Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-9

Geotechnics for offshore wind developments

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ABSTRACT: Offshore wind plays a vital role in the energy transition, with significantly accelerated development required to meet set goals to limit global warming. It is a relatively young industry, with the first offshore wind farm established in 1991, and while many concepts have been borrowed from onshore foundation engineering and offshore oil and gas developments, differences in conditions, size of the seabed area and individual foundations (to name only a few) have resulted in significant evolution of approach and geotechnical solutions for offshore wind developments. This paper captures the state-of-the-art at this point in time and provides an outlook of the innovations needed to accelerate offshore wind build-out, including in established and emerging markets. Highlighting links with other aspects critical to offshore wind developments, the paper focuses on geotechnical solutions, challenges and opportunities from initial project phases of ground model development and foundation concept selection to foundation or anchor design, installation, operation, possible lifetime extension and ultimate decommissioning. Approximately 100 colleagues from academia and industry have directly contributed to this paper through survey responses and in-depth conversations. The picture that emerges is one of innovation, close academic-industry collaboration, continuous evolution and clear identification of opportunities for step changes in improvement.

KEYWORDS: offshore geotechnics, offshore wind, ground model, foundation design, anchors.

1 INTRODUCTION

Offshore wind plays an important role in the global energy transition. To meet the 1.5ºC climate target outlined in the Paris Agreement, the International Renewable Energy Agency (IRENA) estimates that 2,000 GW of offshore wind capacity will be required by 2050. As of the end of 2024, global installed capacity stood at 83 GW (GWEC, 2025). Figure 1 illustrates the global distribution of offshore wind capacity, showing both total installed capacity and annual new installations.

The offshore wind industry began in Europe, with the first offshore wind farm – Vindeby in Denmark – commissioned in 1991. It featured 11 turbines rated at 450 kW each, installed in water depths of just a few meters and located approximately 1.5 km from shore. Over the past three decades, the industry has transformed. While Europe remains a key region, the landscape has shifted: China now accounts for approximately 50% of both total installed capacity and new annual installations.

This geographical shift has been accompanied by an increase in scale and complexity. Today, offshore wind turbines reach capacities of 15 MW or more, with rotor diameters exceeding 220 meters and hub heights around 150 meters. A typical bottom-fixed commercial-scale offshore wind farm may include 80 to 150 turbines, span 1,000 MW or more in total capacity, and be located 30 to 60 km offshore in water depths ranging from 20 to 70 meters, depending on the region and foundation type.

Bottom-fixed foundations dominate the market, accounting for 99.7% of installations. However, floating offshore wind is emerging as a key technology for future deployment. The 2025 Energy Transition Outlook (DNV, 2025) projects that the global installed floating wind capacity will reach 331 GW by 2060 – a substantial share of the anticipated build-out. These trends reflect the global nature of offshore wind and the need for solutions adaptable to a wide range of seabed conditions, water depths and regulatory environments.

This rapid upscaling and expansion into new regions have introduced challenges across all disciplines involved in offshore wind development – from engineering and logistics to environmental assessment, permitting, and supply chain coordination. Offshore geotechnics is among these, where ongoing work continues to develop innovations essential for accelerated deployment.

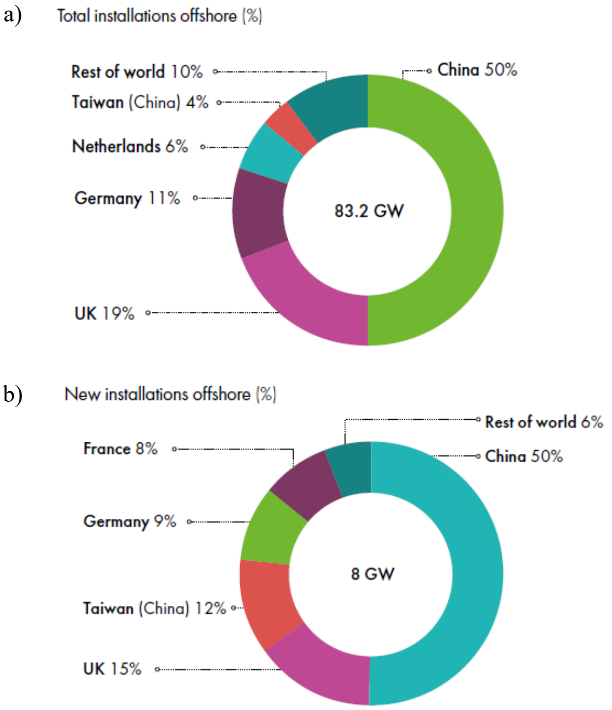


Figure 1. Where is offshore wind capacity being built? (a) Total capacity by the end of 2024, (b) Installed capacity in 2024 (GWEC, 2025)

Five key geotechnical challenges have been identified previously that must be addressed to accelerate progress toward Paris Agreement targets: (i) identifying optimal locations for future offshore wind farms; (ii) improving efficiency in deriving geotechnical design parameters; (iii) enhancing the efficiency of design outcomes; (iv) reducing the time required to complete designs; and (v) lowering the life-cycle cost of delivering offshore wind infrastructure (Gourvenec, 2024). These challenges are particularly pressing given the projected

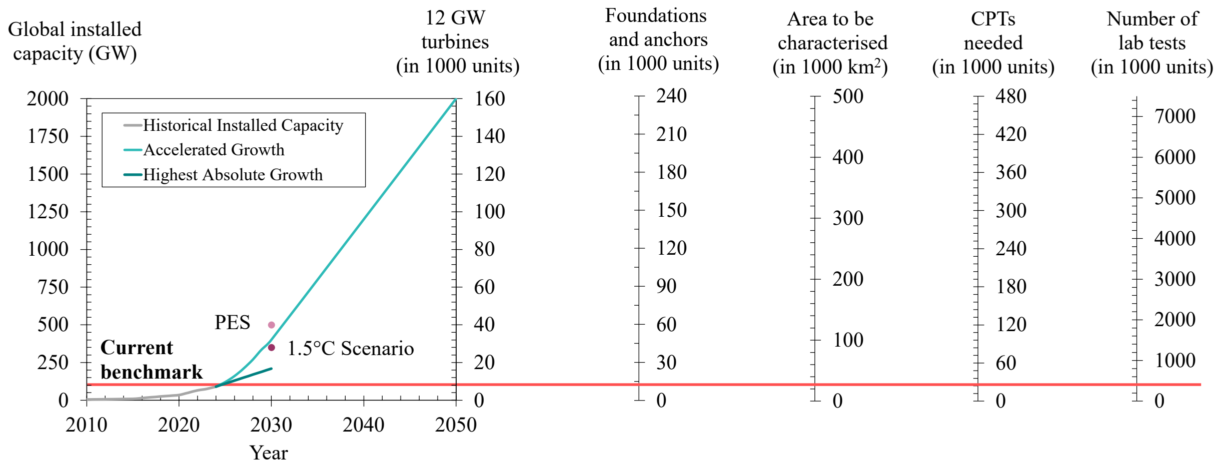


Figure 2. Historical and projected offshore wind capacity growth and the scale of geotechnical engineering challenges required to meet future ambitions (incl. Planned Energy Scenario, PES, and 1.5º Scenario), adapted from IRENA (2024) and Gourvenec (2024).

offshore wind capacity growth, illustrated in Figure 2, which compares historical and projected offshore wind capacity against the Planned Energy Scenario (PES) and the more ambitious 1.5º Scenario outlined by IRENA (2024). Meeting these targets will require a step-change in current practice; incremental improvements alone are insufficient. For example, based on 12 MW turbines, Gourvenec (2024) estimates that the necessary build-out will require approximately a quarter of a million foundations and anchors, characterization of half a million km² of seabed, half a million cone penetrometer tests (CPTs), and 2.5 million geotechnical laboratory tests – far exceeding the capacity of conventional site investigation, design, and installation practices (Figure 2). A paradigm shift is therefore essential to enable offshore wind development at the pace and magnitude required.

In light of this, this paper investigates the current state-of-the-art in offshore geotechnics for offshore wind, examining what drives decision-making, how geotechnical considerations intersect with other project disciplines, and what innovations are required to accelerate build-out toward 2030 and 2050 targets under the Paris Agreement. The paper is structured around the offshore wind project lifecycle, which rather than a linear or monotonic path, is better described as a biased two-way cycle with iterative feedback loops. Rather than trying to cover all possible content, choices have been made such that some topics are deliberately covered more in depth than others, and examples have been chosen for illustrative purposes. The stages considered include: (i) site characterisation and development of ground models; (ii) concept selection and foundation and anchor design; (iii) installation; (iv) operation and maintenance; and (v) lifetime extension and decommissioning. Offshore geotechnics is integral to each phase, not only due to technical challenges such as soil characterisation, installation, and foundation performance, but also because of its central role in managing risk across the asset lifecycle.

To inform this review and ensure industry relevance, the paper draws on input from approximately 100 professionals across academia and industry through: (i) an online survey and (ii) in-depth interviews. The survey comprised 15 questions aligned with the project lifecycle, was launched at the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG) held in Nantes in June 2025, and also distributed via ISSMGE Technical Committee TC209 on Offshore Geotechnics. In total, 92 responses were received, representing research, consultancy, and offshore wind developers in roughly equal proportions (Figure 3). Previous work experience of the survey respondents indicates mobility between research and engineering practice. Experience levels were substantial: 35% of respondents had 15–30 years, 8% more than 30 years, 20% had 10–15 years, and 30% had 5–10 years, with only 7% having less than five years' experience. The survey was designed to take only a few minutes to complete, using single/multiple choice and ranking questions with optional short answers.

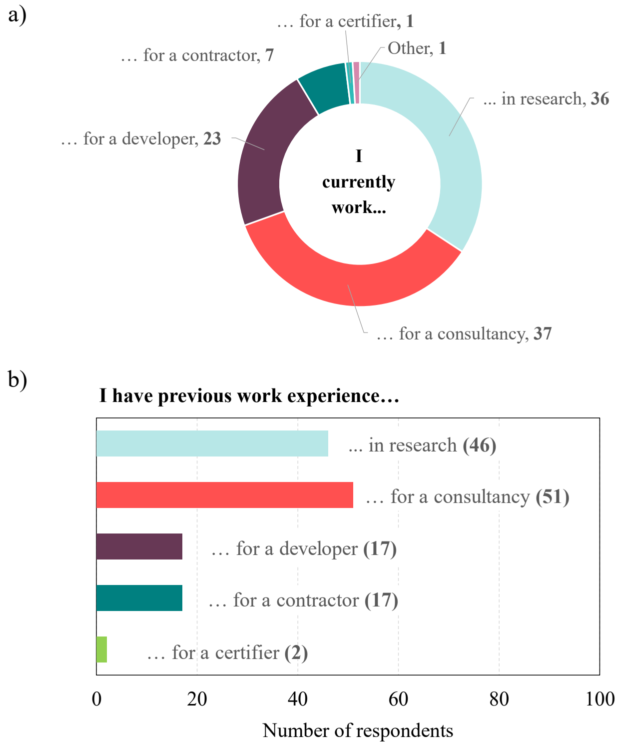


Figure 3. Role of survey respondents: (a) current role; (b) previous experience.

To complement these quantitative insights, 16 in-depth interviews were conducted with developers, consultants, academics, contractors, and certifiers, providing individual perspectives on decision-making processes, technical bottlenecks, and innovation priorities. Drawing on these inputs, the paper synthesizes current practice, emerging research, and industry needs across the lifecycle stages (Figure 4), highlighting innovation through specific examples. The concluding discussion offers reflections, providing possible

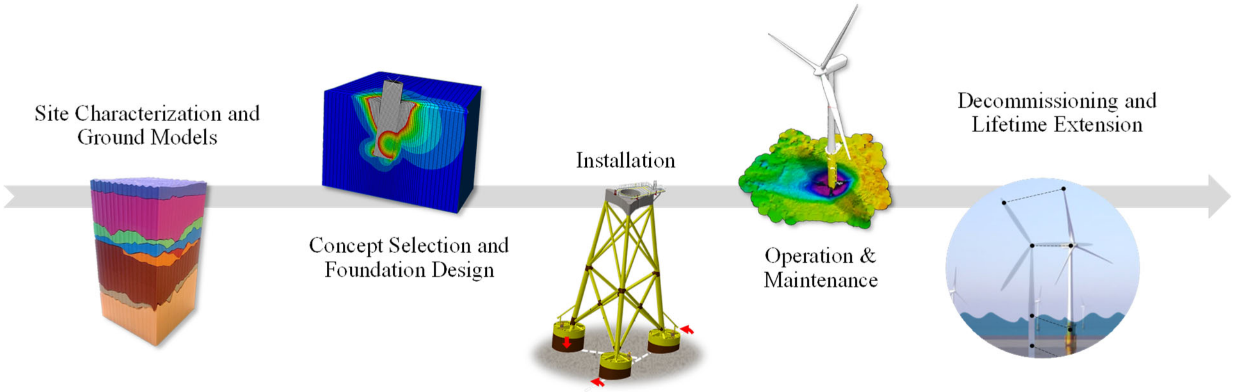


Figure 4. Offshore wind project lifecycle: simplified schematic identifying key stages. Images from NGI and Sparrevik (2019).

pathways on how offshore geotechnics can evolve to meet the scale and pace of offshore wind development.

2 GROUND MODELS

2.1 *Introduction*

Site characterisation is one of the first steps in any offshore wind farm development. It involves assessing metocean factors such as wind and wave magnitude and direction, as well as soil conditions and their geospatial variability. Soil conditions are typically evaluated in a ground model. This section defines what a ground model is, explains its importance and components, describes how ground models are developed in offshore wind, outlines current challenges, and explores workflows for further development.

2.2 *Definition and importance*

A ground model is a 3D representation of the seafloor and subsurface, including processes that may alter them over time. Ground models are built on geological understanding and integrate geological, geophysical, and geotechnical data, often called the “3Gs” (Vanneste et al., 2021; Dimmock et al., 2025). This definition reflects current industry practice. In the survey, most respondents agreed that a ground model “*has a clear meaning defining seabed conditions by fully integrating geological, geophysical and geotechnical data to support the development of the project*” (Figure 5).

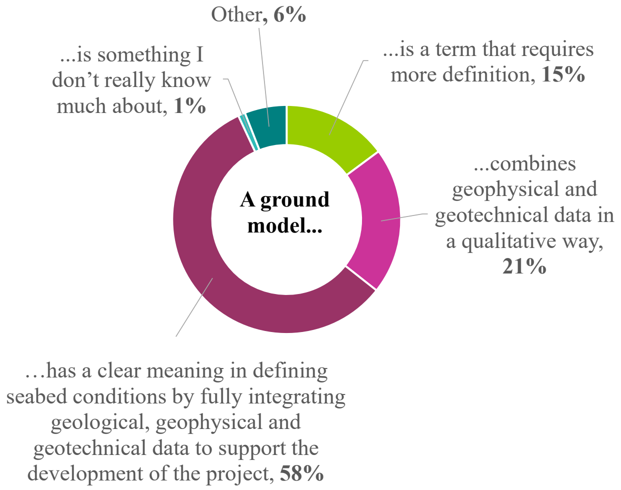


Figure 5. Responses to survey question: “What is a ground model (in the context of offshore wind)?”

Ground models in offshore projects vary in their level of data integration and quality (Klinkvort et al., 2020):

- Basic level: Data are interpreted independently, resulting in qualitative rather than quantitative models.
- Intermediate level: Data are combined to provide a qualitative understanding of the site.
- Full integration: A quantitatively integrated 2D or 3D ground model. These models provide predictive capabilities by estimating soil parameters and their associated uncertainties, which is critical for identifying and mitigating geotechnical risks.

Ground model development typically begins with a desk study that compiles existing geological, geophysical, and geotechnical data, including legacy and public datasets (e.g. ISO 19901-10:2021, International Organisation for Standardization, 2021). At this stage, data from environmental baseline studies (e.g. seabed sampling, imagery, sediment distribution) can provide valuable input for early models (Rattley et al., 2017). This is followed by geotechnical site investigation campaigns designed to fill data gaps. The model is updated as new data become available. Ground models are dynamic tools and should ideally be maintained throughout the project lifecycle, from its initial concept to decommissioning. This iterative approach maximises information, optimises site investigations, and reduces survey costs. For instance, an integrated ground model has been reported to have brought significant economic benefit, e.g. to the East Anglia One offshore wind farm, UK, where the total cost of the site investigation was reduced by 10-15% while level of confidence in the predicted geotechnical parameters improved (Reynolds et al., 2017).

Ultimately, ground models serve as decision-support tools for various applications, including geohazard and risk assessment, layout optimization, and the planning of further investigations (Vanneste et al., 2021).

2.3 *Ground models in the context of offshore wind*

Ground models have long been used across industries, with varying levels of sophistication depending on project goals and site conditions. While the concept is well established in reservoir characterisation for oil and gas or in onshore applications (see e.g. Vitale at al., 2025), the field has advanced significantly with the development of offshore wind.

One of the key differences between ground models for offshore wind and oil and gas developments lies in the nature of the development objectives and the role of the shallow subsurface. Offshore wind farms often span several hundred square kilometres and require detailed understanding of the upper tens of metres of the seabed to support the design and installation of structures and an overall understanding of the upper 100 m, typically over a hundred wind turbine generators (WTGs), along with substations and cables. These sites are commonly located in regions with complex shallow geology shaped by large-scale geological and environmental processes over the past million years, resulting in high geospatial variability.

Offshore wind has required a shift toward fully integrated, 3D quantitative ground models that assess soil properties, spatial variability, and uncertainty in the shallow subsurface across relatively large areas (Vanneste et al., 2021). The need for such models is further driven by the sparse availability of in-situ tests (such as Cone Penetration Tests, CPTs) and boreholes compared to the number of foundations in offshore wind projects, relative to onshore or oil and gas developments. Flexible layouts in offshore wind developments also contribute to this requirement, as foundation types and locations often change during project planning. At the time of the first geophysical and geotechnical data acquisition, the foundation concepts and their exact positions are often not yet decided. Ground models help extrapolate geotechnical data across large distances, estimate soil parameters and assess potential geohazard and geo-engineering constraints at locations without direct measurements, with the potential to quantify uncertainty.

They are relevant not only for offshore wind turbine foundation design, but also for cable routing: a typical offshore wind project can involve hundreds of kilometres of cables, which interact with near-surface sediments that are among the most difficult to characterise, and for planning temporary operations such as jack-up vessel deployment (Mason and Smith, 2016; Society of Naval Architects and Marine Engineers, 2024). In the case of jack-ups, installation is often carried out with soil information (typically CPT) available only at the turbine centre, which is why pre-loading remains a critical measure to reduce the risk of punch-through events. Developing ground models with sufficient resolution to assess leg-specific soil profiles - identifying pockets of shallow gas and boulders - would be highly beneficial.

2.4 *The "ingredients" by discipline*

Ground models are built from contributions across disciplines. The key components are geology, geophysics, and geotechnics, with integration linking information from the different disciplines. Each discipline has its own strengths and limitations and understanding them is important for building reliable models and improving current practice (Vardy et al., 2023). The following sections describe each of them, and Table 1 summarises their main strengths and limitations.

2.4.1 *Geology*

Geology provides the stratigraphical column for a ground model by explaining how soils were deposited and evolved over time. This understanding ensures that geophysical and geotechnical data are interpreted within a consistent regional context and helps resolve discrepancies or discontinuities between datasets. Such geological insight becomes particularly important when dealing with features that introduce significant variability in soil conditions. For instance, tunnel valleys which are large subglacial erosional structures infilled with heterogeneous sediments that are often present in the North Sea are one such example (see e.g. Bellwald et al. 2024). However, many other landforms can similarly be influential in offshore wind farm planning, including sand waves, eskers, tills, contourite deposits, and the presence of boulders. These features can cause abrupt lateral and vertical changes in soil properties, increasing uncertainty in design and installation.

In addition to identifying such features, geological interpretation also provides critical insight into soil state and composition in relation to geological history. For example, proximity to former ice grounding zones, overconsolidation due to glacial loading, and sea level fluctuations can all influence soil behaviour. Understanding these processes is essential for

Table 1. Strengths and limitations in each of the disciplines involved in ground models

Discipline	**Strengths**	**Limitations**
Geology	Offers insight into depositional (and erosional) history and processes.	Largely qualitative.
	Provides global/regional/site-specific context for site interpretation.	Risk of over-interpretation or speculative assumptions when data are sparse ("geofantasies")
	Bridges gaps between geophysical and geotechnical datasets.	
Geophysics	Non-invasive and can cover extensive areas.	A trade-off exists between penetration depth and resolution (for shallow site characterisation, resolution is typically at the metre scale).
	Provides continuous stratigraphic detail and structural information across the site.	Susceptible to noise and artifacts, such as ghosts (interference of up- and down-going energy) and multiples (energy reflected back and forth between seafloor and water-air interface, or internal multiples within/between subsurface horizons).
	Can be used to obtain small-strain properties (e.g., acoustic impedance, Vp, Vs, etc)	Requires time-to-depth conversion and linking seismic and geotechnical properties
Geotechnics	High vertical resolution (centimetre scale).	Sparse spatial coverage across large sites.
	More direct measurement of mechanical soil properties.	Sample disturbance, particularly in sands, which can affect the reliability of lab results.
		Uncertainty in the empirical relations between the measured CPT response and geotechnical parameters.

anticipating geotechnical conditions and reducing uncertainty in offshore wind foundation or anchor and cable design.

2.4.2 *Geophysics*

Geophysics can provide 2D or 3D spatially continuous information about morphology and stratigraphy, making it a key component of offshore site characterisation. Seismo-acoustic methods, including seismic reflection, sub-bottom profiling, and bathymetry, are the main tools used. These techniques allow large areas to be surveyed efficiently and non-invasively, producing data with a resolution typically ranging from decimetres to metres and involving low strain levels. Such datasets are essential for mapping seabed terrain and geological units (Figure 6), detecting anomalies (for instance, boulders or shallow gas), and guiding the planning of geotechnical investigations.

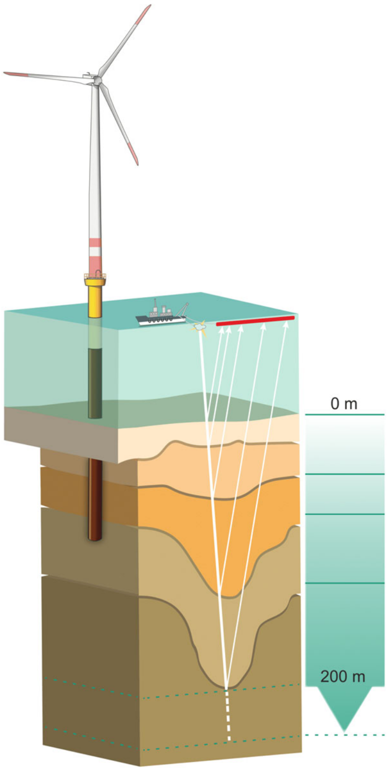


Figure 6. Geophysical acquisition layout showing the depth of interest for offshore wind farms and waves reflected on the different soil layers (Fraunhofer IWES, 2025).

P-wave seismic reflection data remains the primary source of geophysical information for offshore wind projects (Sauvin et al., 2019). It provides excellent spatial coverage but does not directly quantify geotechnical properties. Instead, seismic attributes (such as P-wave amplitude or velocity) are used as input to inversion techniques or multivariate models that combine several attributes to predict soil parameters like stiffness and link well to strength (Klinkvort et al., 2020; Reidy et al., 2025). These models are often data-driven, and they rely on calibration with CPT or borehole data. Recent research increasingly focuses on extracting quantitative information from geophysical data, including the use of machine learning workflows to improve property estimation (Vardy et al., 2023).

2.4.3 *Geotechnics*

Geotechnical investigations give more direct information about engineering soil properties at specific points on a site. The main methods are cone penetration tests (CPT), including seismic CPT, and boreholes with sampling. CPTs are used to estimate engineering parameters through well-known correlations (e.g. Lunne et al., 1997; Robertson, 2009; Schneider et al., 2012) though these may require calibration for a region or site. While widely used, such correlations typically lack formal uncertainty assessments. Regression coefficients are rarely reported, and the underlying datasets often include different soil types and conditions, which limits their reliability. To address the limitations of traditional empirical approaches, alternative methods (e.g. the Bayesian methodology by Feng et al., 2023) are being developed. Borehole samples are sent to geotechnical laboratories for element testing, which is used to determine the soil's strength, stiffness, and consolidation behaviour.

These methods offer high vertical resolution, typically at the centimetre scale. However, spatial coverage is limited. Offshore wind farms often span hundreds of square kilometres, yet geotechnical data are usually collected along a few profiles or at isolated points. This makes it difficult to capture lateral variability in soil conditions solely relying on the direct geotechnical data.

2.4.4 *Integration*

Integration is the step that brings the three disciplines together to build a consistent understanding of seafloor conditions. In the process of the integrated interpretation, the geotechnical data provide the seismo-acoustic data with the information on soil types and geotechnical properties (Rushton and Nguyen, 2019). Meanwhile, seismo-acoustic data can not only facilitate the extrapolation of geotechnical data to the whole area (Eady and Steven, 2025) but also offer improved estimates of density, shear stiffness, and bulk stiffness. In addition, attenuation

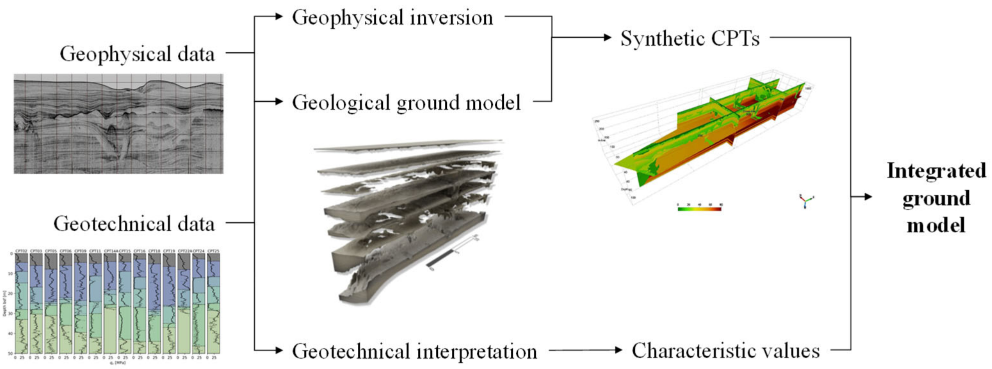


Figure 8. Flow chart of steps involved in developing integrated ground model, adapted from Vardy et al. (2023), Klinkvort et al. (2020) and Sauvin et al. (2022).

(inverse of quality factor) can provide an indication on lithologies. Stratigraphic interpretation across disciplines, supported by geological context, is essential to ensure that soil units and layer boundaries are properly identified and unitised (Pearce et al., 2019). It is a collaborative and iterative process that requires close coordination between domain experts (Peng et al., 2024). The integration process typically follows four steps (Figure 8, adapted from Vardy et al., 2023, Klinkvort et al., 2020, and Sauvin et al., 2022):

1. Interpretation: Combine geological, geophysical, and geotechnical data to define seabed units (unitisation).
2. Seismic inversion: Estimate acoustic impedance (and potentially quality factor) from seismic data and then derive P-wave velocity and density through seismic data by estimating the physical properties that best explains the seismic data while accounting for uncertainty. As an alternative, geostatistical models can be used.
3. Synthetic CPTs: Predict cone penetration test (CPT) profiles from these properties and compare them with measured CPTs.
4. Engineering properties: Derive design parameters from validated synthetic CPTs or directly from seismic data.

Despite this structured approach, integration is challenging. Differences in strain regimes, measured properties, spatial coverage, resolution, and acquisition timing introduce complexity and uncertainty (Sauvin et al., 2022), making the development of integrated ground models far from straightforward. These complexities form the basis of the broader challenges discussed in the next section.

2.5 *Challenges in developing ground models*

Integrated ground models are powerful tools for consolidating site information, reducing risks and providing opportunity for optimisation during the design and installation of offshore wind farms. However, their development faces challenges that span integration, communication, technical limitations, and financial constraints.

Integration challenges arise from the inherent difficulty of combining different data types (geological, geophysical, and geotechnical data) into a consistent interpretation. On one hand, geotechnical data provide sparse but ground truth information for soil types and engineering properties, which is essential for calibrating and validating geophysical signals (Rushton and Nguyen, 2019). On the other hand, geophysical data provide spatial continuity, enabling extrapolation of geotechnical properties across the entire site. Geophysical surveys typically cover large areas but at lower resolution and in a small-strain domain, while geotechnical tests provide high-resolution data at discrete points and at higher strain levels. In addition, in geotechnical characterisation, design parameters such as shear strength and stiffness do not only depend on strain level, but also on drainage conditions and stress history (with geology playing a key role in understanding the stress history). This adds a layer of complexity when trying to relate bulk physical parameters that can be obtained from geophysical data, making this process non-linear and non-unique. For this, machine learning workflows are often employed (Vardy et al., 2023).

Additional challenges include noise-to-signal ratio and time-to-depth conversion uncertainties, which depend on the acoustic velocity model and can introduce significant depth errors in layer boundaries (Vardy et al., 2023; Peng et al., 2024). The geological setting and depositional history significantly influence spatial variability, emphasizing the value of sound geological understanding. Soil and rock conditions can change over relatively short distances (on the order of metres) in complex environments, increasing the risk that geotechnical data are not fully representative of site conditions, that features may be missed, and that the relationship between geophysical and geotechnical properties becomes more ill-posed, as illustrated in Vardy et al. (2023) for example locations. Data are typically acquired at different times, introducing inconsistencies that complicate integration, particularly if there is seabed mobility. Also within geotechnical data, discrepancies can occur when CPTs and boreholes in close proximity suggest different layering or unitisation. Furthermore, mismatches between seismic profiles and geotechnical sampling locations are common and offsets greater than a few meters can already reduce confidence in unitisation and establishing correlations (Vanneste et al., 2021).

Tracking and propagating uncertainty through the integration process is critical but challenging. For example, errors in velocity models affect depth correlation between seismic and geotechnical data, which in turn influences layer boundary definitions. Advanced workflows, including CPT predictions and comparison with measured CPTs, are used to quantify aleatory and epistemic uncertainties (Vardy et al., 2023, Feng et al., 2023). Finally, integration is also a human challenge: specialists from different disciplines often use different terminology and approaches, which can lead to **language barriers**. For example, common terms in geophysics like *attenuation*, *seismic attributes*, *stacking*, and *inversion* are often interpreted as *dissipation of energy*, *derived parameters*, *averaging*, and *back-analysis* in geotechnics – though there is not always a direct equivalent.

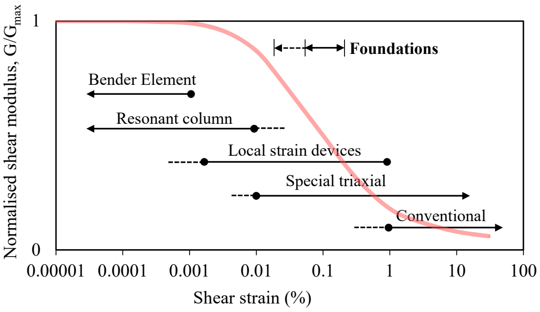


Figure 9. Typical strain ranges in a shear modulus reduction curve, along with the methods best suited for deriving it.

Technical challenges within individual disciplines are equally significant. Focusing on geotechnical characterisation, laboratory and in-situ testing present a range of challenges that affect data reliability and interpretation. An example is the determination of small-strain shear modulus, G_{max}, which can vary significantly depending on the method used: whether inferred from geophysical data, measured via SCPT or PS logging, or obtained in the laboratory using either resonant column, bender elements or local strain devices in triaxial tests Figure 9 illustrates a typical shear modulus reduction curve, indicating the strain ranges and the methods commonly employed to derive it.

CPT technology continues to evolve, with developments enabling deeper penetration without pre-drilling (see e.g. Yetginer-Tjelta et al., 2022, or Koreta et al., 2023). The understanding of issues such as partial drainage, effect of fine contents and rate effects has improved in recent years (see for instance Carotenuto et al., 2023, or Ramsey and Tho, 2023). In addition to these mechanical and interpretation advances, specialized CPT variants have emerged to fit the technology for purpose in offshore wind applications. The Thermal CPT (T-CPT) integrates sensors to measure in-situ thermal conductivity of soils, a critical parameter for subsea and buried power cables, as their performance depends on efficient heat dissipation into the surrounding ground (Vardon et al, 2019). Similarly, the Magnetic Resonance CPT (MR-CPT) leverages magnetic resonance principles to characterize soil porosity and link it to bulk density and fluid content, providing a non-destructive, high-resolution approach to understanding soil structure. Cyclic CPTs apply repeated loading during penetration and consistently show a reduction in sleeve resistance in both clays and sands, providing a practical means of evaluating how soil strength and interface behaviour evolve under repeated loads (O'Loughlin et al., 2024). Initial investigations were carried out in chalk (Diambra et al., 2014), and later studies extended the method to overconsolidated clays (Shonberg et al., 2019) as well as sands and silts (Brandish-Lowe et al., 2023). In addition to sensor-enhanced or loading-modified CPT probes, other devices, such as the ROBOCONE (Creasey et al., 2023), have been developed to impose controlled soil–structure interaction paths in situ, enabling direct characterisation of the horizontal, vertical, and torsional responses rather than inferring them from penetration resistance.

Reliability of laboratory data, largely due to variations in laboratory quality, is another concern. Inter-laboratory variability can be substantial, as shown in projects where several labs tested the same sample and returned different results (see for instance Yamashita et al., 2009; Dufour et al. 2024). National standards also differ globally - they sometimes specify slightly different methods for measuring the same parameter - which adds significantly to this uncertainty, as shown by Blaker et al. (2015). Also sample quality, preservation, transportation and handling strongly influence test outcomes. Offshore sands often arrive in bags, and the behaviour depends on how these samples are reconstituted, and the previous history is accounted for (see e.g. Quinteros and Carraro, 2025). For instance, pre-shearing (typically a small cyclic deviatoric stress applied to the soil before cyclic testing) can simulate prior cyclic loading but also modifies the material response, particularly by altering its fabric (see e.g. Torgersrud, 2025); whether to include it should be clearly defined. Depending on reconstitution, the same sand may either contract or dilate under shearing – differences that can have major implications for design where cyclic loading governs. Sampling and subsampling itself remains a challenge, especially when preserving in-situ pressure and dissolved gas is critical, or when sampling fissured clays. Improved methods such as fixed piston push sampling can help retain structure and pore fluids.

The survey revealed that, despite technical challenges, the most commonly perceived obstacle to developing an integrated ground model is **financial commitment at an early stage** in the project (Figure 10). Building a comprehensive integrated ground model requires early-stage investment in data acquisition, processing, interpretation, and integration. Balancing the relative cost of data acquisition against project maturity is challenging, and determining the minimum data density necessary to achieve acceptable prediction errors remains site-specific and dependent on geological complexity (Vardy et al., 2023). For example, having high-density 3D data that could affect foundation placement early in a project can result in cost savings. However, that investment (which realistically spans over 2-3 years considering planning, execution and evaluation of a 3D survey) may be lost if the project does not proceed, and only recovered after the wind farm has been operating for some time.

The perceived value of ground models varies across organisations and project stages, and its value is often more clearly recognised when something goes wrong. Regional development models also influence this dynamic. The in-depth interviews revealed that in China, **compressed development timelines** of only two to three years for offshore wind projects leave insufficient time to build sophisticated ground models. This limits foundation design optimisation, although increasing economic pressure is beginning to drive efforts toward optimisation. Even with less compressed timelines, other factors may still lead to suboptimal ground models. These include the availability of vessels and experienced subcontractors, including the integration of laboratory testing. This is particularly relevant in emerging regions, where local content requirements and a developing industry can limit access to experienced resources and know-how, which in turn may result in poor quality data.

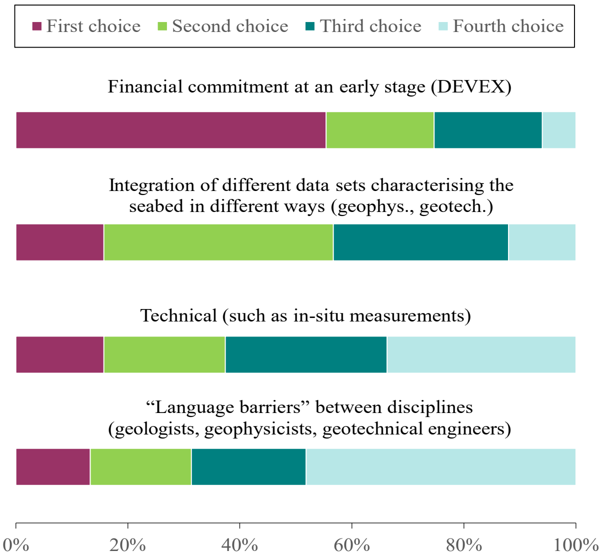


Figure 10. Common challenges to developing an integrated ground model, responses from survey.

2.6 *Changes required to accelerate workflows*

The previous section highlighted key challenges in ground model development. To accelerate progress toward climate goals by 2050, targeted improvements are needed. This section focuses on three priority areas: workflow optimisation, automation, and standardisation. These priorities are supported by survey results in Figure 11, which reflect industry views on their potential value.

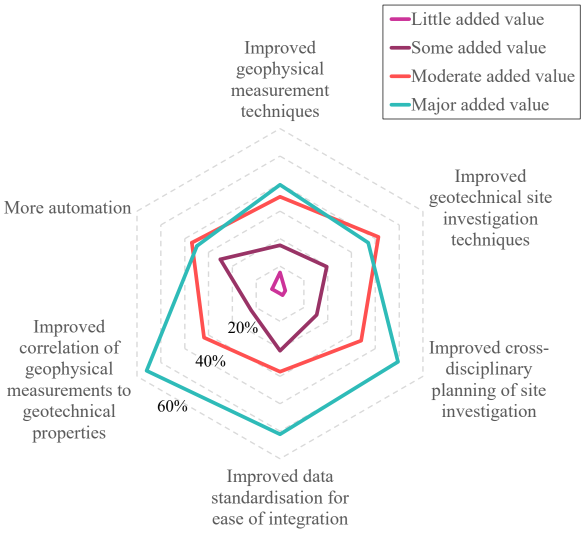


Figure 11. Responses to survey question: "How much added value would these improvements bring to the development of an integrated ground model?"

Workflow optimisation is important for making ground model development more efficient. Survey responses show strong support for better cross-disciplinary planning and improved site investigation methods, with nearly 90% of participants seeing moderate to major added value. An example of improved site investigation methods is presented by Santos et al. (2023), who explore methods to increase the accuracy and repeatability of G_{max} measurements using seismic CPT.

Interviewees highlighted that shortening lead times is another aspect of workflow optimisation. This could be achieved by reducing reliance on laboratory testing and increasing the use of in situ testing, provided that quantitative information directly relevant to design can be obtained in situ. This approach would help mitigate compounding uncertainties related to sample disturbance, re-consolidation to estimated in-situ stresses, and other factors. However, certain properties such as clay plasticity still require laboratory testing, and visual inspection of the material remains important. While there may be future incentives to increase reliance on in situ testing for design parameters to speed up developments, it is expected that laboratory testing will still be a necessary part of foundation design.

Ground models for floating sites will also require adapted workflows. These sites are typically in deeper waters with less glacial influence, resulting in softer marine sediments and simpler stratigraphy compared to nearshore fixed-bottom sites. For example, Rasmussen et al. (2024) describe Gulf of Maine sites dominated by very soft fine-grained sediments, while Petrie et al. (2022) present Utsira Nord with marine and clay-rich layers. These conditions may simplify data interpretation and enable more streamlined modelling approaches. However, deeper water settings also introduce additional considerations for ground models (such as mass transport deposits, sediment discontinuities, and faults) as these features are vital for estimating the potential for future submarine slides that could impact development.

Approximately 65% of respondents see moderate to major value in **automation**. In this context, automation refers to the use of algorithms or scripted workflows to reduce manual effort in repetitive or time-consuming tasks. Automation shows clear benefits for specific tasks such as data processing, particularly in large-scale projects. However, the complexity of automation varies significantly depending on the data type. For example, processing CPT data is relatively straightforward, while processing seismic data involves more technically demanding steps. Each site also presents unique challenges, and insights from in-depth interviews suggest that standardisation may, in some cases, be more beneficial than automation.

Standardisation is widely seen as important for improving integration and efficiency. Nearly 80% of survey participants rated its value as moderate to major. Nevertheless, differences in regional practices, legal frameworks, and conventions (such as the use of metric versus imperial units) continue to complicate integration. Addressing these inconsistencies is critical to reducing manual work and improving consistency across workflows.

Regional approaches to site investigation and data acquisition further illustrate the varying degrees of standardisation and centralisation across the offshore wind industry. In the Netherlands and Belgium, site investigation data (sometimes very detailed) are made available by the authorities to accelerate the development and reduce costs for the bidding. Denmark is also moving toward a more centralised model for preliminary site investigations. In the Asia-Pacific region, particularly Japan, the government is implementing centralised preliminary investigations with the aim of reducing risks, shortening lead times, and creating a more predictable environment for investors. A key focus of the Japanese system is to minimise conflicts with fisheries. In contrast, in Taiwan, site investigation remains the responsibility of the developer, which can result in multiple developers surveying the same site to support their bids.

These examples highlight how regional frameworks influence the timing, cost, and availability of geotechnical and geophysical data. Greater alignment and standardisation across jurisdictions could help reduce duplication of effort, improve data quality, and support more efficient ground model development.

3 DESIGN

Design is a key stage in offshore wind projects, influencing both cost and performance. It involves selecting suitable foundation concepts, considering site conditions, and meeting industry standards. This section looks at the main factors affecting concept selection, provides an overview of common foundation concepts, and discusses current design challenges such as requirements in current guidelines and certification issues. It also reviews design drivers and ongoing research, from serviceability to installation, and ends with suggestions for improvements based on the survey results.

3.1 *Concept selection*

Concept selection is influenced by multiple factors, including both geotechnical and non-geotechnical considerations. Ciavaglia et al. (2023) describe a typical workflow for this project phase, primarily from a geotechnical perspective. Key factors include the supply chain constraints, availability of vessels for site investigation (SI) and installation, turbine size and vessel availability for that turbine size. Survey responses (Figure 12) show that geotechnical and geological conditions play a prominent role in concept selection, followed by considerations such as water depth, supply chain and a proven track record with a particular foundation design.

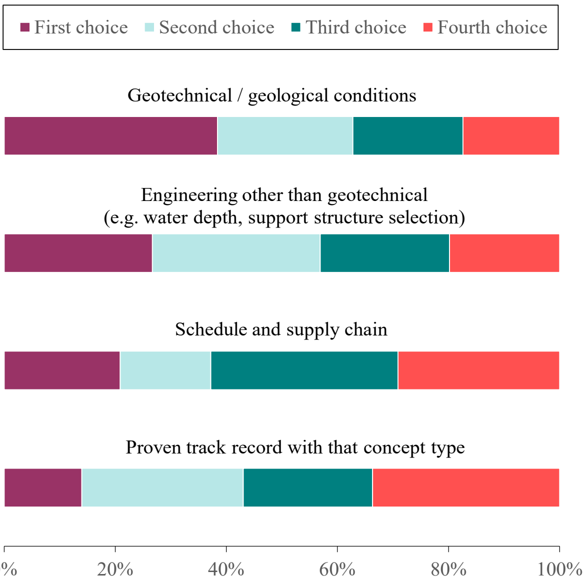


Figure 12. Factors that influence concept selection, responses from survey.

Most survey responses were based on project experience (Figure 13), with the largest group (35%) having 15-30 years' experience and 63% having more than 10 years.

Insights from in-depth interviews with a smaller number of industry representatives highlighted that cost is critically important. Risks and opportunities – including geotechnical challenges – are often evaluated in monetary terms to support informed decision-making. Capital expenditure (CapEx) in offshore wind developments is high (GWEC, 2025; NREL, 2024; ORE Catapult, 2025) and therefore has a far-reaching influence on the entire project.

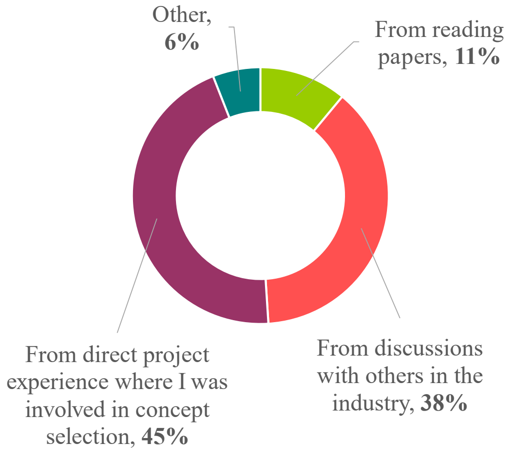


Figure 13. Experience in concept selection, responses from survey.

Figure 14 shows how the installed capacity of foundation concepts and anchoring systems for offshore wind turbines has evolved over time. Figure 15 illustrates some common substructures and foundations. For many years, **monopiles** have been **the default concept choice**, followed by jackets (piled jackets or suction bucket jackets) and high-rise pile caps. High-rise pile cap substructures (Figure 16) are more common in Asia than in Europe. They consist of multiple piles driven into the seabed, connected by a flat, stable cap that supports the wind turbine tower (Wang et al. 2018).

All interviewees confirmed that monopiles remain the default choice for bottom-fixed offshore wind due to their high level of **industrialisation** and comparatively perceived low cost. This applies globally, even at sites with significant risk of monopile-boulder interaction. Other foundation concepts are considered only when monopile foundations are not economically feasible. This can occur due to:

- Water depth: Monopiles are currently used in water depths of up to 60 m, and in some cases even 70 m. While they could be designed for larger water depths, they become economically uncompetitive because longer monopiles introduce dynamic challenges. As length increases, the natural frequency of the support structure decreases, making it harder to avoid resonance with wave and turbine excitation frequencies. Addressing this requires larger diameters and added stiffness, which increases design complexity and cost.
- Ground conditions: For example, very soft soils off China which favour pin-pile jackets, while seabeds with shallow bedrock may lead to the use of suction bucket jackets.

Jackets tend to be more expensive than monopiles due to manufacturing and installation. Jackets are welded manually, which contrasts with the automated industrialised production of monopiles. The reliance on manual fabrication also limits parallel production capacity, as only a few yards have suitable facilities, which further drives up jacket costs. Installation is a also a multi-stage process: first, piles are driven into the seabed, often using a pile installation frame (template) for precise positioning; then, the jacket structure is lowered onto the piles, with the legs either stabbing into pre-installed piles or driven through skirts on the jacket; finally, grouting secures the connection between the piles and jacket.

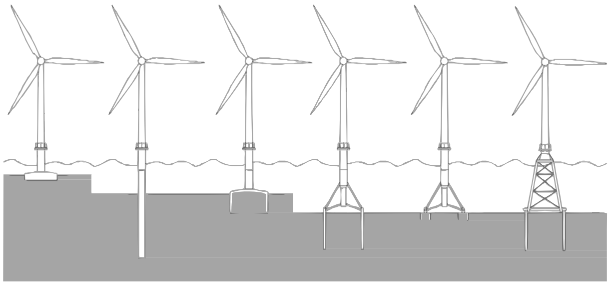


Figure 15. Common substructures and foundations, adapted from Kallehave et al. (2015). From left to right: gravity-based, monopile, monocaisson, tripods and piled jacket.

A recurring theme is **risk**: monopiles are the default solution because most of their associated risks in typical projects have already been addressed. Choosing any other concept – or introducing improved design and installation methodologies for existing concepts – introduce new learning curves for the organisation and requires confidence in the alternative concept. This can be seen in a geotechnical consideration that is rising in prominence: **installation risk**, such as pile run (rapid,

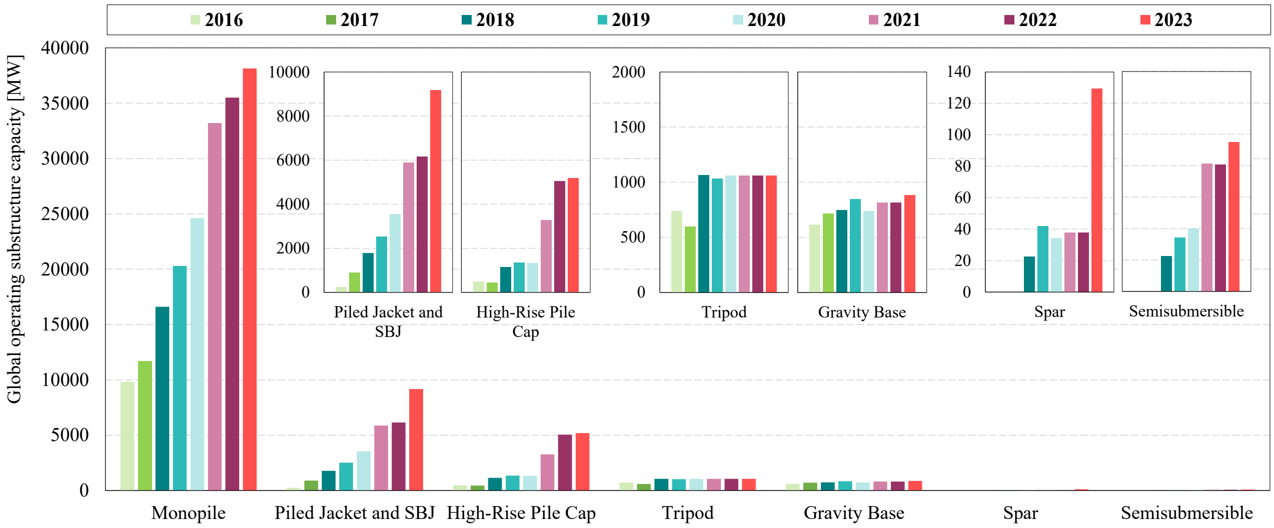


Figure 14. Evolution of installed capacity of foundation concepts and anchoring systems for offshore wind turbines by foundation type from 2016 to 2023. Source: NREL.

uncontrolled penetration, with incidents reported off Taiwan) or refusal during installation. Vibro-driven pile installation is increasingly considered as an alternative to impact-driven installation, especially where there is risk of pile run. The offshore wind industry is gaining experience with vibro-driving of these large diameter piles and confidence in post-installation pile performance.

Offshore wind farms are large, highly complex infrastructure developments at sea, with a multitude of interfaces between teams and organisations. To manage this complexity, the foundation concept needs certain level of **standarisation**, including technical aspects extending through the supply chain as well as non-technical aspects. For example, the turbine manufacturer (typically not a geotechnical engineer) should be able to model the foundation, since they are responsible to evaluate the loads above the transition piece. Insurance companies and lenders, willing to invest in the project, fall under non-technical (but clearly important) aspects. Certification, on the other hand, does not typically affect concept selection, as the certifier is often only engaged later – a missed opportunity in some cases.

Another parameter influencing concept selection is the **maturation of technical solutions,** as new aspects gain in importance when the offshore wind industry moves to a new region. For example, seismic considerations can be design-driving in parts of the Asia-Pacific (APAC) region. Confidence in understanding monopile behaviour under seismic conditions was still developing when the offshore wind industry first established in Taiwan, which influenced the selection of piled jackets as the preferred foundation solution. Local content requirements (e.g. fabricating foundations locally) can also play an influential role.

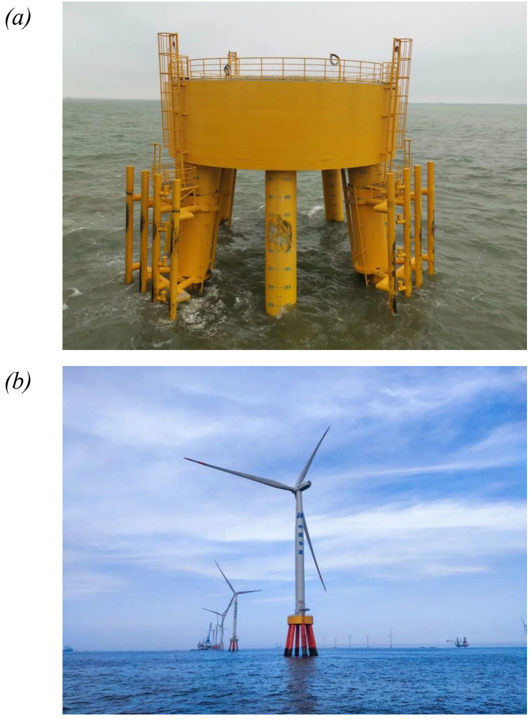


Figure 16. High-rise pile cap substructures: (a) in Yuhuan, China (International Wind Power, 2021), and (b) in Cangnan 4, China (DiscoverWenzhou, 2022).

Supply chain considerations are often critical. A robust global supply chain for monopiles significantly contributes to the continued dominance of monopiles, including the availability of vessels. These vessels are evolving to accommodate the increasing size and weight of turbines and monopiles. However, the rapid and continuous evolution of turbine sizes adds challenges to turbine and vessel selection, as these typically must be booked several years in advance. This requires anticipating future trends alongside the progression of offshore wind project activities, including geotechnical foundation design. Furthermore, these trends must be anticipated over an even longer time horizon for the design and production of new offshore wind installation vessels.

Returning to the central theme of risk, early geotechnical risk assessment was highlighted as essential, as concept selection is evaluated in terms of risk. A pragmatic way to address risks is to assign costs to the consequences. The cost model is viewed as key to the risk assessment and can be represented as a risk and opportunity matrix, for instance, to evaluate opportunities that an alternative foundation concept may offer. Offshore wind projects are facing margin pressures due to a variety of factors, including rising costs, supply chain disruptions and macroeconomic challenges, hence costs are tightly controlled. As decisions are made at a managerial rather than technical level, assigning cost to each option allows informed decision-making, where the best option is typically seen as the lowest-cost option. Therefore, being able to **quantify uncertainty** in geotechnics and in engineering calculations – and the probability of specific outcomes – is valuable for the industry. An increasing number of projects are on the edge of being risk acceptable. With more data collected, risk can be reduced (e.g. risk of installation refusal especially at complex sites, also depending on the installation method not only the foundation concept).

It is important to distinguish between typical projects and **pilot projects** with respect to risk and timeline. The timeline and level of innovation in each project depends heavily on the discovery of less familiar materials or any other conditions. Examples of innovative foundation solutions are discussed for instance in Palix (2025), which draws on experience from a number of offshore wind farms off the French coast that include rocky formations.

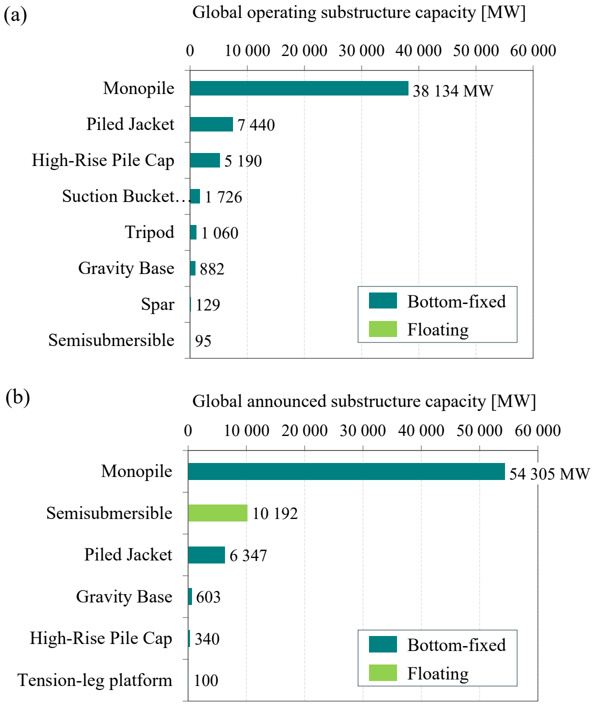


Figure 17. Offshore wind capacity by foundation type: (a) operating capacity by 2023, (b) publicly announced capacity by the end 2023, adapted from McCoy et al. (2024).

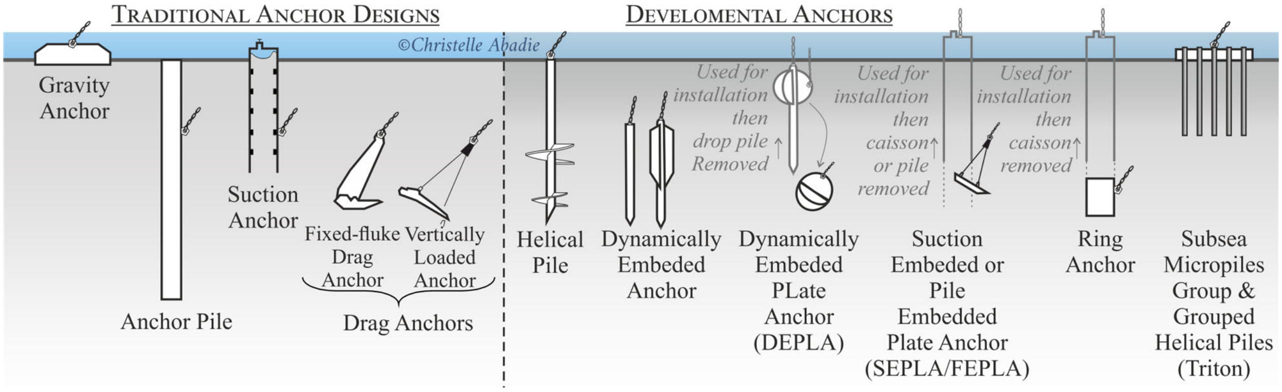


Figure 18. Anchoring systems for floating offshore wind (Abadie, 2025).

Looking towards the future, the offshore wind industry is expected to continue evolving, as it has over the past decades. Historical constraints, such as anticipated limits to monopile dimensions, have consistently been surpassed through advances in manufacturing, installation vessels, and lifting equipment. The data from NREL (McCoy et al., 2024), presented in Figure 17 supports this trajectory: monopiles remain the dominant substructure type in both the global operating fleet (38.1 GW) and publicly announced capacity by the end of 2023 (54.3 GW). However, the increase in announced capacity for floating substructures, particularly semisubmersibles (10.2 GW), indicates a diversification where anchoring systems will become more prevalent. This trend reflects the industry's response to deeper water sites and broader geotechnical challenges. Figure 18 illustrates a schematic view of a selection of anchoring systems for floating offshore wind, including traditional anchor designs as well as developmental anchors. Not all anchors are symmetric in geometry, which affects their suitability for sharing mooring lines.

Geotechnical challenges are closely linked to concept selection, as soil and seabed conditions can constrain the feasibility of different substructure types. While geotechnical research contributes with valuable input at this stage, its advancements are often more widely in the context of detailed foundation design and installation, which is the focus of the sections.

3.2 *Geotechnical design*

Foundations for offshore wind turbines are designed according to the limit state philosophy, which ensures structural safety and serviceability under defined loading conditions. This involves verifying performance against ultimate limit states (ULS), such as failure or collapse, serviceability limit states (SLS), such as excessive deformation or displacement, as well as ensuring safe installation to the planned depth. In this context, design drivers are the dominant factors that govern foundation sizing.

Survey responses (Figure 19) indicate that design drivers vary across foundation concepts: serviceability considerations are most important for monopiles, while piled jackets and anchors are primarily governed by ultimate limit state requirements. Suction bucket jackets stood out as the concept most influenced by installation risk, although successful installation is critical for all foundation types. Early availability of a high quality, quantitatively integrated ground model was viewed by the survey respondents as the most significant factor (29%) for improving foundation/anchor design in terms of cost and reliability, followed by incorporating recent advances in technology or research into design guidelines (23%). Figure 20 summarises these findings.

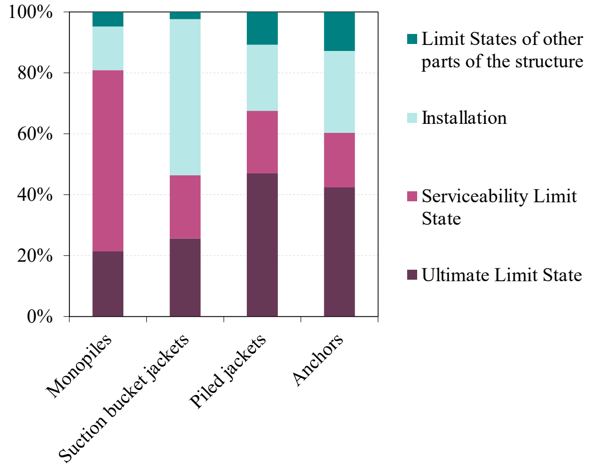


Figure 19. Key design driver by foundation concept, responses from survey.

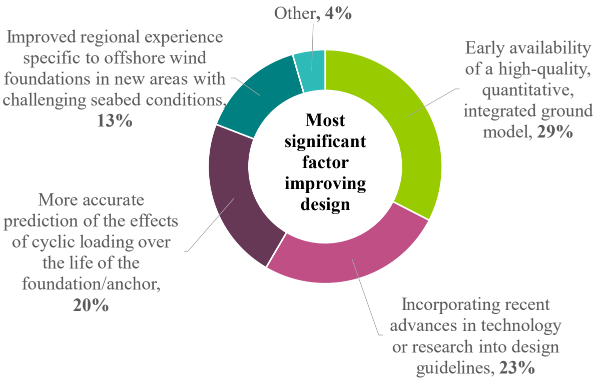


Figure 20. Factors that could significantly improve cost and reliability in foundation/anchor design, responses from survey.

There was strong agreement among the survey respondents (Figure 21) that the geotechnical design for different foundation and anchor types is at varying levels of maturity, reflecting different states-of-the-art. This was echoed in the interviews.

Interview responses also highlighted themes related to foundation design and its intersection with certification and standardisation, including:

- Installation and the effect of the installation process
- Predicting offshore wind turbine response to cyclic loading over the design life
- Standards and certification
- Uniformity across the industry

Respondents also suggested aspects that could accelerate offshore wind development and guide future research. These aspects are elaborated in the following sub-sections.

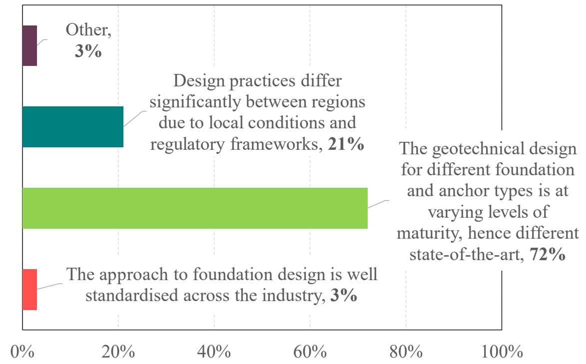


Figure 21. Responses to survey question: “Which of the following statements do you think best describes the current state of practice in offshore geotechnics for offshore wind energy developments?”

3.2.1 *Installation and the effect of the installation process*

Traditionally, foundations for offshore wind turbines have been designed based on capacity and stiffness, with only a check that installation is possible. Installation considerations are increasingly moving into focus, and it may become necessary to optimise for installation as well. Installation refusal is not only becoming more likely, but it is also very expensive (potentially tens of millions of dollars for a single incident) and there may no longer be straightforward mitigation measures such as a larger hammer to achieve penetration to target depth.

Understanding foundation installation in complex (e.g. layered, heterogeneous) seabeds is gaining prominence, including the effectiveness of installation strategies and post-installation foundation performance. For **suction buckets**, where installation has been identified as a key design driver (Figure 19), contributions from research and industry together have moved the industry forward as synthesized in Bienen et al. (2025). Suction bucket installation has been demonstrated in clean sand, silty sand, clay and layered soil conditions, with expected in-service performance now supported by field measurements (Shonberg et al., 2017; Hamdan et al., 2023, Harte et al., 2025).

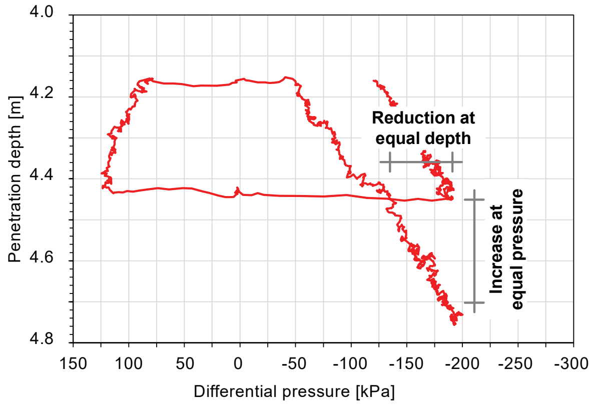


Figure 22. Suction pressure versus vertical displacement during pressure cycling, modified after Sturm (2017).

Installation strategies such as **pressure cycling** (Tjelta, 2015; Sturm, 2017) can assist in penetrating the suction bucket skirts to target depth while keeping the required suction within allowable limits and limiting plug uplift. The reduction of penetration resistance at equal depth and the increase in penetration at equal pressure after pressure cycling is illustrated in Figure 22. Two-way pressure cycling, where penetration is reversed in each cycle, has proven effective in clay based on both centrifuge and field test data (Mani et al., 2024b). Skirt friction, which is reduced by pressure cycling, also reduces short-term uplift capacity compared to monotonic suction installation; but uplift capacity recovers over time through consolidation, as demonstrated by extraction data from centrifuge tests (Mani et al., 2024b). In sand, pressure cycling was found to be less effective in reducing penetration resistance; the modest reduction achieved at greater depths was shown to be regained after a few days (O’Loughlin et al, 2023). These findings, two-way pressure cycling being effective in clayey soils but less so in sandy soils, are consistent with full-scale field trials (Jones and Harding, 2023). Pressure cycling in layered soils has been shown to be effective when the applied suction remains below the pressure required for plug uplift (Mani et al. 2024a).

Suction bucket installation can be predicted with established methods. Existing CPT-based prediction approaches can be extended to incorporate cyclic data, with good agreement shown against pressure-cycled suction bucket installation data from centrifuge tests and field trial installations (Mani et al., 2024a, b). Pressure cycling has been beneficial in installing the 114 suction bucket jackets at the Seagreen offshore wind farm but remains challenging in heterogeneous soil conditions, where a CPT profile may represent only 0.0015% of a single suction bucket footprint (Hamdan et al., 2025). Monitoring of eleven suction bucket jackets for up to six months post-installation documented the effects of grouting under the lid, turbine placement and scour protection on the natural frequencies (Gütz et al., 2025).

Issues such as **monopile-boulder interactions** (Nietiedt et al., 2023; Randolph et al., 2025; Zinas et al., 2025) are primarily evaluated in terms of structural integrity of the pile, which may lead to design changes such as increasing wall thickness to mitigate the risk of pile tip damage and extrusion buckling.

Limiting acoustic emissions during the installation process is increasingly important in some regions, driving attention towards foundation solutions such as suction bucket jackets and innovation in monopile installation methods (discussed later). Foundation stiffness post-installation, particularly for monopiles, has received research attention (e.g. Phuong et al., 2016; Bienen et al. 2021, Fan et al. 2020a, b, Staubach et al., 2020; 2022) but remains an area that requires further study, especially for vibratory installations. For example, Wang and Lehane (2023), assessed several p-y approaches for predicting lateral pile response in sand following impact- or vibro-driven installation, while Ghasemi et al. (2023) suggested adjusting stiffness parameters within the PISA framework to better capture the lateral response of vibro-driven piles in sand.

The effect of suction installation on the post-installation response of suction bucket jackets has also been an area of interest, with Bienen et al. (2025) providing an overview of findings from recent research and field monitoring.

3.2.2 *Predicting offshore wind turbine response to cyclic loading over the duration of the design life*

Following installation, foundations are subject to millions of load cycles over the duration of their design life. While the initial stiffness may be affected by the installation process, as discussed above, the foundation response is likely to change from this initial post installation state during the design life due to cyclic loading (e.g. Staubach et al., 2020). Cyclic behaviour should be accounted not only in foundation design, but also in structural load analyses, as this significantly improves the accuracy of load predictions (see, for instance, Page et al., 2019). In particular, accounting for foundation damping in load analyses has been shown to provide more accurate fatigue load estimates (Sørum et al., 2022, Bergua et al., 2022).

In the geotechnical design, the cyclic response can be design-driving, and the significant body of research devoted to offshore wind foundation response under cyclic loading reflects the effort to improve understanding and prediction methods (e.g. Byrne et al., 2025; Pisanò et al., 2025). However, the first offshore wind farm was only constructed in 1991; hence, there is limited field data covering the full 30-year design life to validate predictions. While cyclic degradation is often assumed, the response may also include periodic recovery, or even overall stiffening (e.g. Sturm, 2014 or Nicolai et al., 2017). In addition, displacement or rotation accumulation could be more critical than changes in stiffness over the design life. As many of these aspects remain unresolved, and the cumulative effects are rarely considered, confidence in current methods for predicting foundation response over the duration of the design life is low. The complexity of offshore wind turbine foundation response to cyclic loading stems from the multitude of factors influencing the behaviour, including soil type, properties and state, magnitude, rate, directionality and eccentricity of average load and cyclic load amplitude, to name a few.

A structured approach for predicting foundation performance under long-term, coupled effects is the Whole-Life Geotechnical Design (WLD) philosophy (e.g., Gourvenec, 2022). WLD formalises the concept of repeatedly checking geotechnical limit states against the current soil properties, which are updated to reflect preceding actions and accumulated responses. This contrasts with traditional single-check "worst-case" methods and enables consideration of time-dependent changes in soil behaviour. For the geotechnical design of offshore wind foundations, WLD provides a basis for modelling the processes that the soil undergo under cyclic loading. These processes include cyclic degradation (i.e. softening caused by excess pore-pressure generation, reducing shear strength, and stiffness) and subsequent consolidation, which restores strength and stiffness as pore pressures dissipate and void ratio decreases. Figure 23 illustrates this evolution, drawing on experiments by Hodder et al. (2013) and further developed by O'Loughlin et al. (2020). These experimental insights were followed by the development of an effective stress framework by Zhou et al. (2019), which estimates penetration resistance by accounting for changes in soil strength due to remoulding and reconsolidation. Capturing this evolution is essential for predicting ratcheting, defined as accumulated displacement or rotation, which is critical for assessing long-term foundation performance under cyclic loading.

Figure 24 illustrates the concept of whole-life imposed actions and evolving soil response through superposed monotonic and cyclic actions (Gourvenec, 2022). Various modelling approaches can be employed to capture events and their impact in a cumulative manner, depending on the required speed and complexity. Cyclic contour diagrams, derived from laboratory element tests (e.g., direct simple shear, triaxial), relate stress ratio and number of cycles to strain or pore-pressure accumulation (Andersen, 2015). These diagrams allow complex storm histories to be condensed into an equivalent number of cycles (N_{eq}), which informs cyclic degradation factors in design. For higher fidelity, 3D finite-element (FE) models incorporating advanced constitutive laws are used to simulate deformation accumulation and changes in stiffness. Examples include SANISAND-MS (Liu et al., 2019) as an implicit model simulating individual cycles, and the High-Cycle Accumulation (HCA) model (Niemunis et al., 2005) as an explicit approach that transitions from low-cycle simulation to an accumulation mode while preserving long-term trends. A comparison of implicit and explicit modelling approaches against laboratory test results is presented in Jostad et al. (2020).

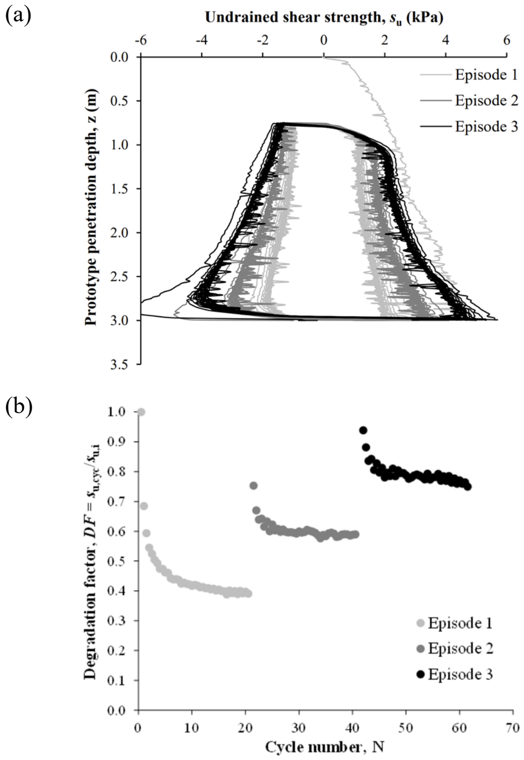


Figure 23. Changing in soil strength due to cyclic remoulding and reconsolidation, after Hodder et al. (2013) and O'Loughlin et al. (2020).

Other models focus on reproducing foundation–soil interaction under cyclic loading, such as p–y curves or macro-element formulations. For monopiles, projects such as MIDAS (Pisanò et al., 2025) have developed CPT-based cyclic soil-reaction models for 1D analysis in sands to improve predictions of deflection and rotation accumulation. Similarly, the PICASO project (Byrne et al., 2025) advances monopile design under lateral cyclic loading, interpreting field observations within the HARM framework (Houlsby et al., 2017). For anchors, macro-element models like CLAP (Abadie and Page, 2025) have been introduced to represent the response of anchors to multidirectional loading, including prediction of accumulated displacements and rotations.

3.2.3 *Standards and certification*

Certification of an offshore wind farm development includes verifying the foundation design to ensure that it meets safety and performance standards. This process, often conducted by independent third-party organisations, provides checks within the project development phase and reduces risk for investors and insurers.

Certification must comply with standards that follow a certain hierarchy. Although certifiers are typically not involved until later in the project, involving them early (especially for players newer to the industry) can save money, as making corrective changes during certification is difficult. This ultimately relates to risk management and navigating the space between developer, designer, and certifier. It includes agreement on the basis for the certification and which aspects

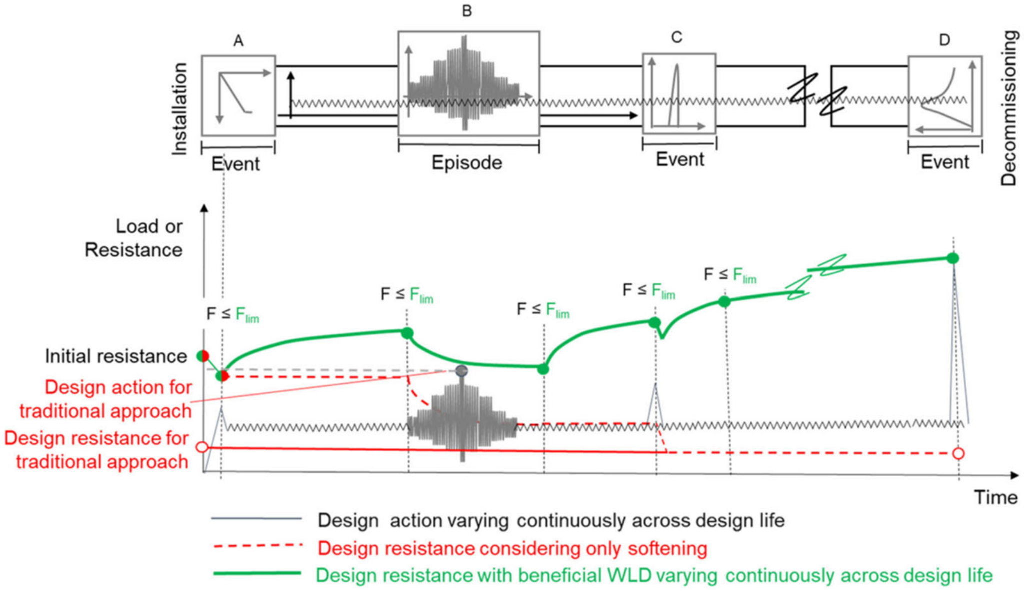


Figure 24. Schematic of whole life imposed actions and resistance illustrated through superposed monotonic and cyclic actions and evolving soil response (Gourvenec, 2022).

are to be certified, within regional requirements. In some countries, for instance, installation is not part of certification but still affects fatigue design. Other aspects may include the allowable tilt over the design life of the structure, which is typically limited to 0.5º (of which usually 0.25º may be tolerated during installation and the remaining 0.25º over the millions of load cycles over 30 years of operation).

Industry standards are generally not prescriptive, allowing flexibility in approach and room for evolution of the state of practice. This means certification may be provided on the basis of monitoring of the field response, and design challenges such as cyclic degradation of the foundation response may not be comprehensively addressed in the standards. As a result, a wide range of approaches to predicting cyclic foundation response over the design life are submitted to the certifier, with their validity still uncertain. The industry agrees that reaching consensus on how to predict offshore wind foundation response to cyclic loading over the design life is important, including factors such as the effect of scour protection on the performance. This may require development of improved models (e.g. Kheffache et al., 2025).

Any useful model needs to be anchored in science, developed with practical application in mind, and validated against physical measurements, including field observations.

3.2.4 *Uniformity across the industry*

The offshore wind industry is not seen as uniform. Even within Europe, there is large variability, according to the interviewees. This extends to use of certain methodologies – for example, the PISA design approach for laterally loaded monopiles (Burd et al., 2020; Byrne et al., 2020) – which in practice sees many interpretations or is even applied in ways that are not consistent (e.g. using undrained cyclic contour diagrams to correct drained p-y curves).

The design basis may also differ regionally (with the SPT rather than CPT underpinning design in Japan) and is not at the same level of advancement around the world. Opportunities to optimise foundation design are often linked with the generosity of the timeline, with China for instance opting for compressed timelines over optimised design, as discussed above.

Coordinating an idealised benchmark exercise across the industry and the regions with offshore wind worldwide would provide insights into the variability of approaches and results. Such an exercise could highlight the range of predictions and provide pointers for improvements that could enhance the uniformity across the industry.

3.2.5 *Accelerating development and suggestions for future research*

Looking forward, several aspects could accelerate the development of offshore wind.

The **speed of the approvals processes** is a significant non-geotechnical factor in which improvements could accelerate development.

Finding **agreement on modelling foundation response under long-term cyclic loading** and adoption of an industry-wide agreed methodology as discussed above would be beneficial. A recent blind prediction test (Machaček et al., 2025) highlights the dispersity of predicted results. This issue is becoming more pressing as turbines become larger and natural frequencies fall closer to excitation frequencies. As a result, accurate modelling of stiffness and damping, including the effects of scour protection, increases in importance. Global installed offshore wind capacity reached 83 GW (GWEC, 2025), and the vast majority of bottom-fixed offshore wind turbines are supported by monopiles. None of these thousands of turbines have been seen to tilt excessively, which may suggest that current design is conservative with respect to foundation displacement and rotation.

Monopiles have been installed in a range of **challenging soil conditions**, including sites with boulders or glauconitic soils, and are being considered in offshore wind farm developments in Australia where seabeds may feature variably cemented carbonate sediments. Research is under way to continue to advance understanding of the installation and post-installation response and determine the limits of practical monopile application. Currently, uncertainty of expected response – particularly regarding refusal and pile tip damage, or pile run – translates into **installation risk**.

Across the offshore wind industry, there is strong interest in vibro-driven pile installation as it can be faster, cheaper, and less noisy than impact-driven pile installation (hence avoiding noise mitigation measures). Because the pile is held by the clamps of the vibro-driver, which is suspended from the crane, the risk of pile run is also mitigated. **Prediction methods for vibro-driven piles** have been developed (Holeyman and Whenham, 2017; Holeyman et al., 2020; El Haffar et al., 2023; with AllWave-VDP and GRLWEAP available as commercial software) but could still be improved to capture key aspects of the response, correlated to in situ penetrometer testing. Refusal may currently be predicted with higher accuracy than pile penetration velocity, and confidence remains low in estimating the remaining fatigue life of the steel pile after installation. Vibro-driving is expected to produce lower fatigue (and hence larger remaining fatigue life) in most cases than many large impact blows. Measuring stresses during vibro-driven installation can increase certainty. A further complication is that vibro-piling is seen as operator and case dependent, with the operator adjusting the static load held back by the crane (crane tension or hook load) and the applied vibration in response to the conditions while the eigenfrequency of the system changes with pile penetration.

Combining vibro-driving with water jetting could significantly influence the industry, as acoustic emissions during pile installation would drastically reduce with the reduction in penetration resistance. This technology has been trialled (Arntz et al., 2022; Konstadinou et al., 2023). In a separate development, patented technology that relies on **jetting** to substantially reduce the resistance of the surrounding sandy soil to allow the pile to penetrate. This low noise technology was tested on three monopiles at the Gode Wind 3 offshore wind farm (Ørsted, 2024). Effects on the post installation foundation performance need to be understood and accounted for in foundation design.

A potentially disruptive change in foundation design would be **designing directly from in-situ testing**, which could reduce cost and time. Laboratory testing seen as expensive and time consuming and often lies on the critical path of offshore wind projects, potentially delaying design. Design directly from in situ site investigation data would significantly accelerate development. If design methods were standardised and based on cone penetrometer testing (CPT) data, this could accelerate development and improve uniformity across the industry. Foundation design may, as a consequence of the absence of laboratory testing, be less optimised, but a small degree of conservatism would likely be negligible overall. Philosophically, this reverts to risk appetite and industry regulation. It also provides impetus for academia and industry to collaborate in the development of accurate CPT-based prediction methods and adoption of penetrometer testing protocols (and possibly penetrometers other than piezocones) to obtain relevant in situ data for reliable design.

A less radical challenge to the established design process is discussed in Shonberg (2024), which illustrates **opportunities within project timelines to make foundation design decisions** while retaining flexibility in parts that have a shorter lead time. Drivers beyond geotechnical factors need to be considered, including interaction with other disciplines such as primary steel and supply chain considerations (decisions need to be made to meet deadlines). For example, acknowledging different lead times for jacket and pin pile fabrication means final design decisions need to be aligned with the fabrication timeline of the components. In this case, the pile diameter was fixed early to match the jacket design, while the final pile length was optimised later as more geotechnical information became available.

Analysing existing data could be revolutionary. There is a vast amount of laboratory test and in situ penetrometer test data, as well as performance data from many installed offshore wind turbine foundations across of the North Sea, and increasingly in other regions as well. Data sharing across the industry would aid the creation of integrated ground models (addressing the survey response of the importance of early availability of high quality ground models) and also facilitate closing the loop between predicted and observed response, which can then flow into further improvement of models. Field-validated prediction models enjoy high confidence and acceptance across the industry, such that support of their incorporation into guidelines would likely receive strong support.

Some of these examples will be discussed further in the following sections.

4 INSTALLATION

Successful installation is essential for a foundation to perform as intended and support a wind turbine throughout its design life. Installability (e.g. drivability for piles) is checked during the engineering design phase, and installation equipment is selected based on anticipated requirements to overcome penetration resistance. Offshore, the operator plays a key role in executing and influencing the installation process.

Industry perceptions of installation practices were explored through the survey. As discussed above, each foundation type is at a different level of technological maturity and presents different challenges and requirements associated with installation, both from design and operational perspectives. This variation was reflected in responses to the statement: "*The operational aspects of foundation and anchor installation are at a similar state of the art across the industry*". A majority of respondents (72%) disagreed, while 28% agreed (Figure 25).

Survey participants noted that monopiles have received more attention than other foundation types, whereas anchors for floating offshore wind are still less mature and less commonly used. Respondents also highlighted the absence of standardised methods for predicting installation behaviour, with practices varying across organisations and often relying on internal experience. Operational challenges such as the scale of equipment and the need for custom solutions were frequently mentioned. Limited transparency and knowledge sharing were also identified as factors contributing to inconsistency across the industry.

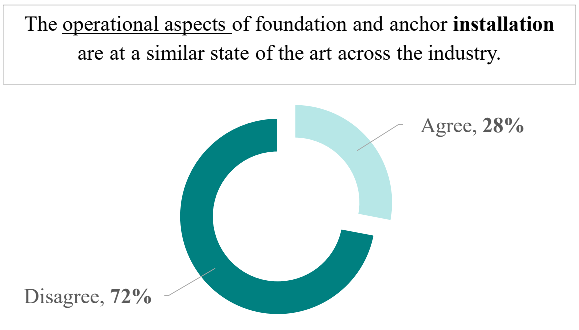


Figure 25. Responses to survey question: "The operational aspects of foundation and anchor installation are at a similar state of the art across the industry."

Given the uneven state-of-the-art in installation practices and the prevalence of piles both as foundation and anchoring solutions, survey responses indicated significant **innovation** potential in low-noise pile installation. Specifically, 49% of respondents saw this as a key area for future development (Figure 26), and interviewees also anticipated that low-noise installation techniques can significantly change the industry in future. This section will therefore focus on innovations in foundation installation of piles.

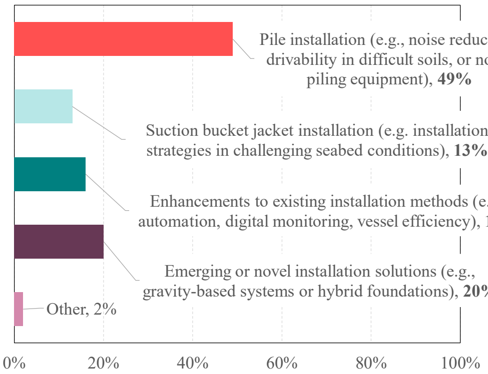


Figure 26. Responses to survey question: "Where do you see the most significant innovation in foundation installation, considering recent, current, or near-future developments?"

Vibro-driving, jetting, and screw piles were frequently mentioned as promising methods to reduce noise, improve drivability, and accelerate operations. Several participants highlighted the growing maturity of vibration-based technologies and the potential of suction bucket jackets and anchors in specific soil conditions. Innovations in digital tools, such as digital twins and installation monitoring systems, were also noted for their potential to improve accuracy and reduce offshore work. Respondents emphasized the need for better soil resistance prediction models and more reliable installation in challenging ground conditions. Overall, the feedback suggests that innovation is being driven by environmental constraints, logistical efficiency, and the need to adapt to increasingly complex geotechnical settings.

4.1.1 *Reducing acoustic emissions driving innovation*

This section focuses on innovative methods to reduce acoustic emissions during monopile installation as monopiles are currently and remain predicted to be the dominant foundation solution (Figure 17).

The traditional impact-driven pile installation has a percussive acoustic signature, with individual hammer blows impacting the pile (in air), causing deformation in the pile which leads to the sound radiating into the water column but also being propagated through the seabed. Tsouvalas et al. (2022) and Erbe et al. (2025) provide further information on pile driving and acoustic emissions.

The larger the penetration resistance, the more energy is required to be supplied to the pile through the impact hammer to facilitate installation. This is generally correlated with larger piles (required to support larger turbines) and stronger soils.

As pile driving noise can cause temporary or permanent hearing loss, other injuries and behavioural changes in marine mammals, especially those that rely on sound for communication and navigation, limits have been placed on acoustic emissions during the construction phase of offshore wind farms. These differ by jurisdiction and can specify limits based on peak sound pressure level and sound exposure level at a certain distance (e.g. the German BSH), or consider sound exposure over a time period (such as in the US, BOEM 2023). Some regulations consider the ambient (background) noise level when setting limits, e.g. Australian guidelines.

Acoustic emissions can be mitigated at the source, though noise barriers (bubble curtains) are the most common measure, often in combination with receptor protection strategies (such as restricting construction activities to specific seasons to minimise the impact on sensitive marine life and/or soft starts whereby the impact energy of the hammer is reduced at the start and gradually increased to its nominal value with the idea being to allow fish or marine mammals to move away).

The noise regulations have prompted a number of **alternative methods** to be considered **for pile installation** for offshore wind farms. Some of these aim to modify the impulse signature (e.g. PULSE®, EQ-Piling), others are borrowed from onshore practice, e.g. vibro-driven pile installation, or add another element such as torsional vibration (Gentle Driving of Piles GDP) or water jetting to vibro-driving or indeed rely solely on jetting. These are all at different Technology Readiness Levels and will be discussed in turn. Lowering acoustic emissions below the threshold negates the need for mitigation measures, which translates into cost savings but also further CO_2 savings if the additional vessel(s) and diesel-powered compressors to generate bubble curtains are not required. Further, alternative pile installation methods may substantially reduce pile fatigue.

The PULSE® is a module that can be used in combination with an impact hammer and has been used on a number of offshore wind farm installations. It consists of two pistons in a housing with an adjustable column of fluid in between which allows control of the impact characteristics, such that the length of an impact may be doubled. The corresponding reduction in acoustic emissions may or may not be sufficient to operate without a bubble curtain, depending on the conditions.

The Menck Noise Reduction Unit (MNRU) also changes the force characteristics of the hammer to transfer the energy over a longer period, which results in a reduction of the underwater noise peak by 9-12 dB.

EQ-Piling (Figure 27) also aims to reduce noise emissions at the source by delivering the impact over a time that is 15-20 times longer than that of conventional impact-driving. This is achieved by using a large sea water tank, lifted by hydraulic cylinders, as the drop weight and employing nitrogen buffers to act as cushions. This technique is not limited to a certain anvil or ram weight size. It is currently undergoing certification and has not yet been employed on offshore wind farm construction. The prolonged blow resembles more a push or jacked installation, which may increase stresses around the pile tip and inside the pile. A system designed for investigation of the geotechnical response due to a single blow at realistic stress levels in a geotechnical centrifuge is described in Quinten et al. (2022).

Figure 27. EQ-Piling technique (IQIP).

Vibro-driving results in overall lower acoustic emissions but also a different acoustic signature (Tsouvalas et al., 2022; Erbe et al., 2025) resembling a continuous hum rather than individual blows. Rapid yet controlled pile installation makes vibro-driving an attractive choice for offshore wind construction, though confidence in the post installation foundation stiffness is not yet established as the industry lacks experience with piles installed to full depth by vibro-driving. To date, vibro-driven monopile installations offshore have been completed by impact-hammering. Equipment hire and the time required to switch from vibro-driving to impact-hammering as well as the impact-hammered part of the pile installation all add to the cost.

Vibro-driving is a well established dynamic pile installation method that has been employed in commercial wind farm construction and is extensively used onshore as well. Pairs of eccentric counter-rotating masses generate vertical vibrations, with the applied dynamic force resulting from the combination of eccentric moment and vibration frequency. To install large diameter monopiles by vibration, substantial dynamic forces are required. This is met by modularised design, e.g. using four units with 640 kgm eccentric moment each supplies a total eccentric moment of 2,560 kgm. This eccentric moment together with the frequency of vibrations (squared) give rise to the applied dynamic force.

The static driving force results from the self-weight of the system, but the crane may hold back some of the self-weight by applying crane tension or hook load, where pile penetration is expected to be rapid. During easy vibro-driving, pile penetration speed therefore tends to be limited by the crane release speed. The hook load changes the applied static force, but not the mass or the dynamic force and frequency.

Sufficient pile upward displacement in each cycle, resulting in reversals of the pile shaft resistance and friction fatigue over the duration of vibro-driven installation, full unloading of the tip resistance and softening of the soil below the pile tip leading to tip resistance degradation has been identified as important in vibro-driving (Rodger and Littlejohn, 1980; Dierssen, 1994; Cudmani, 2001; Massarsch et al., 2021; Kazemi Esfeh et al., 2025a), though this requirement may be tempered by dynamic effects and excess pore pressure (Kazemi Esfeh et al., 2025b). The amplitude of the pile displacement is linked to the eccentric moment and dynamic mass of the system with soil resistance influencing the amplitude and pile elasticity becoming important near refusal.

Vibro-driving is a dynamic process which promotes coring (rather than plugging) and reduces stresses along the pile shaft as well as below the tip. The overall pile penetration progress is influenced by the interplay between dynamic and static forces, which can be modified by the operator during installation by application or release of hook load. Piles can be installed by vibro-driving even in dry very dense sand (e.g. Mazutti et al., 2024; Simonin et al., 2025). Recent contributions to advancing understanding of the complex mechanisms governing vibro-driven pile installation include Viking (2002), Doherty et al. (2015), Vogelsang (2016), Chrisopoulos and Vogelsang (2019), Labenski and Moormann (2019), Massarsch et al. (2021), Staubach et al. (2022), Kazemi Esfeh et al. (2025b).

Methods to predict vibro-driven pile installation include proprietary software based on wave equation analysis such as AllWave VDP and GRLWEAP which use empirical factors (Jonker, 1987; Smith, 1960; Randolph and Simons, 1986) to tune shaft and pile tip response in different soils.

Vibro-drivability predictions are not yet at the same level of maturity or accuracy as those for impact-hammered pile installation, though the models are being continuously improved through back-analysis of data from vibro-driven pile installations, e.g. Whenham and Holeyman (2010) compared vibro-driving prediction methods with experimental data and results from full-scale sheet pile vibro-driving tests. As a result of proprietary prediction methods, differing levels of in-house experience and largely confidential field data sets there is significant variation in methodology and knowledge across the industry.

Vibro-driving has been trialled on individual piles offshore (Anholt, Riffgat) and has more recently been employed to install multiple piles in offshore wind farms featuring different soil conditions from sand (Kaskasi) and clay (Moray West) to more complex layered seabed conditions with silts (Hai Long) or glauconitic soils (Coastal Virginia Offshore Wind).

Confidence in post-installation pile performance is lacking, with conflicting reports of measured lateral stiffness being softer or stiffer than impact-driven piles (e.g. Anusic et al., 2019; Achmus et al., 2020; Labenski, 2020; Stein, 2022; Kementzetzidis, 2023; Peccin da Silva et al., 2023; Mazutti, 2024). This is an area of ongoing research.

A **combination of axial and higher frequency torsional vibrations** forms the basis of the GDP concept, which stands for Gentle Driving of Piles. GDP has been used in field tests of 0.762 and 1.6 m diameter piles in field tests at the Massvlakte site at the Port of Rotterdam but not yet offshore. The medium scale field tests included impact-driven and (conventionally) vibro-driven piles for comparison. While results are encouraging, the field data invariably contended with soil heterogeneity and onshore unsaturated soil conditions, which made comparison between tests more difficult and resulted in complex cyclic pile stiffness trends due to the interplay of pile–soil gapping and soil fabric changes.

Another idea to reduce penetration resistance particularly near the pile tip that is being proven up is the **combination of vibro-driving with water jetting**. The Vibrojet® method is being advanced through technology readiness levels (TRL) with the SIMPLE III project expected to elevate the concept to TRL7. Large-scale offshore tests in sandy soils are planned, with the data expected to support certification. Comparisons with impact-hammered and vibro-driven pile installations with respect to cost, underwater noise and fatigue damage in the pile are planned and any differences in refusal depth between vibro and Vibrojet® installations evaluated. Lateral stiffness post installation will also have to be understood.

Available prediction methods for vibro-driven pile installation do not yet include the effect of simultaneous torsional vibrations or water jetting and will need to be further developed.

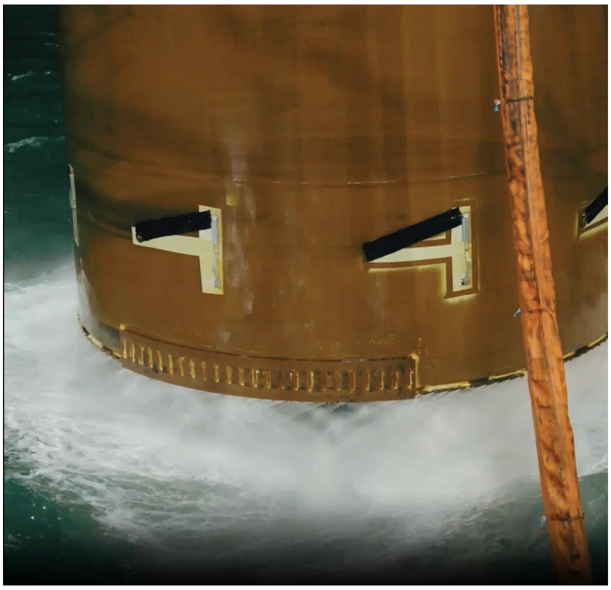


Figure 28. Field tests of pile with water jetting at the Gode Wind 3 wind farm (Ørsted).

Relying solely on **jetting**, this innovative installation method was successfully tested on three monopile foundations at the Gode Wind 3 wind farm in Germany in sandy soil (Figure 28). These foundations now support 11 MW turbines, and the tests reported a substantial further decrease in underwater noise levels to values only marginally above the ambient noise.

A number of these **innovative developments in pile driving** for offshore wind foundations have in common that they **address multiple aspects at the same time** – reducing noise emissions during the pile installation process, but also lowering fatigue in the pile and reducing cost which at least in part stems from faster (yet controlled) installation that does not require additional noise mitigation. The result is more substantial than incremental improvements. A quote from the survey seems fitting here: “Everything reducing actual offshore work (i.e. vessel efficiency, novel hammer / installation techniques, etc) has the largest impact on projects.”

4.1.2 *Additional aspects and ongoing/future research*

Installation complexities can be design driving, as discussed above. Offshore wind foundation installation into chalk (Figure 29a) has been supported by research efforts e.g. through the ALPACA project (Buckley et al., 2023; Jardine et al., 2023; McAdam et al., 2024), with offshore wind farms such as Westermost Rough and Wikinger now in operation. While experience exists in different variably cemented carbonate sediments (Figure 29b) from the oil and gas industry e.g. off Australia (Watson et al., 2019); vibro-drivability of large diameter monopiles and their post installation response is uncertain, though understanding of mechanisms underpinning pile run, for instance, may be transferable (Erbrich and Randolph, 2025). Innovative solutions for offshore wind foundation installation methods in rocky seabeds for a number of French projects are summarised in Palix (2025). Little experience exists in offshore wind foundation installation in glauconitic soils (Figure 29c), with ongoing research documented in DeGroot et al. (2023), Perikleous et al. (2023), Westgate et al. (2023), Konstantinou et al. (2025), Pisanò et al. (2025). Vibro-drivability and post installation lateral performance experience in these soil conditions, albeit after impact-hammering at the end of the pile installation process, may be gained initially from commercial wind farms. Systematic research will play a crucial role in developing prediction methods based on physical mechanisms governing vibro-driving and to guide the industry through advanced understanding of the effects of vibro-driving input on the soil-structure interaction. This may provide confidence in the post installation stiffness that can be achieved with vibro-driving alone, i.e. not requiring impact-driving (with the necessary noise mitigation measures) to finish the pile installation process.

Predicted and measured pile response has been documented to **differ** (e.g. Kallehave et al., 2015; Stuyts, 2023). The reason for the systematic under-prediction of stiffness is not clear and could be multi-factorial. The effect of the installation process is not currently routinely taken into account, at least not directly, in pile design for lateral loading. Effects such as those from scour protection, may also need to be understood, as investigated e.g. in Stuyts (2023) for a number of Belgian offshore wind farms. Back-analysis of wider datasets across multiple wind farms can provide further insights and aid attribution of the reasons for the differences, which allows targeted improvement to be implemented going forward.

The **supply chain** constantly evolves with the industry and will adapt to changes in installation methodology, as it has adapted to challenges brought about by regional peculiarities such as the Jones Act in the US where piles are directly transported to the offshore installation location rather than being brought onshore and handled through a port.

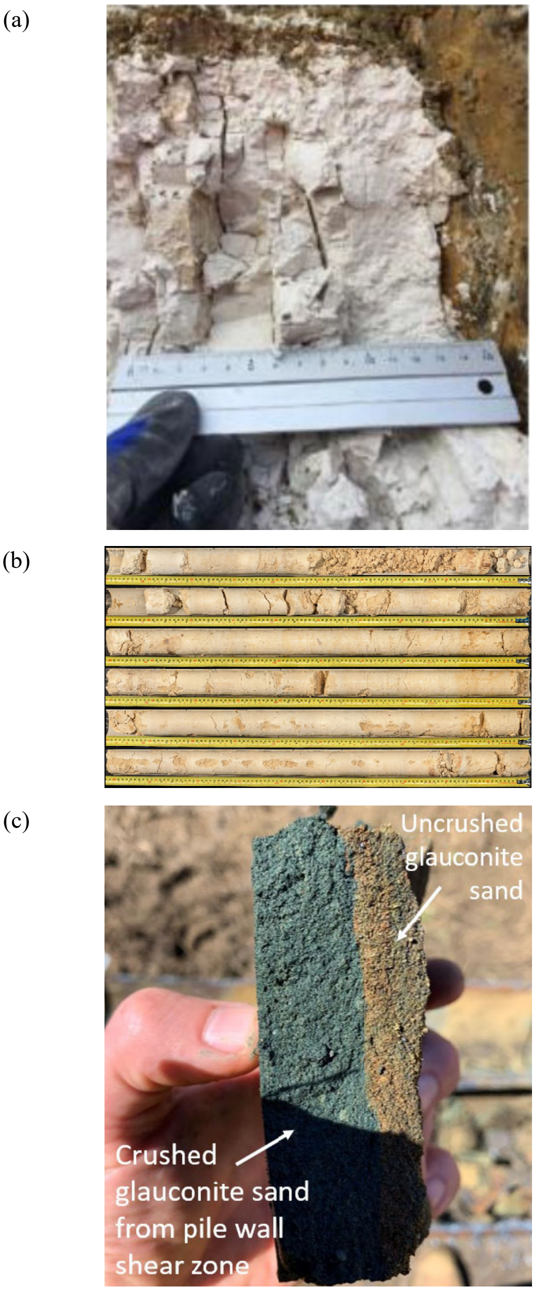


Figure 29. Examples of (a) chalk (Vinck et al., 2025), (b) variably cemented carbonate sediments (Ahsan et al., 2025), (c) glauconitic sand (DeGroot et al., 2023).

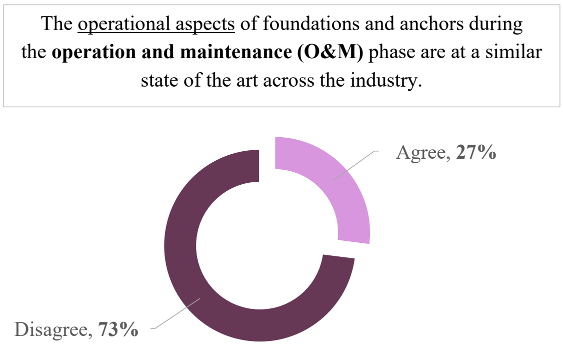
The preceding focused on foundations for bottom-fixed offshore wind, largely monopiles, as **floating offshore wind is much less mature** and not yet developed at commercial scale. As a consequence, there is less experience to date with **anchors** in offshore wind, though significant research effort has recently been dedicated to a range of different anchoring solutions (with Cerfontaine et al., 2023, evaluating current technologies and future innovations) including helical anchors which have received significant research attention recently. Helical or screw anchors are associated with low acoustic emissions during installation paired with accurate positioning and high axial resistance, though the latter may be less of an advantage in a catenary mooring system. Requirements for the installation equipment may be reduced if low crowd (axial compressive) force is applied, which has been shown to lead to increased post-installation capacity as well (e.g. Cerfontaine et al., 2022; Wang et al., 2023), though the torque requirement remains largely unchanged. This is investigated to be mitigated through use of groups of smaller helical anchors (e.g. Sha et al., 2025) and innovative proposals such as water-jetted installation (e.g. Nietiedt et al., 2025). The optimal anchoring solution for a project may not be the anchor type that offers the most efficient geotechnical design as the choice depends on a range of factors including the selected mooring configuration (drag anchors are unsuitable for shared moorings, for instance) and the supply chain.

5 OPERATION AND MAINTENANCE

5.1.1 *State of practice and challenges*

In the context of foundations for offshore wind, the operation and maintenance (O&M) phase includes the activities and considerations necessary to ensure the performance and safety of structural components. These typically include visual inspections to detect issues such as corrosion or scour, Structural Health Monitoring (SHM) to track loads, vibrations, and environmental conditions, and maintenance of critical systems such as cathodic protection and grout connections in bottom-fixed foundations, or mooring line tension in floating structures.

Survey responses to the statement: *"The operational aspects of foundations and anchors during the O&M phase are at a similar state of the art across the industry"* (Figure 30) show that most respondents (73%) disagreed, while 27% agreed.



The operational aspects of foundations and anchors during the **operation and maintenance (O&M)** phase are at a similar state of the art across the industry.

Figure 30. Responses to survey question: "The operational aspects of foundations and anchors during the operation and maintenance (O&M) phase are at a similar state of the art across the industry."

Among the various O&M activities, individual responses focused on **structural health monitoring**, data analysis, and modelling. An example of the mounting of a SHM system is shown in Figure 31. Respondents noted that while monitoring of monopile natural frequencies is well-established, standardised approaches for other foundation types are lacking. O&M practices vary widely between developers and are often shaped by internal priorities and confidentiality. The use of digital twins and long-term performance monitoring tools is inconsistent, and access to complete datasets, including metocean conditions, remains limited.

Instrumentation is recognised as **a key enabler for closing the loop between design and performance**, improving predictive methods and confidence in outputs. However, interviewees highlight that implementation is challenging due to fragmented project structures, where the beneficiary of the data is often not the party responsible for planning and funding instrumentation. In addition, the teams responsible for design and those analysing operational data are typically separate.

Figure 31. Mounting the SHM system at BKR01 for Ørsted. Photo: NGI (2014).

Research groups with access to design information and operational data have brought valuable insights into the performance of offshore wind foundations. For **monopiles**, Kallehave et al. (2015) compared measured and design natural frequencies for more than 400 installed offshore wind turbines, highlighting discrepancies up to 20% for the first natural frequency. Hald et al. (2009), and more recently Stuyts (2023) and Kheffache (2025), compared measured and predicted bending moments along the length of the pile. Page et al. (2019) examined predicted and measured natural frequencies and fatigue damage equivalent moments at seabed, for the same data evaluated in Norén-Cosgriff and Kaynia (2021). Stuyts et al. (2023) reported on in-situ pore pressure monitoring around a wind turbine monopile. For **suction bucket jackets**, Shonberg et al. (2017) presented monitoring data from Borkum Riffgrund I, the first SBJ supporting an offshore wind turbine collected between September 2014 and January 2016. This included in-place response to loading, long-term structural behavior, vertical stiffness response, load transfer along the bucket skirt, and variation of pore water pressures.

Beyond routine monitoring, instrumentation also enables observation of rare, high-impact events - such as extreme waves (see e.g. Hansteen et al., 2003) or vessel collisions - that can inform future design standards.

5.1.2 *Improving understanding of long-term behaviour through operational data*

Operational data collected during the life of an offshore wind farm offers considerable potential to improve understanding of how foundations and anchors behave under real loading conditions over time. While there are examples where such data have informed design improvements (Wood and Thilsted, 2025), their use in practice remains limited. Yet, these data can play a critical role in verifying design assumptions and revealing soil and structural responses (e.g. Anderson, 2022) - particularly under cyclic and multidirectional loading.

For **bottom-fixed structures**, the long-term **effects of cyclic loading** on soil response and consequently on foundation stiffness, damping, and permanent deformation over 25–30 years of operation have been a central topic of research. These effects vary depending on factors such as soil type, soil state, loading magnitude, direction and frequency, drainage conditions, foundation type and dimensions, and installation method. Depending on these factors, the soil may exhibit different degrees of stiffness and strength degradation, pore pressure build-up, densification and stiffening, and accumulation of permanent strains. At the foundation level, this may translate into reductions or increases in capacity, changes in stiffness and damping characteristics, and accumulation or recovery of permanent rotations and displacements.

Several methodologies (e.g. Andersen, 2015, incorporated in DNV-RP-C212, 2019) have been proposed to account for some of these effects. However, there is still a lack of consensus on how to incorporate cyclic loading into design, and which assumptions are acceptable in each case. This was highlighted by interviewees and in the survey, where 20% of the participants selected a *more accurate prediction of the effects of cyclic loading over the life of the foundation/anchor* as the factor that would most significantly improve foundation or anchor design in terms of cost and reliability (Figure 20). In practice, engineers must balance the need for accuracy with the effort required to model complex phenomena. For example, assumptions about pore pressure build-up under low-frequency loading or minor stiffness recovery after densification may be omitted when their impact on overall performance is negligible or data are insufficient. Using operational data to identify which factors most influence long-term behavior can help prioritize what to include, reduce uncertainty in cyclic response, and pave the way toward a unified methodology.

For **floating structures**, understanding the effects of multidirectional cyclic loading (and how to model them) is particularly important for **shared anchors.** Equally critical is gaining insight into the mechanisms that lead to gap formation and trenching (Bhattacharjee et al. 2014; Colliat et al., 2018; Sun et al., 2020), given the lack of standardised methodologies. The research front is advancing in this area. Recent studies have explored the mechanisms leading to **trenching** (see for instance Randolph et al., 2020; Wang et al., 2020; Rui et al., 2024; Rui at al.; 2025), developed models to predict these processes and assess their impact on design (Feng et al., 2019), as well as investigated gapping in anchors and its consequences (see for instance Fu et al., 2020).

Efforts to understand the effects of multidirectional cyclic loading have focused on element-level behaviour, centrifuge tests, and 1-g model tests (see e.g. Rudolph et al., 2014; Herduin, 2019; Luo et al., 2024; Abadie, 2025, Chalhoub et al., 2025 or Zabatta et al., 2024). Within this broader research landscape, several modelling approaches have emerged, including CLAP (Abadie and Page, 2025), which compute anchor response in the time domain and at real speed - making them suitable for direct comparison with operational data - and are conceptually aligned with whole-life geotechnics principles. However, operational data from floating wind farms have not yet been applied in this context**.** With several floating demonstration projects now operational and more are in planning, the opportunity to link field data with research efforts is both timely and critical to de-risk anchor design for floating offshore wind.

Analyses of operational data can do more than validate design assumptions and support consensus on methodology: they also provide a foundation for lifetime extension strategies. In cases where monitoring systems were not installed during construction, **retrofitting instrumentation** offers a practical solution. This approach has already been demonstrated at the Block Island Offshore Wind Farm (Hines et al., 2023), the first commercial offshore wind farm in the United States.

6 LIFETIME EXTENSION AND DECOMMISSIONING

As offshore wind farms reach the end of their design life, operators face decisions on whether to decommission or extend lifetime or repower. While decommissioning remains the default option, lifetime extension and repowering can improve asset utilisation and reduce environmental impact. This section outlines current practices and challenges in decommissioning, explores strategies for extending operational life, and highlights geotechnical research critical for safe and efficient end-of-life planning.

To understand the scale and complexity of these processes, it is useful to look at early examples of decommissioning, starting with the first offshore wind farm, Vindeby in Denmark. This wind farm was commissioned in 1991 and decommissioned in 2017 after 25 years of operation. Vindeby comprised eleven turbines of 450 kW capacity each. The decommissioning process began with removing one blade (17 m long, 2.2 t) using a mobile crane and placing on a jack-up vessel, followed by the nacelle (weighing 27.6 t) with the two remaining blades (Figure 32), and finally the tower (20 t). The conical reinforced concrete gravity foundations were broken up in situ mainly by hydraulic demolition shears and a hydraulic hammer but also milling tools, with the concrete rubble removed. The subsea cables (3 km array, 3 km export) were pulled from the seabed, rolled onto a drum and cut into smaller pieces. Everything that could be recycled was recycled, including melting the steel and the concrete from the foundations. Vindeby, and the few other wind farms that have been decommissioned to date, were close to shore (~1.5 km) in shallow waters.

Figure 32. Decommissioning of the Vindeby offshore wind farm (source: Ørsted).

In contrast, decommissioning onshore wind turbines is well-established, as ease of access reduces complexity of the process. **Decommissioning of offshore wind farms**, on the other hand, remains immature and will need to evolve as ORE Catapult forecasts that 3.5 GW of offshore wind capacity will come to the end of life by 2035. This represents hundreds of turbines, most of them founded on monopiles. It is not only the number of turbines and foundation elements that require end-of-life processes to evolve, it is the scale as well, the distance from shore and water depth. Furthermore, China's offshore wind industry (although it started later than Europe) has rapidly become the largest in the world, meaning that end-of-life strategies must scale globally to meet these challenges.

Survey responses (Figure 33) indicate that *the state-of-the-art with respect to decommissioning of offshore wind foundations will likely look different in different regions due to differences in regulatory framework (38%)*, *will likely evolve from the North Sea region and be adapted in other regions (30%)* and *will likely look significantly different for the offshore wind compared to the oil and gas industry (27%)*. Currently, most countries require full removal of offshore wind farms at end of life, although France allows partial removal.

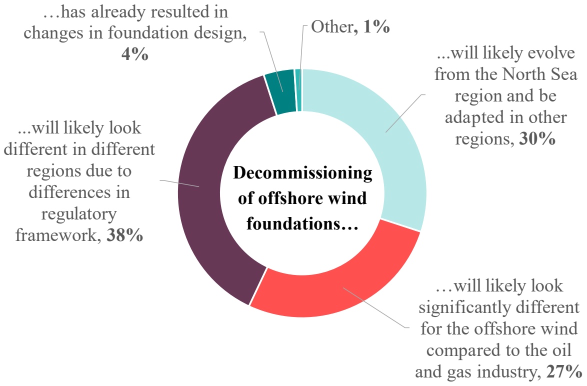


Figure 33. Responses to survey question: "The state-of-the-art with respect to decommissioning of offshore wind foundations…"

While decommissioning is the default option, it is not the only possibility:

- Lifetime extension may allow some offshore wind farms to operate beyond their original design life.
- "Partial repowering" involves upgrading ageing components such as the blades, generator, requiring new certification.
- "Full repowering" means replacing all components but the foundations.

These approaches can maintain or increase asset utilisation, often offering higher yields, lower maintenance costs and environmental benefits by delaying eventual decommissioning. There may be limited scope for repowering as the original foundations are unlikely to be able to support modern large turbines and small turbines may not be available and also affect the economics of the solution. Liu et al. (2022), compare different repowering choices for the example of China's first offshore wind farm, Donghai Bridge. Like any other aspect of offshore wind farms, there are challenges other than technical, e.g. regulatory.

The **end-of-life decision-making process** requires planning, and possible lifetime extension or repowering require consideration of aspects including the extent of reusable infrastructures, fatigue life, regulatory and social license. This can be evaluated in terms of risk – and cost, with ORE Catapult (2025) providing indicative values, to assess the expected profitability and Topham et al. (2019), concluding that recycling offshore wind farm components could pay for nearly 20% of the total decommissioning costs with the study focusing on monopiles as the predominant foundation type. In the UK, The Crown Estate has already extended the leasing terms to up to 60 years (ORE Catapult, 2025) to allow two full project lifecycles, meaning that repowering can already be considered early in the planning. Legal uncertainties have been flagged as a significant concern by the International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 42 on wind turbine lifetime extension.

Focussing on **geotechnical considerations**, significant research effort is under way aimed at improving understanding of aspects including damping which affects fatigue life, ageing (which refers to long-term changes in soil-structure interaction) and accumulated cyclic effects on expected removal resistance, which can inform removal strategies. Industry guidance is currently lacking.

Foundation damping plays into foundation design as it contributes to fatigue life prediction but is discussed further here as evaluation of the actual remaining fatigue life is important in end-of-life decision making for offshore wind turbine foundations. Current design guidelines lack detailed guidance and the differences in predictions as well as measured to theoretical results can be significant (Malekjafarian et al., 2021; Dahl et al., 2025). The actual fatigue life if also affected by changes in seabed (scour, possible gapping) over the operational lifetime of the foundation (Beuckelaers, 2017). This is an area of ongoing research, but full-scale measurement data of the foundations response of modern large offshore wind turbines will also play an important role.

Jardine (2023) synthesizes the key mechanisms of time-dependent foundation behaviour in clay, chalk and sand as follows and with a view to decommissioning procedures:

- Consolidation, with effective stresses, strains and state evolving to steady state conditions as excess pore pressures dissipate over time.
- Changes in fabric due to the foundation installation and/or loading process, which may involve breaking of cementation bonds or particles at the micro scale and/or at the meso to macro scale formation or closure of fractures in soft rocks.
- Creep processes, e.g. arching stresses evolving with time, that result in continued changes in strain and state.
- Chemical processes such as corrosion at the interface between the foundation and surrounding soil.

At this point, many uncertainties remain and significant research is required. Research to date has focused on piles, and these remain the dominant foundation solutions for offshore wind. The growth in low noise solutions will require differentiation as the long-term changes around vibro-driven piles or helical anchors can be expected to differ. Suction buckets should be able to be decommissioned as quietly as the installation through reverse pumping action. However, the pressure required for extraction may be higher than that for installation. A 30% increase in required pressure after 303 days has been reported and attributed to set-up effects in the clay (Hamdan et al., 2025). Ageing following suction installation will need to be understood for the planning of decommissioning activities. Under lid grouting, which is often applied to ensure contact between the suction bucket lid invert and the soil plug, may further complicate decommissioning.

Even with complete understanding of the relevant processes, their implications for soil-structure interaction in the long term and appropriate predictive methods, substantial uncertainty remains over the actual life history that the foundation has experienced.

The loading history is important, hence accurate reliable data on the actual cyclic loading over the lifetime (including during installation) and the structural health of the wind turbine components is valuable in informing the end-of-life decision-making process. In other words, monitoring of offshore wind farms can be crucial for lifetime extension.

Fatigue life consumed during installation of impact-driven (mono-)piles is fairly well understood, but fatigue assessments for vibro-driven piles do not yet enjoy the same level of predictive confidence, though this will be boosted over time through measurements of the actual stress cycles during pile installations, and the actual installation process offshore may have differed from assumptions made in the office. Monitoring and documentation of the actual history is important.

Similarly, assumptions are made in the design phase that influence the predicted fatigue life consumed during operation. The actual cyclic loading over the 25 or 30 years of operation may differ though, and structural health is also influenced by the initial quality and structural integrity as well as timing and level of interventions during the operation and maintenance phase, which may affect load transfer through the offshore wind turbine system. Paired with the current lack of confidence in the accuracy of predictions over such long time frames, predicted and actual fatigue may not necessarily align. It is clear then that data paucity also impairs evaluation of decommissioning options, which was discussed from the perspective of cyclic loading but has also been investigated in terms of environmental impact, considering the options of full removal or leaving the scour protection only or the scour protection and foundation in place (e.g. Spielmann et al., 2023).

Digital twins enable proactive asset management over the lifetime of the offshore wind farm which is expected to be beneficial for the end-of-life decision-making process. This is developing, though hampered by the fact that data sets tend to be incomplete, e.g. with metocean monitoring missing, and not every offshore wind turbine is instrumented. Further, instrumentation, monitoring and lifetime extension tend to be led by separate teams.

A shorter initial design life paired with lifetime extension can pose a more viable business case according to the International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 42. This was also echoed in the interviews.

7 DISCUSSION

This paper has provided a snapshot in time of the current state of research and practice in geotechnical engineering and its intersections with other key aspects of offshore wind farms: from ground model development, concept selection and geotechnical design to installation, operation, and decommissioning.

At the core of all these activities lies **risk management**. In geotechnical engineering, risk primarily arises from uncertainty, often due to limited high quality data and from modelling simplifications. This leads to a practical question: when it comes to modelling, what is the **right balance between model complexity and efficiency**? What, then, defines effective geotechnical optimisation?

Historically, offshore wind farms have been successfully developed at complex sites using relatively simple models, well before integrated ground models and synthetic CPTs were available. Since then, advances in modelling have led to significant improvements, which consequently resulted in reductions in monopile weight (e.g. Muir Wood and Thilsted 2025). However, pushing for more detailed modelling may, in some cases, add little value relative to its cost and time implications. This raises an important question: is there a threshold beyond which increasing modelling complexity no longer delivers meaningful improvements in design outcomes?

An **alternative path to optimisation** may not lie in increasing complexity, but in rethinking the data inputs themselves. Reducing reliance on laboratory testing and instead **deriving design relevant properties directly from in-situ measurements** could streamline the process. Promising research is already pushing in this direction, with developments in small-strain stiffness measurements from seismic CPTs and cyclic response characterisation via cyclic CPTs, as discussed earlier. These approaches may allow us to obtain critical geotechnical parameters for the design of foundations for offshore wind turbines. Looking ahead, future developments will likely increasingly include quantitative geotechnical properties for design directly from geophysical data and advancing site investigation tools and procedures to better support design based on in-situ measurements. Integrating in-situ data into design methodologies and ensuring adoption of these in practice **will improve efficiency** in geotechnical design.

Much of the current knowledge base has been developed for North Sea conditions. As offshore wind expands into **new markets, regional differences become more relevant**. For instance, Lakeman et al. (2025) discusses differences between the North Sea and the APAC regions, providing the example of Japan, which has traditionally relied on the SPT rather than the CPT for geotechnical design. These differences extend beyond site investigation practices to whole-life considerations, such as cyclic loading under typhoons versus North Sea storms. A significant broadening of approaches can be expected as regions currently described as “new” become established and methodologies adapt to local conditions. Regional databases can play a critical role in this transition, as these can support design methods based on in-situ site characterisation measurements, validated through back-analysis of physical modelling and field data.

While the focus has been on geotechnical challenges, the discussion has also highlighted **intersections with regulatory frameworks and the supply chain**. The maturity of the offshore wind industry in a region is also important, which emphasizes the value of published case studies that contain relevant details, e.g. specific survey strategies, vessels and equipment employed at various project stages. These would assist in refining survey strategies, data acquisition for foundation design and geohazard mitigation as well as leverage local expertise to adapt to the complexities in new offshore wind regions like APAC.

A **shared database** – such as across the North Sea – could revolutionise ground model development and installation planning. Open-access site investigation data (e.g. the Netherlands Enterprise Agency, https://offshorewind.rvo.nl/) enables seabed characterisation at regional scale, providing context and facilitating the development of correlations for engineering properties such as stiffness. This also calls for closer coordination across geo-disciplines and refinement of site investigation strategies to ensure that data acquisition supports both ground model development and design requirements effectively. Standardisation and regulation of best practices will be important enablers of process efficiency. Industrialisation of monopiles has catapulted the industry forward and will continue to play an important role in foundation and anchoring choices. Together, these efforts could accelerate approvals, strengthen regional supply chains for relevant foundation concepts, and de-risk projects.

Instrumentation and monitoring can provide avenues for learning, identify optimisation potential and yield crucial data for end-of-life decision making. Challenges remain - not only survivability of the instrumentation and long-term data gathering, but also in continuity across project phases, where responsibility often shifts between teams and organisations. Ideally, instrumentation should be planned early and integrated into design and fabrication, since it has the potential to affect or be affected by the installation operation. However, practical constraints, such as limited communication between instrumentation and asset management teams during early stages, complicate this integration.

It is not just about new instrumentation and monitoring - **vast amounts of installation and operational data already exist and could drive disruptive change**. There is broad agreement among the interviewed developers, consultants, contractors and certifiers that analysing these data could be revolutionary. Demonstrating reliable and accurate predictions would further boost confidence or reveal specific opportunities for improvement across the design life cycle, with the field data intrinsically capturing the effects of preceding history. However, turning this potential into reality is a complex non-geotechnical challenge that would require coordination across organisations and robust data governance.

Continued advances in technical solutions – together with efforts to overcome non-technical challenges – will define the pathways forward for offshore wind geotechnics.

8 CONCLUDING REMARKS

This paper has provided an overview of the stat-of-the-art of geotechnical engineering of offshore wind farms, drawing on a bespoke survey designed to gather input from a large number of individuals across the offshore wind industry and academia as well as in depth conversations, in addition to recent publications. Using an idealised simplified project life cycle, selected examples highlight current areas of uncertainty and innovation. Offshore wind is an industry where research and practice are closely intertwined, as seen in the speed at which research-driven solutions emerge and the proportion of practitioners with research experience as well as researchers with industry backgrounds, as captured by the survey. This synergy is a strength that is expected to continue to drive innovation, enabling the significant acceleration required in order to achieve the build-out of offshore wind capacity required to meet the climate targets set out in the Paris Agreement.

9 ACKNOWLEDGEMENTS

Many individuals have contributed to this paper. We thank all respondents to the survey as well as colleagues at NGI and COFS, UWA, and the following for insightful conversations and feedback: Marten Vanneste, Rasmus Klinkvort, Mark Randolph, Hendrik Sturm, Jan Dührkop, Christian LeBlanc Thilsted, Neil Morgan, Pauline Suzuki, Sylvie Raymackers, Avi Shonberg, Yiorgos Perikleous, Youhu Zhang, Sarah Elkhatib, Tim Pucker, Luís Berenguer Todo Bom, Volker Herwig, Iona Richards, François Bertrand, Santiago Quinteros, Per Sparrevik, Thomas Langford, Phil Watson.

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