dimensional seismic (3D UHRS) data is growing in popularity for offshore wind projects. In 2023-24, RWE Renewables acquired four 3D UHRS surveys, a record high for the company. The drivers for 3D UHRS data acquisition within RWE Renewables are explored in this paper.

3D UHRS removes the problem of having to interpolate geological features over gaps between 2D lines and allows investigation from all angles, bringing higher resolution to the interpretation of the subsurface and improving confidence in the ground model.

Despite the benefits inherent in acquiring 3D UHRS data, 2D serves an important purpose and is still widely used at RWE and across the industry. Initial reconnaissance 2D UHRS surveys are looked upon favourably by projects as they reduce initial survey costs and can be more widely available, particularly in some emerging markets. Several 2D UHRS survey campaigns are, however, often needed when the subsurface is more complicated than originally thought, or when infrastructure locations (known as layout) change or contractors request extra data during the construction phase.

On sites with complex ground conditions, it is best practice to increase the number of 2D UHRS lines to detect small scale geological features with significant soil properties or geohazard potential (e.g. OSIG Renewables guidance 2022, BOEM CFR Part 585, DNV-ST-0126). 2D lines, acquired in one survey or over multiple survey campaigns, can end up being spaced every ~100 m or more, and require orthogonal "crosslines" or "tie-lines" to support seismic interpretation. Those initial low site survey costs, can mount up through the full life cycle of a project. A one-hit 3D UHRS survey is therefore an appealing option to reduce multiple rounds of permit applications, decrease health and safety risk from multiple offshore site surveys, greatly reduce subsurface geo-risk and reduce site investigation cost throughout a full project life cycle. In addition, 3D UHRS can be an essential way to reduce the overall site characterisation timeline, which can be critical path to some projects.

If the only factor controlling the decision of 2D vs. 3D UHRS is ground conditions and these are known to be relatively benign, a 2D UHRS option is acceptable.

However, widely spaced 2D seismic lines can still miss important smaller-scale geological features. These subsurface geological features such as paleochannels, faults, concentrations of boulders, peat beds, shallow gas and glacial eskers can be smaller than the distance between 2D seismic lines (at 100-200 m line spacing, for example) and even if these features are identified, they may be difficult to accurately resolve or delineate based on 2D lines alone. Even with 3D seismic data, several authors have shown that only the higher resolution 3D options (~3-10m horizontal bin sizes , ISO 19901-10) can fully resolve important geological features, such as a 70m wide glacial gas-filled esker (Kirkham et al., 2021), polygonal faults or iceberg plough marks (Lebedeva-Ivanova et al., 2018) and hence, the need for 3D UHRS acquisition systems and processing workflows. 3D UHRS surveys are now commonly acquired with multiple sources, commonly Sparkers, multiple streamers, and positioning equipment suitable to generate data with horizontal resolutions on the 0.5 to 1m-scale (Duarte et al., 2017).

The focus of this paper is to explore the drivers for the four 3D UHRS surveys acquired by RWE in 2023-24. The drivers differed from project-to-project and range from: (1) technical, such as identification and resolute characterisation of geohazards and soils heterogeneity, (2) permitting timelines and, (3) supply chains which can change layouts. The 3D UHRS surveys covered three different designs: full lease area, wind turbine generator (WTG) corridors or WTG-specific.

2 DRIVERS FOR THE SELECTION OF 3D UHRS DATA

2.1 Technical Considerations: Geohazards and Geological Variability

Geohazards and geological variability can severely impact project costs, infrastructure design, schedules, construction and installation, health and safety risk, and generate environmental complications. In the history of construction projects worldwide, there are numerous examples where unforeseen ground conditions have led to increases in overall project costs and indeed, in some cases, ultimately constructability (SUT, 2022).

Many different types of geohazards can exist in the marine environment (e.g. IOGP, 2011). The manageability of the risk associated with geohazards is dependent on the ease of avoidance or amount of engineering effort that may be required to mitigate the hazards presence (Hill et al., 2013). Risk matrices and pentagons are useful ways to follow the reduction of risk as different mitigations are taken (e.g. Figure 1).

Recommendations for improvements in the geological, geophysical and geotechnical databases are given to projects to mitigate different risks (e.g. Figure 1). Through the life cycle of offshore wind projects, geophysical data with improved spatial and temporal resolution decreases risk, however, the emergence of different geohazards and an evolving understanding of their impact on engineering design or installation can cause modifications to the linear path of data collection.

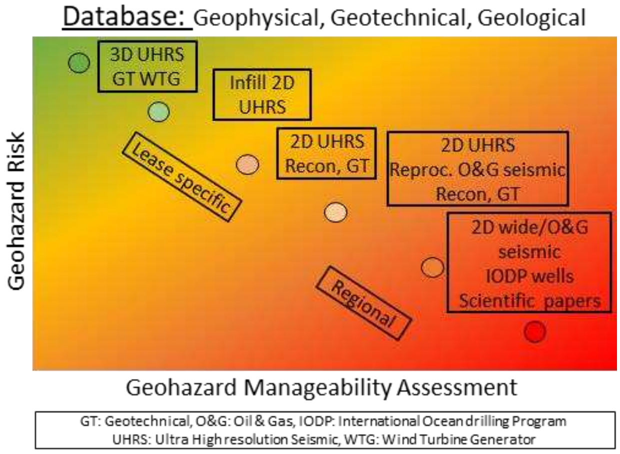

Figure 1. Geohazard risk matrix. Improvements in database (vertical resolution, coverage and type) to mitigate risk.

While 2D UHRS can help de-risk some geohazards there are a sub-set of subsurface geohazards for which 2D UHRS data is not an adequate mitigation. One of the challenges with using 2D UHRS data is that it is not spatially accurate due to “out-of-plane” effects. An acoustic signal (e.g. from a Sparker), as it travels through the water column and through the subsurface, propagates and expands. When a geological boundary comes into contact with that signal the wave front will reflect (assuming high enough acoustic impedance contrast), generating a reflection from any point along that wave front. Therefore, the wave front is potentially reflecting energy back to the receiver from a geological feature several metres away from the planned location of the 2D seismic line (out-of-plane energy). In essence, what you see on the 2D line can be a feature located many metres away from where the line was acquired. This is very problematic for localised and/or small geohazards like pockets of shallow gas, faults and subsurface boulders. Based on the spreading-out of the seismic energy (Fresnel zone) the geohazards can be ~5m away from the 2D line (@40m water depth, within top ~40-60 m of seabed), which can be approximately half the diameter of a typical monopile foundation. 2D UHRS data will not reduce uncertainty on the lateral and vertical location of small geohazards (e.g. boulders), and micro siting distance will need to be greater to accommodate this.

Micrositing may reduce wind yield, negatively impacting project economics. In addition, additional location-specific geotechnical data will be required where soil properties are expected to be highly variable over a short distance potentially resulting in programme delay or an acceptance of a greater level of geotechnical risk.

3D UHRS data allows better positioning relative to 2D and better resolution (not only detection) of small-scale geological features since the geometry of 3D surveys allow reflections to be imaged in a more accurate spatial position, minimising "out-of-plane" effects. The positional accuracy of the 3D UHRS data is then driven by the precision of the navigational data, the bin spacing of the processed data and the wavelength of the source signal (related to velocity and source frequency) (Lebedeva-Ivanova et al., 2018). In the case of such small geohazards, true horizontal resolution, i.e. the minimum distance between two objects before their individual identities are lost (Sheriff, 1991) is needed in the sub-metre scale so that boulders can be accurately positioned and dimensioned. With common 3D UHRS surveys, data can now be acquired to provide navigational accuracies as good as ~ 0.7-1m and horizontal resolutions of discrete targets in 1 to 2m ranges (migrated data). With boulders as small as 25.6 cm ("Udden-Wentworth scale" from Udden, 1914, Wentworth, 1992), (or 20cm, BS5930:1999) imaged by seismic data in the 1-2m horizontal resolution range, individual boulders are less than the minimum horizontal resolution achievable with migrated 3D UHRS, and therefore discrete objects are likely boulder clusters or larger boulders. With a cluster of boulder-sized objects in the subsurface there is potential for buckling or pile-tip refusal leading to the loss of a very expensive foundation as well as preventing jacking of installation vessels.

2.1.1 Example Project A

Project A is in construction planning phase and has four main subsurface geohazard risks; peat, boulders, faults and shallow gas (Figure 2). 2D UHRS data was inherited in the early stages of this project and acquired with a relatively sparse line spacing of >200 m. Even with this line spacing, potential occurrences of peat, shallow gas and faults could be interpreted with an acceptable level of confidence and avoided either in the original layout or via micro siting following seismic re-processing to uplift data quality.

However, quantifying and mitigating risk due to subsurface boulders was more challenging. Seabed data at the site showed numerous seabed boulders that correlated with outcrop/sub-crop of deeper glacial units. Conversely, subsurface diffraction picks targeted towards identifying boulders were fewer than expected, potentially due to attenuation of seismic energy in complex glacial units.

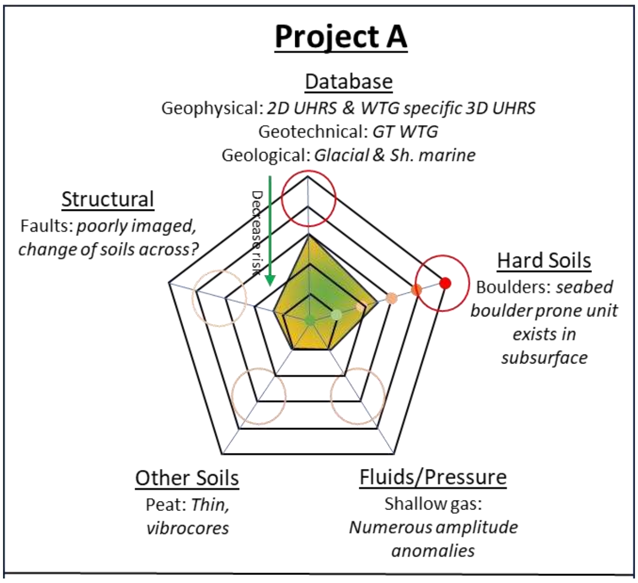

Figure 2. Risk pentagon (top) for project A. Geohazards were a key factor driving recommendation for 3D UHRS (circles). Once 3D UHRS is collected, risk decreases for all hazards (shaded area).

Given, the high boulder risk indicated by seabed data and the lack of information between 2D UHRS lines, it was decided to acquire WTG specific 3D UHRS to mitigate the risk. 3D UHRS data would have the additional advantage of addressing limitations of 2D UHRS data in both accurately positioning and sizing subsurface targets. Figure 2 presents how upgrading from widely spaced 2D UHRS to 3D data helps reducing project risk for the main geohazards but also impacts cost and timeline. In the case of project A, these were managed by acquiring mini 3D cubes of data (400m wide to cover micrositing and installation) at targeted WTG locations based on geological context to de-risk pile refusal and/or buckling as well as installation risk.

2.1.2 Example Project B

Project B is in an early-phase of development. Multiple WTG layouts and foundation options are possible, and there is limited legacy geotechnical data to characterise the subsurface. From existing reconnaissance scale 2D UHRS and onshore outcrops of equivalent units, the subsurface geology within the array area is interpreted as the result of sub-glacial deposition and deformation and post-depositional modification, followed by ice proximal and shallow marine deposition. Geohazards for installation are numerous and include high strength over-consolidated soils, thick gravel layers and boulders, high lateral and vertical heterogeneity, and shallow gas (Figure 3).

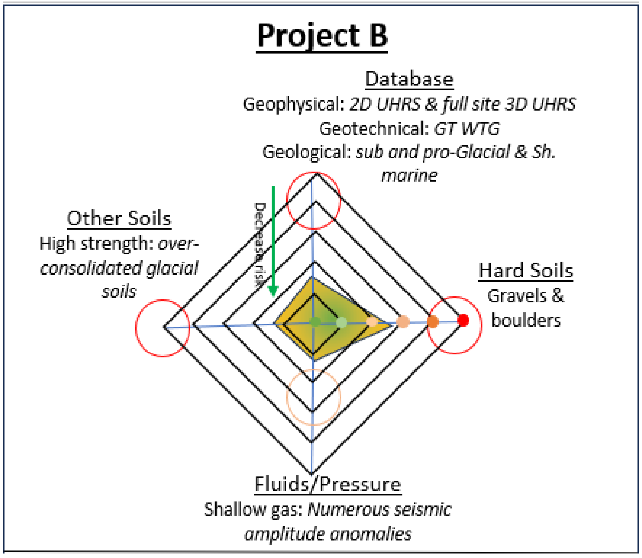

Figure 3. Risk pentagon (top) for project B. Geohazards were a key factor driving recommendation for 3D UHRS (circles). Once 3D UHRS is collected, risk decreases for all hazards (shaded area).

2.1.3 Example Project C

A site-wide 3D UHRS survey was recommended and carried out to mitigate the project risks and support geotechnical data acquisition (Figure 4). As discussed earlier in this paper, 3D UHRS is the only accurate way to position and possibly dimension subsurface point diffractors (possible boulders), as well as image complex structural geology through 3D migration. 3D processing techniques also help suppress data artefacts caused by shallow water depths (surface multiples). Site-wide coverage of 3D UHRS data also enables the complexity and context of the geology to be fully understood, to accurately determine lateral extents and thicknesses of challenging lithologies for pile driving. The survey provides seismic data coverage over all potential WTG layouts and associated installation jack-up positions. Analysis of 3D UHRS is the best tool for layout optimisation as well as for micro siting, to avoid risks from the expected geohazards on site.

Project C is in advanced development phase and is being developed in separates phases. Significant 2D data coverage took place in the early development phase across the full site, with a 100m main line spacing and 300m crossline spacing. A turbine layout has been developed for one area, while a layout is in advanced development for the second. 2D UHRS and sub-bottom profiler (SBP) data confirmed the presence of numerous geohazards to foundation and cables installation. The subsurface tells a story of early to mid-Pleistocene deltaic deposition, followed by deposition associated with multiple phases of glaciation and interglacial periods throughout the middle to late Quaternary, followed by ice-marginal and shallow marine deposition. In addition, early development data provided strong evidence for significant glacio-tectonism, in which soils were heavily deformed through the convergence of two advancing ice sheets. The 2D UHRS data revealed numerous foundation design and installation risks such as significant vertical and spatial heterogeneity of soils with high likelihood of over-consolidated and low strength soils particularly in heavily glacio-tectonised areas as well as paleochannels infilled by a large variety of soils. Additional geohazards include presence of subsurface boulders, gravel lags, peat and shallow gas (Figure 4).

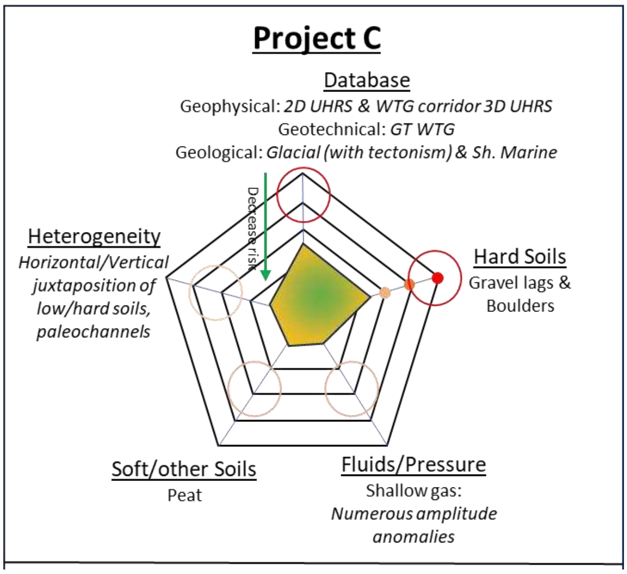

Figure 4. Risk pentagon (top) for project C. Geohazards were a key factor driving recommendation for 3D UHRS (circles). Once 3D UHRS is collected, risk decreases for all hazards (shaded area).

Whilst site-wide 3D UHRS (1-2m bin size) survey would be highly beneficial to fully understand and thus mitigate the known geohazards, due to the sheer size of the twin sites, this approach was not deemed to be feasible because of the time required to complete full coverage acquisition, the significant cost and the exceptionally large data volumes to be expected.

A more efficient solution was therefore to acquire 3D UHRS in corridors, allowing detailed refinement of the existing site-wide 2D UHRS seismic interpretation. This approach, whilst more efficient and thus mitigating programme risks for detailed design of foundations, is heavily dependent on the development of a turbine layout that will not move away from these corridors. Due to the uncertainty in supply chain for manufacture and provision of turbines of varying output, it was necessary to design a flexible turbine layout that can be used without revision of the survey layout. This is important for UHRS acquisition acquired with the "corridor" based approach, as a significant change in layout beyond that of micro siting (50m), may result in additional data requirements, which exposes the project to increased commercial and programme timing risks.

2.2 Permitting Considerations

Not all offshore wind farm sites carry high ground risk. Some sites without significant glacial processes and with prevalent Quaternary sections (reduced risks from consolidation and cementation) can, however, carry other project risks that can be mitigated with 3D UHRS data.

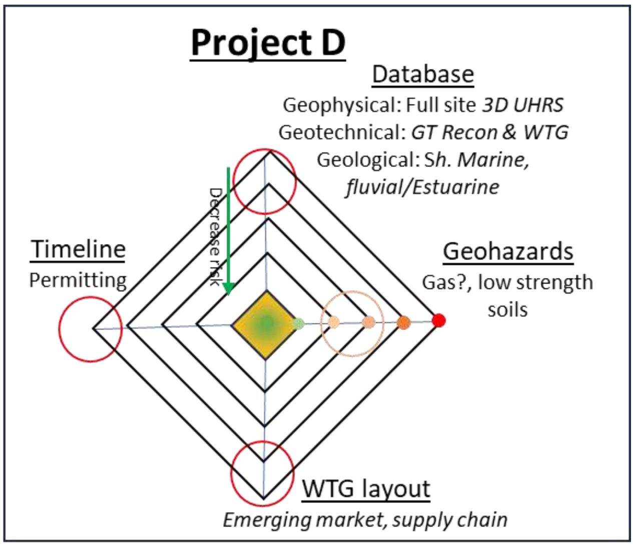

Figure 5. Risk pentagon (top) for project D. Main risks as drivers for 3D UHRS were permitting timelines and infrastructure layouts from supply chain uncertainty (circles).

2.2.1. Example Project D

The recommendation for 3D UHRS for project D was less centred around ground geo-risk and more related to permitting, timelines and supply chain risk. In terms of permitting, most marine surveys using seismic sources (e.g. airguns, sparkers, boomers) require permits from regulatory bodies which come with survey mitigations for marine mammals. In some cases, the work required to secure a permit can impact timelines, and the mitigations can, in some cases, be detrimental to the quality of the data. Thus, by selecting 3D UHRS, the number of seismic surveys over this project's development lifecycle was reduced removing multiple permitting applications (Figure 5).

2.3 Timeline Considerations

2.3.1 Example Project B

With acquisition of full lease area 3D UHRS for project B prior to finalisation of the WTG layout, a potential bottleneck in the project development timeline has been mitigated. If using 2D UHRS, a seismic survey could only have been conducted following finalisation of the WTG layout, to ensure 2D lines along each WTG row, which would add a potential time delay to the development. By opting to carry out a site-wide 3D UHRS survey, the site investigation team has reduced the pressure of the overall site investigation and development timeline. By covering all potential infrastructure or installation jack-up locations, the project has eliminated the requirement for any further seismic surveys should the WTG layout change. While requiring an initial marginally higher survey cost for 3D UHRS (e.g. 50m sail lines) when compared to 2D UHRS (100-200m sail lines), the efficiency and optionality provided by 3D UHRS ultimately reduces the project development timeline and full life cycle project spend.

3D UHRS has been identified as a key tool to help planning the detailed geotechnical site investigation. By ensuring that geological conditions and geohazards are fully understood, the 3D UHRS will help to ensure the distribution of sampling boreholes and laboratory tests are planned across all soil units and conditions. This optimisation of the site investigation strategy will help to reduce uncertainty or conservatism in any geotechnical interpretation and resulting foundation design, as well as assessment of installation challenges. Furthermore, by enabling a greater understanding of the geology prior to the geotechnical site investigation, a recommendation for the most technically robust acquisition method can be justified and planned to help with recovery of challenging soils such as using sonic coring for thick coarse deposits, rather than rotary drilling. Sufficient quantity of good quality samples for laboratory tests is crucial for site characterisation and design. Reduced confidence in laboratory tests results can lead to challenges with design certification which would also impact the project timelines.

2.3.2 Example Project D

Another reason for the recommendation for full-site 3D UHRS on project D was an unprecedented pre-consent (phase of development) timeline to meet permitting requirements. This required almost two years of near continuous geophysical survey. Geophysical site surveys are generally planned to run across end of spring and summer months to take advantage of calmer seas to reduce weather related downtime. Project D's permitting timeline required around-the-year survey and thus a vessel and UHRS system that could decrease weather downtime as much as possible. The solution was a 3D UHRS system with a vessel suitable for working in higher significant wave heights and an acquisition set up tailored to work in sub-optimal weather conditions (e.g. deeper towed streamers). Not all weather related downtime could be mitigated, especially related to the workability of the seismic sources, however, a significant amount of time was saved by not needing to pull the equipment onto the deck every time a worsening weather window approached. The 3D UHRS system, with improved winter workability and the ability to get an initial processed volume directly off the vessel, with no discernible impacts on data quality due to deeper towed streamers, allowed the permitting timeline to be met.

2.4 Supply Chain Considerations

Projects located in countries with an emerging offshore wind industry tend to have higher risk profiles due to uncertainties in supply chains. It takes longer for infrastructure layout decisions to be made, and this makes planning of geophysical site survey more challenging. Generally, repeat surveys are needed as layouts change so that each WTG is located on a 2D UHRS line and a geotechnical location. Projects try to mitigate this uncertainty with dynamic or flexible layouts, often with spare locations and multiple spacing scenarios, however, projects with higher expectations of layout changes are best mitigated with 3D UHRS as it removes the need for repeat survey (e.g. project D).

3 CHALLENGES

3D UHRS data acquisition for offshore wind has been ongoing for decades, however, future challenges and/or optimisations are needed for acquisition, processing and interpretation as well as data management. In regions with emerging offshore wind markets, not all contractors have vessels, equipment and/or competency in-country. This can decrease the pool of contractors available for 3D survey, making 2D UHRS options more attractive in those regions. Should contractors bring into their fleet a new vessel, they are often not shaken down for 3D UHRS survey work. This, combined with inexperienced crew, can lead to additional delays or poor-quality data. The entry into the market of contractors with experience of 3D seismic from the oil and gas industry has increased the contractor and vessel pool. Companies with supercomputing capabilities readily available, can reduce processing timelines and manage the large data volumes. Established 3D seismic contractors and those that have worked with the same vessels and same equipment set-ups over multiple past surveys are favoured.

Although a key reason for recommending 3D UHRS may be mapping of small-scale features, challenges remain in terms of sufficient positioning sensors on the towed array to achieve the required accuracy for ultra-high-resolution data. Seismic data bin sizes are of the order of 1 x 1m (or less), and absolute positioning accuracy at the common mid points should be less than half the bin size to ensure that more advanced processing workflows are reliable. To achieve this, it would ideally involve positioning sensors at multiple points along the seismic streamers. However, the reality is that this is challenging for most contractors both in terms of cost, availability and practicality of deployment. Further, due to the vast quantities of data involved, data management is a real challenge for both live streaming of data from vessels to onshore processing centres and transfer and storage of final datasets that can be in the terabyte size. The sizes of data involved can also cause problems in terms of suitability of some seismic interpretation and visualisation software. For 3D seismic data to be interpreted with true 3D workflows, the industry needs experienced staff and suitable software. The full potential of 3D cannot be realised without changes to interpretation workflows (e.g. volume attributes, auto tracking), which if applied correctly can decrease interpretation timelines.

4 CONCLUSION

In 2023-24 RWE Renewables collected four 3D UHRS surveys across a range of projects, with three different survey designs and using a variety of contractors. Factors driving the decision to recommend 3D UHRS varied from high subsurface geological and geohazard risk to permitting timelines, and supply chain uncertainties. While ground risk is often the key risk driving the recommendation of 3D UHRS, other factors need consideration.

Although challenges exist for 3D UHRS, future demand will hopefully drive investments in acquisition equipment, supercomputing processes for big data and training of vessel crew new to 3D UHRS work.

3D UHRS reduces the chance that additional geophysical data may be required due to its increased coverage when compared to 2D UHRS. Tier one contractors (costly contracts related to manufacturing and installation) may request additional survey if there is considerable uncertainty and installation risk. If

risks are not better constrained then there is the potential for uplift in the contract costs for tier 1 contractors, or different sharing of risk between contractor and developer, all of which can significantly impact CAPEX spend an order of magnitude above the DEVEX site investigation spend and introduce project delays. If CAPEX exceeds planned costs, project profitability will be impacted.
It is often hard to quantify all these impacts and risks during early phases of project development. Many of the decisions made during DEVEX are inter-related with far reaching consequences. However, 3D UHRS acquired early in the project timeline represents an opportunity to make better informed decisions. This reduces uncertainty and potential for over conservatism, which may cause significant uplift in costs later in the project development and construction. Taking a holistic view of a project, from early development through to installation, can lead to significant site investigation cost savings if recommendations for 3D UHRS are executed, as well as allowing project and permitting timelines to be met.

AUTHOR CONTRIBUTION STATEMENT

First Author: Conceptualization, Investigation, Formal Analysis, Writing- Original draft. **Other Second Author**: Investigation, Writing- Original draft, Writing – review & editing. **Additional Authors**: Investigation, Writing- Original draft.

ACKNOWLEDGEMENTS

The authors would like to thank RWE Renewables for permission to present this material.

REFERENCES

British standard 5930:1999 (1999). Code of practice for site investigations, British Standards Institute, UK.

BOEM (2023). Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585, Bureau of Ocean Energy Management, Renewable Energy Programs, USA.

DNV (2021). DNV-ST-0126 Petroleum and natural gas industries — Specific requirements for offshore structures Part 10: Marine geophysical investigations, DNV AS, Oslo.

Duarte, H., Wardell., N., Monrigal., O. (2017) Advanced processing for UHR3D shallow marine seismic surveys, *Near Surface Geophysics*, Volume(15), pp. 347-358, https://doi.org/10.3997/1873-0604.2017022.

Hill, A. W. (2013). Fundamental and Specific Marine Geohazard Risk Assessment Categorisation, In: *Offshore Technology Conference*, Houston, USA, https://doi.org/10.4043/24211-MS.

ISO (2021). ISO 19901-10:2021 Support structures for wind turbines, International Standards Organisation, Geneva.

International Association of Oil & Gas Producers (IOGP) (2011). Guidelines for the conduct of offshore drilling hazard site surveys, Geomatics Guidance Note 18-1.

Kirkham, J. D., Hogan, K. A., Larter, R. D, Self, E., Games, K., Husse, M., Stewart, M.A., Ottesen, D., Arnold, N. S., Dowdeswell, J. A., (2021) Tunnel valley infill and genesis revealed by high-resolution 3-D seismic data, *Geology*, Volume(49), pp. 516-1520, https://doi.org/10.1130/G49048.1.

Lebedeva-Ivanova, N., Polteau, S., Bellwald, B., Planke, S., Berndt. C., Henriksen Stokke, H. (2018) Toward one-meter resolution in 3D seismic, *The Leading Edge*, Volume(37), pp. 818-828, https://doi.org/10.1190/tle37110818.1.

Sheriff, R. E. (1991). *Encyclopedic Dictionary of Exploration Geophysics*, 3rd ed., Society of Exploration Geophysicists.

Society for Underwater Technology (2022). Guidance notes for the planning and execution of geophysical and geotechnical ground investigations for offshore renewable energy developments, Bureau of Ocean Energy Management, Renewable Energy Programs, Updated by SUT Offshore Site Investigation and Geotechnics (OSIG) committee, London.

Udden, J, A., (1914) Mechanical composition of clastic sediments, Geological Society of America, Bulletin, Volume(25), pp. 655 - 744, https://doi.org/10.1130/GSAB-25-655.

Wentworth, C, K., (1922) A scale of grade and class terms for clastic sediments, *Geology*, Volume(30), pp. 377 - 392, https://doi.org/10.1086/622910.