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

ISBN 978-2-85782-758-0

Geotechnical site characterisation challenges for floating offshore wind – a developer's perspective

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ABSTRACT: Site investigation strategies for offshore wind developments vary widely across the industry. These are, amongst others, driven by site complexity and size, particular geohazards, permitting and consenting requirements, certification requirements, potential foundation concept(s) and layout, project schedule and budget constraints, availability and capability of survey vessels and data acquisition systems, and operational constraints.

This article presents typical challenges engineers are faced with when scoping and planning geotechnical and geophysical site investigations during the feasibility and development phases of the offshore wind park. Focus will be given to floating offshore wind developments, which may include many anchor points and significant layout uncertainty. Key considerations are anchor foundation type and the choice to adopt foundation location-specific investigations versus characterizing the site with investigation locations distributed in a grid. The latter implies a risk-based approach to anchor in-place design and installation assessments with the objective to significantly reduce the risk of cost and schedule overrun.

Keywords: offshore wind; geotechnical; site characterisation; floating; anchor; gridded.

1 INTRODUCTION

Geotechnical site characterisation practice for offshore wind has been on a steep learning curve over the last decade or so. With ever increasing lease areas, geological and geotechnical complexity, water depth, foundation size and numbers of foundations installed, the industry has made big steps. Significant effort has gone into development of new and more data acquisition tools and methods to interpret, integrate and present the very large data sets.

However, big steps are yet to be made to cope with the challenges of offshore wind development for the decades to come, see e.g. Gourvenec (2024).

Geotechnical site investigation strategies for offshore wind developments vary widely across the industry. These are, a.o., driven by site complexity and size, particular (geo)hazards, permitting and consenting requirements, certification requirements, foundation concept(s) and layout, project schedule and budget, availability and capability of survey vessels, data acquisition systems, and operational constraints, and last (but not least): risk appetite.

Above list is, by no means, complete, and many more project-specific conditions can be mentioned that could result in significantly varying scopes of work and phasing of the investigations.

The objective of this paper is to highlight some key aspects and dilemmas that drive geotechnical site investigations with particular focus on floating wind development, and to present some possible solutions.

2 STANDARDS AND GUIDELINES

Industry standards and guidelines are the common starting point for scoping any geotechnical site investigation.

The latest version of Standard ISO 19901-8: marine Soil Investigations (2023) now includes lower carbon energy. Section 5 highlights the typical sequence of four key activities:

1. Desk study.
2. Geophysical site investigations.
3. Marine soil investigations (one or more phases).
4. Data integration studies.

No specific guidance is given on minimum or typical scopes of work for various foundation types and/or subsea infrastructure.

Geophysical investigations should precede geotechnical soil investigations to inform and optimize the program. Back-to-back execution of these campaigns is typically not preferred as it limits the time for quality data interpretation and reporting.

DNV Standard DNVGL-ST-0126 Support structures for wind turbines (2021), Section 7.3.1.3 states that *"For multiple foundations such as in a wind farm, the soil stratigraphy and range of soil strength properties shall be assessed per foundation location"*. With further guidance stating *"When very homogeneous soil conditions prevail, such assessment may cover a group of foundations within the entire area of a wind farm, or it may consist of all the foundations within a sub-area of a wind farm. Such sub-areas are typically defined when groups of wind turbines within a wind farm are widely separated."*

DNVGL-RP-C212 Offshore Soil Mechanics and Geotechnical Engineering (2019) includes an important additional clause (S2.1.2.3): "For multiple foundations such as in a wind farm, the soil stratigraphy and range of soil strength properties shall be assessed within each group of foundations or per foundation location, as relevant."

OSIG Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments (2022) has particular focus on offshore wind developments.

Detailed guidance is provided for the four key activities mentioned above. The main message is that *"Geotechnical risk management is an <u>iterative</u> process, that comprises the collection, collation and interpretation of potential and actual geological and geotechnical hazards, in order that the risk of these hazards to the project can be identified and properly quantified. This is a continuous process, which is maintained throughout the life cycle of a project, in order to manage the ground risks until the residual risks are considered to be acceptable"*.

The Guidance Notes differentiate between Reconnaissance surveys (investigations for site characterisation) and Engineering surveys (site investigations for detailed design and construction), implying a minimum of two geophysical and geotechnical investigation phases.

Table 7 of the Guidance Notes provides example geotechnical scopes of work for various foundation structure types. A minimum of one geotechnical investigation point (sample borehole or Cone Penetration Test - CPT) per structure is recommended.

In summary:

1. No explicit code requirements are listed for geotechnical scopes of work for offshore wind developments.
2. A minimum of two geophysical and geotechnical investigation phases is typically required.
3. Recommended Practice varies but leans towards a CPT or sample borehole (in seabed and/or downhole mode) at each foundation structure as a minimum.
4. Scope depends on foundation structure "importance" and site complexity (informed by geophysical survey).

DNVGL-RP-C212 leaves some room for a grouped approach, this is further explored in section 4 on floating developments.

3 FIXED DEVELOPMENTS

3.1 Foundation types and depth

Fixed offshore wind turbines could be founded on monopiles, jacket foundations or gravity bases. Jacket structures can be founded on driven piles or on suction piles/buckets. Monopiles currently dominate the market, water depth and soil conditions permitting.

Monopiles are particularly suited for competent ground conditions (sands and stiff clays, limited layers of (very) weak rock) and typically penetrate to about 25m to 40m below seabed. Jacket piles typically penetrate much deeper, in the range 50m to 80m below seabed, whereas suction buckets usually do not penetrate deeper than about 15m. Gravity bases are typically only considered when pile foundation installation is not feasible due to hard (rock) layers at relatively shallow depth and competent soil conditions are present at or near seabed level.

It is noted that these are approximate numbers only and the combination of water depth and soil conditions can result in significantly different penetration depths than stated above.

Offshore substations (OSS) are normally founded on piled jackets and often govern the maximum foundation depth for the overall wind development. Piles could penetrate as deep as 100m below seabed for these structures.

Foundation installation depth is an important parameter when designing geotechnical site investigations as it defines the required acquisition spreads, e.g. seabed systems and/or downhole drilling and sampling and testing equipment.

3.2 Geotechnical site investigation practice

Geotechnical investigation practice for fixed wind developments would normally rely upon a phased data acquisition approach. A minimum of two phases is required, but more phases are sometimes needed for complex projects and depending on risk appetite.

The first (reconnaissance) phase is driven by geological site complexity and particular geohazards and sim to target all geotechnical soil units that are significant for preliminary foundation design. These units are identified and interpreted based on the reconnaissance geophysical campaign.

The geotechnical campaign would comprise sampling boreholes, preferably co-located with CPTs to maximize correlation of in-situ data with laboratory test results. The acquired data set is input in preliminary foundation in-place and installation design and Wind Turbine Generator (WTG) layout studies.

During the reconnaissance phase, site-wide characterisation of cyclic and dynamic soil (degradation) parameters based on advanced laboratory testing on the acquired samples is already performed. These advanced laboratory programs are typically on the critical path and are important input for both preliminary and detailed designs.

The second (detailed engineering) data acquisition phase should again start with a geophysical campaign with the objective to finalize the site layout, foundation concept(s) and approximate target foundation penetration depths for each WTG and OSS location.

Foundation design is sensitive to location specific water depth and site conditions (i.e. wind, waves, current, and geotechnical conditions). Therefore, each WTG (and OSS) foundation should be investigated with a CPT (in seabed and/or in downhole mode), exceeding foundation installation depth, as a minimum.

Additional boreholes are normally required to acquire additional undisturbed samples in soil units important for design and to supplement the reconnaissance phase laboratory data set.

The combined geophysical and geotechnical data is normally integrated and interpreted into a Ground Model (GM) and corresponding Geotechnical Interpretative Report (GIR). These deliverables are the key inputs for other design packages in the project and are updated and revised each time when new data becomes available.

3.3 Pre-investigated sites

Some European countries (e.g. The Netherlands, Germany, Denmark) provide site investigation and interpretation data as part of the lease tender documentation. These data sets serve to de-risk site conditions and ultimately result in lower development costs.

A prime example is the Dutch practice coordinated by RVO - Netherlands Enterprise Agency to share these data sets in the public domain and provide a wealth of data and studies as input into the tender design phase. These data sets and studies well-exceed reconnaissance phase minimum requirements and enable relatively advanced foundation design at a very early stage of the project.

After project award, typically only a CPT campaign at the panned WTG locations is required together with a limited laboratory test program targeting specific soil units important for the selected foundations and (preliminary) geometries.

4 FLOATING DEVELOPMENTS

4.1 Introduction

Particular challenges emerge for planning and executing geotechnical site investigation for floating wind developments.

Contrary to fixed foundations, anchor foundations are relatively non-sensitive structures. In-place design is governed by anchor holding/pull-out capacity (Ultimate Limit State - ULS) and not by response (Serviceability Limit State - SLS) or fatigue (Fatigue Limit State - FLS) of the combined foundation and superstructure.

This section highlights three key challenges and potential solutions for designing and planning geotechnical site investigations for floating wind.

4.2 Challenge 1: Volume of work

A typical layout is shown in Figure 4-1 below, illustrating the vast number of anchor foundations that need to be designed and installed.

Typically, between 3 and 6 anchor points are required for each floater. For a full-scale commercial development of (say) 100 WTGs, this would imply 300 to 600 anchors.

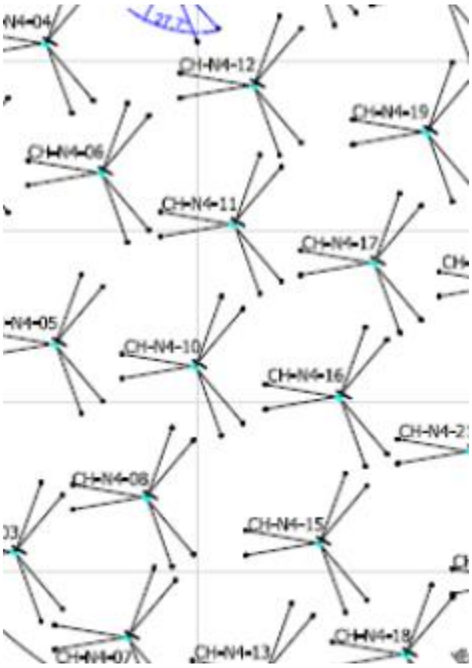

Figure 4-1: Example floater and anchor foundation layout.

4.3 Challenge 2: Uncertainty in development concept

Commercial floating wind developments typically go through several concept design loops where the floater, mooring and anchoring concepts are defined.

More than one concept can be taken forward relatively far into the project. As a result, final layout and anchoring concept(s) are subject to change, even in late stages of the project development. This is a major complicating factor when designing and planning the site investigation programs.

Anchoring concepts typical include:

- Drag Embedment Anchor (DEA).
- Driven anchor pile.
- Suction anchor pile.
- Embedded plate anchor.
- Gravity anchor.

DEA and gravity anchors would typically require only shallow geotechnical investigations of up to 10m depth.

Predominantly horizontally loaded pile and plate anchors would typically require an intermediate investigation depth, ranging between 10m and 30m.

Permanent and vertically loaded TLP anchor piles could require indicative investigation depths between 50m and 100m.

New and innovative anchoring concepts (not listed above), including shared anchoring solutions are being developed at the time of writing this paper.

In summary, full scale commercial floating wind developments require a very large number of foundations to be designed and installed, with. added uncertainty in final anchor layout, anchor concept(s) and associated site investigation depth range.

4.4 Challenge 3: Schedule bust

Figure 4-2 schematically shows how multiple phases of geophysical and geotechnical (geoscience) campaigns could fit into the various stages of project development.

Due to the potential very large volume of work, with added complexity and uncertainty of the

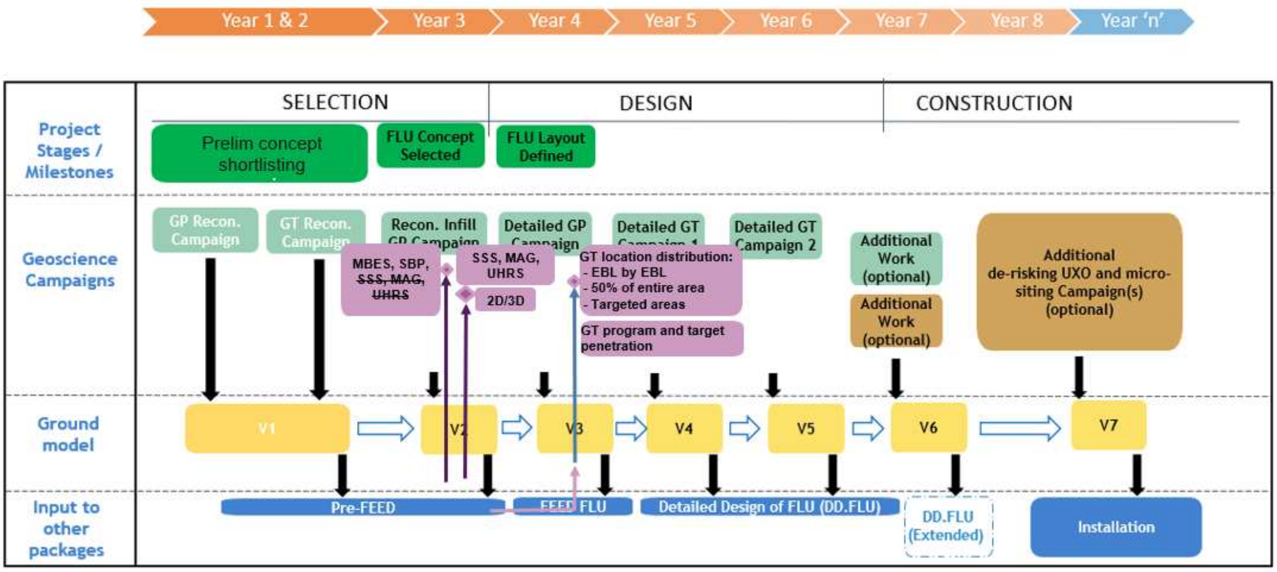

Figure 4-2: Development phases for floating wind – schematic.

development concept, it is quickly seen that significant schedule issues arise if fixed development concept site investigation strategies (as described in Section 3.2) are extrapolated to floating wind developments.

Potential solutions are described in the following section.

4.5 Potential solutions

Trying to investigate all anchor foundation locations would generally not be recommended due to:

1. Very large number of locations, and
2. Likelihood of late layout changes.

Even if all locations are investigated, there is a high likelihood that relatively small floater layout changes result in very large shifts in anchor locations (>100m), in particular for catenary-type mooring configurations.

This then would imply that a significant (and unrealistic) amount of re-work would be required to accommodate layout changes and to revisit site investigation locations.

One potential solution is to depart from foundation-specific investigations and to design the anchors based on a grouped approach, applying conservative (risk-based) design soil parameters for both anchor in-place and installation assessments for each group/zone.

A zoned (or grouped) anchor design approach could be defended as:

1. ULS strength criteria govern both anchor in-place and installation design, and
2. Anchors are not manufactured on individual (location specific) basis.

The proposed investigation concept is schematically shown in Figure 4-3. Geotechnical investigation locations are planned on the intersection of the geophysical 2D Ultra High-Resolution (UHR) survey lines for data correlation purposes.

The primary investigation tool is the CPT (either in seabed or in downhole mode) to reduce investigation and data delivery timelines. Deep-push seabed CPT systems have already proven their value (In suitable ground conditions) and can save significant time and budget.

A limited number of strategically positioned boreholes are also required to enable site-wide correlation of strength and stiffness parameters from laboratory tests with data derived from CPTs.

The grid resolution would be dictated by site complexity and survey phase. Coarser grids can be selected during the reconnaissance phase, and infill surveys can be performed in a denser grid during more detailed investigation campaigns at a later stage, where also focus can be given to areas with higher geotechnical complexity or specific geohazards (e.g. rock outcrops, glauconite, boulder fields, etc.), if required.

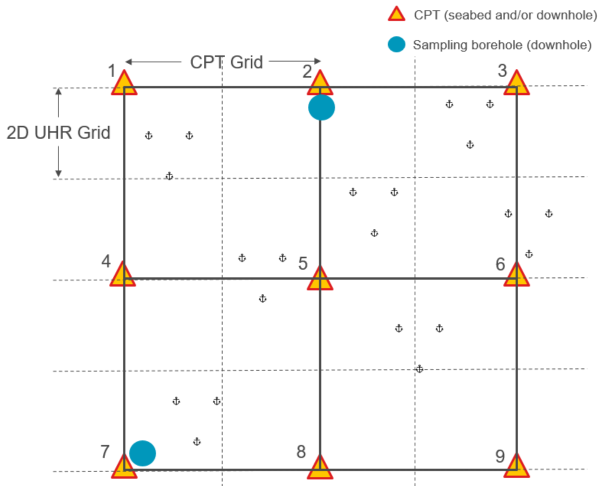

Figure 4-3: Gridded site investigation concept.

The grouped anchor design approach is conceptually shown in Figure 4-4. The focus should be on selecting sufficiently conservative design parameters for both in-place and installation design.

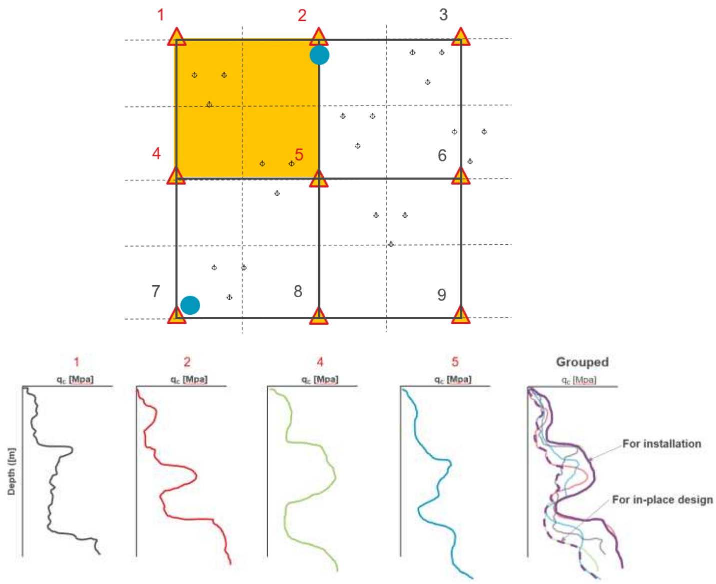

Figure 4-4: Grouped anchor design concept.

Obviously, it is not as simple as selecting envelope CPT traces of the four corner points to bound the design parameters within a box.

Seismic inversion techniques and synthetic CPTs have the potential to quantify parameter ranges and prediction uncertainty within a zone (laterally and vertically). 3D UHR data may ultimately be used to maximize data interpretation and correlation for this purpose, although this will come at significant costs.

The ultimate objective would be to balance site investigation costs and time/effort versus anchor design and installation optimizations. On hand had, all anchor foundations within a zone should meet minimum holding capacity requirements with sufficient margin of safety, and on the other hand significant overdesign should be avoided. Finally, all anchors within a zone should be installable to their design target depth(s).

The integrated ground model is foreseen as the primary tool to collate and visualize not only factual and interpreted geotechnical and geophysical data sets, but also anchor design and installation results.

5 CONCLUSIONS

Future geotechnical site investigations for floating wind should steer away from anchor location specific geotechnical site investigations. Instead, a gridded site investigation concept is proposed to enable a zoned (or grouped) anchor design.

A zoned (or grouped) anchor design approach could be defended as:

1. ULS strength criteria govern both anchor in-place and installation design, and
2. Anchors are not manufactured on individual (location specific) basis.

The integrated ground model is foreseen as the primary tool to collate and visualize not only factual and interpreted geotechnical and geophysical data sets, but also anchor design and installation results.
It is important to note that all stakeholders involved in the development phase, e.g. operators, design houses and installation contractors should eventually buy-in with the proposed site investigation strategy and design and installation concept.

To this end, it is foreseen that quantification of geotechnical data prediction uncertainty, and ultimately project risk, is key to support acceptance.

AUTHOR CONTRIBUTION STATEMENT

Sjoerd de Wit: Conceptualization, Investigation, Methodology, Writing- Original draft, Writing – Review & Editing.
Joris Siermann: Conceptualization, Writing – Review & Editing

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