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Site investigation and geotechnical design strategy for offshore wind development

Investigation géotechniques et stratégie de conception pour le développement d'éoliennes maritimes

Muir Wood A.
DONG Energy

Knight P.
Parsons Brinckerhoff

ABSTRACT: The development of multi billion euro Offshore Wind Farms presents geotechnical engineers with the opportunity to create comprehensive detailed ground models incorporating a large variety of geotechnical hazards. However the political structure of renewable energy projects often leads to a fragmented development team, with no one party appointed for the whole design process. Inexperienced clients are often commissioning surveys because they think that they want to do a survey rather than for an engineering reason. This leads to unclear specification, and a resulting survey that does not add the expected value to the project. The authors demonstrate in this paper how site investigation and ground modelling practices that are followed as routine in the design cycle of onshore projects can be adapted and applied to add significant value to offshore renewable projects. This paper seeks to set out a structure for development of the ground model for offshore wind projects, and demonstrates how clients can ensure their surveys are adding value to the design strategy for their projects.

RÉSUMÉ : Grâce au développement très coûteux de fermes éoliennes en mer, les ingénieurs géotechniciens, ont l'opportunité de concevoir des modèles de sol détaillés et exhaustifs qui peuvent rendre compte d'un large éventail de risques géotechniques. Cependant la structure politique conduit au fait que les projets concernant les énergies renouvelables se trouvent bien souvent menés par diverses équipes de conception sans véritable coordination. Des clients inexpérimentés ont souvent recours à des sondages dans le seul but de faire des sondages et non pour des raisons techniques. Cela conduit à avoir des cahiers des charges souvent imprécis qui n'apportent rien à la valeur attendue du projet. Les auteurs démontrent dans cet article comment les études de terrain et les pratiques de modélisation du terrain utilisées systématiquement dans les projets sur terre peuvent être adaptées et appliquées aux projets en mer et peuvent augmenter leur valeur considérablement. Cet article propose une structure de développement des modèles terrestres pour les champs d'éolienne en mer et démontre comment les clients peuvent s'assurer que leurs sondages valorisent les stratégies de conception de leurs projets.

KEYWORDS: geotechnical hazard management, site investigation strategy, ground model development, offshore wind farm

1 INTRODUCTION

The offshore wind industry in Northern Europe started with the development of small demonstration projects. In recent years these have significantly increased in size, and many of the current projects are now multi billion euro investments, with development times in excess of five years. The industry can demonstrate many examples of how lessons learnt and knowledge gained from the earlier projects have been incorporated into the recent larger projects, ultimately leading to lower capital and operational expenditure per MW of power generated.

Through this process the design methodology and codes (e.g. DNV 2011) which were originally predominately based on the experience of offshore oil and gas infrastructure have also continued to develop and there are many examples of good practice in current projects. However, for geotechnical site investigations this learning process has not been completely positive. It leads to a tendency to base the scope of the investigation on a specification for a previous projects, rather than on what is most appropriate for the site and specific development.

The authors have been involved in the design of over 15 projects, which when built will total more than 8GW of power. A review of these projects shows that they have all spent comparable money on site investigation - typically approximately 1% of the project capital costs (which on the current large projects leads to investigations costing in excess of €30M). However the success of the investigations in managing

the geotechnical risks and bringing value to the projects is extremely variable.

2 EXAMPLE PROJECTS

Typical problems that the authors have experienced are: investigations not planned to mitigate project specific geotechnical hazards; poor recording and interpretation of geological information; planning of surveys not based on the results of proceeding investigations/studies; and surveys not specified by the foundation designers.

Some specific examples of good and poor practice on projects are detailed in the following sections. The project names have not been stated however the approximate construction cost of each project is given.

2.1 *Poor practice*

2.1.1 *Project 1 – value ~€2bn*

The site investigation comprised site wide sub-bottom geophysical survey with three rounds of geotechnical works: (1) met mast borehole; (2) site wide boreholes; (3) seabed CPTs on every foundation location. Extensive advanced lab testing and down hole geophysical methods and pressuremeter tests were undertaken.

Issues included: the detailed designer was appointed after the site investigation was completed; insufficient time was allowed for the interpretation of the geophysical and geotechnical

surveys; early CPT refusal and lack of boreholes on location meant that insufficient information was collected at many locations; and, the advanced cyclic testing undertaken was not optimised for the design load being applied to the soil.

The above issues meant that stratigraphy was not certain for the full foundation depth leading to very conservative design and uncertain driveability.

2.1.2 *Project 2 – value ~€0.3bn*

The site investigation comprised a site wide sub-bottom geophysical survey with several rounds of geotechnical works comprising CPTs and boreholes.

The primary issue was the detailed designer being appointed after the site investigation was specified. The boreholes were not deep enough and insufficient information was gathered about the bedrock.

The developer had to commission another round of geotechnical investigation to gather further information for design and risk mitigation, which resulted in project delays and additional costs.

2.1.3 *Project 3 – value ~€1.5bn*

The site investigation comprised a site wide sub-bottom geophysical survey with staged geotechnical works comprising CPTs and boreholes. Extensive advanced lab testing and down-hole geophysical methods and pressuremeter tests were undertaken.

Again, the detailed designer was appointed after site investigation had been undertaken, resulting in an insufficient number of boreholes to allow an efficient design.

2.1.4 *Project 4 – value ~€0.1bn*

The site investigation comprised a site wide sub-bottom geophysical survey with staged geotechnical works comprising CPTs and boreholes.

The specification for the surveys was directly copied by the client from one of their previous projects in very different geology, and the detailed designer was appointed after the site investigations had been undertaken. This resulted in the geophysical techniques not being suitable for the geology and the developer had to repeat the geophysical survey to an enhanced specification.

2.2 *Mediocre practice*

2.2.1 *Project 5 – value ~€1bn*

The site investigation comprised sub-bottom geophysical survey with one round of geotechnical investigation comprising full depth CPTs and boreholes.

The geophysics was incorrectly scoped, so when planning the geotechnical campaign, the detailed designer could not utilise the geophysics. The project programme was also compressed, meaning the geotechnical campaign was carried out in one stage.

More value, cost savings and mitigation of geotechnical risks could have been achieved with a collaborative geophysical and geotechnical interpretation and a staged geotechnical campaign with ground model development.

2.2.2 *Project 6 – value ~€1bn*

The site investigation comprised sub-bottom geophysical survey with one round of geotechnical investigation comprising full depth CPTs and boreholes with geophysical borehole logging.

Again, the geotechnical campaign was carried out in one stage with the scope being developed whilst offshore. A more cost effective survey could have been achieved with a staged geotechnical campaign with ground model development.

2.3 *Good practice*

2.3.1 *Project 7 – value ~€2bn*

The site investigation comprised sub-bottom geophysical survey with multi-stage geotechnical investigation comprising CPTs and boreholes. Extensive advanced laboratory testing was undertaken.

The foundation designer was involved in the specification of the surveys, and a ground model was developed based on collaborative geophysical and geotechnical interpretations. The geotechnical investigations were specified considering the confidence in the ground model and the foundation design.

2.3.2 *Project 8 – value €1.5bn*

The site investigation comprised sub-bottom geophysical survey with multi-stage geotechnical investigation comprising CPTs and boreholes.

The early geophysics identified a considerable geological hazard which was successfully mitigated (Liingaard et al. 2012) through ground model development based on collaborative geophysical and geotechnical interpretations. A multi-stage geotechnical investigation allowed the detailed designer to develop a specific design method and scope the investigations to verify the variations from design codes.

3 SUGGESTED APPROACH

The above projects highlight the issues regarding quality and more importantly the effectiveness of the geotechnical investigations. There are common problems with scoping and management of site investigations. The offshore wind industry should look to the experience gained on projects in other fields of engineering, especially the lessons learnt by large onshore infrastructure projects. In particular they should: consider more formal approaches to the management of geotechnical risk; accept that a staged site investigation will deliver the most cost effective results; and, consider a contracting structure that brings the detailed designer onto the project from a very early stage.

3.1 *Management of geotechnical risk*

Managing ground risks solely through the traditional practice of thorough site investigation will not lead to the most cost effective project. Simply undertaking the most detailed site investigation that the budget will pay for leads to investigations being undertaken that are not specifically targeting the unknowns that are truly affecting the project, and also does not allow for the fact that the acceptable level of risk at construction is very different depending on the project developer and their attitude towards risk.

Developers should therefore seek to apply a more formal approach of managing geotechnical risk so that the site investigation specifically targets the unique project hazards. Clayton (Clayton, 2001) suggests formal processes for managing geotechnical risk, these have been adapted to form the recommended process detailed in Figure 1.

Figure 1 shows a design team led approach to planning, undertaking and reviewing effective site investigations. The design team identifies all hazards affecting the project (design, installation, operation and decommissioning). An assessment is made of the significance of those hazards in consultation with all project stakeholders. The site studies/investigations are planned to specifically target the hazards. The results are studied and the residual hazards reviewed. The consultation is repeated with the stakeholders and the need for further investigation evaluated.

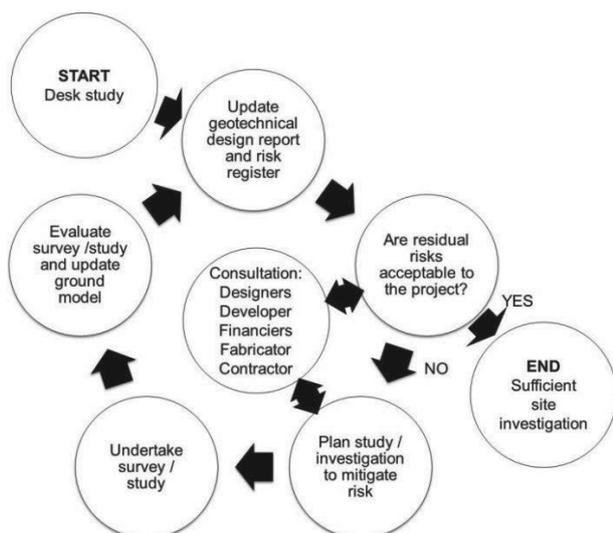


Figure 1. Risk based approach to managing geotechnical hazards

In managing this risk based approach it is essential that the designers appreciate that developers will have different acceptable levels of risk (Figure 2). This level of risk will depend on developers' sources of funding, project timescale and contracting/procurement strategy. The acceptable level of risk will also change as a project develops.

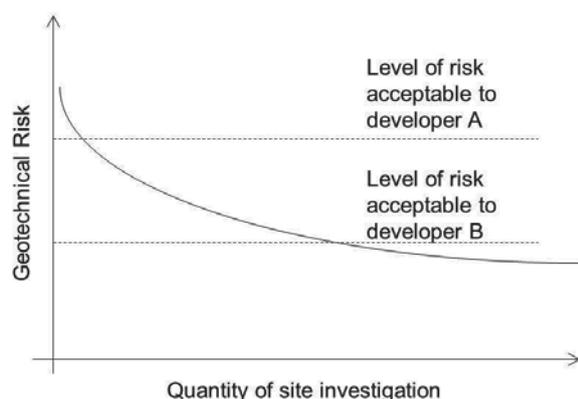


Figure 2. Acceptable level of geotechnical risk to a developer

3.2 Staged site investigations

All of the projects reviewed in Section 2 had separate stages of site investigation comprising a geophysical followed by a geotechnical campaign. However the good practice projects had a multistage geotechnical campaign. Eurocode 7 (EC7) (BS EN 1997-2:2007) states that "Ground investigations should normally be performed in phases depending on the questions raised during planning, design and construction". The code goes on to define two distinct phases of investigation – preliminary investigation and design investigation.

The multistage geotechnical investigation allows for a comparatively cheap ground-truthing geotechnical campaign early in the design process. This campaign gives the designer sufficient information to confirm the expected ground model and develop a preliminary design solution. The design investigation will then be significantly more effective, since it can utilise the most effective methods of investigation for the ground conditions, and fit the foundation type and dimensions that are being designed.

The strategy outlined in Figure 1 will be most effective when repeated several times; designers should be wary of trying to understand all ground based hazards in one stage of geotechnical investigation. A simple preliminary investigation

combined with the existing understanding of the site will often provide the best value to the developer at an early stage.

3.3 Develop contracting structure that allows early appointment of the designer

Many of the example projects detailed in Section 2 had ineffective site investigations because the detailed designer for the foundations was not appointed until after all site investigations had been completed. These projects appointed engineers solely to organise and supervise a single phase of site investigation who were not otherwise engaged in planning or design of the project. "This practice inhibits continuity or integration of project development, with the prospect that the site investigation will not be coupled with other features of the project planning process and will, in consequence, not provide adequate answers to vital questions and will not allow consideration of innovative methods of working". This quote from Muir Wood (Muir Wood 2000) is just as applicable to offshore wind farm developments as it is to the tunnelling projects it was originally written to describe.

Instead developers should seek to engage a designer at the start of the development phase, who has the competence and ability to provide the geotechnical engineering for the whole project. This allows the foundation design and the scope of the site investigation to develop with the project, which mitigates project risks and delivers cost effective site investigations.

This is the approach taken by most infrastructure projects of equal size and complexity to these offshore wind developments. As these projects have demonstrated, this does not prevent the use of different project procurement mechanisms, provided that mechanisms such as novation are available to the developer.

4 APPLIED EXAMPLE

The strategy detailed in Section 3 is being applied to the first project of the Hornsea Round 3 development area as follows.

4.1 Engineering contract setup

For this project, the developer – DONG Energy is using in-house engineers to undertake the geotechnical design and engineering. This capability is supplemented by the use of additional consultants appointed to the projects for long term positions. This setup gives an integrated approach to engineering and development. Different parts of the project will have different procurement strategies; where the developer chooses not to progress the detailed design in house the design for that element will be contracted to another party, with the original in-house design team maintained in a reviewing capacity.

4.2 Desk study

Prior to the desk study, no geotechnical design parameters were available. The principal geotechnical risks at this stage are shown in Table 1. At this point, the site investigations cannot be specified as the foundation type, ground conditions and design requirements are not understood.

Table 1. Design parameters and primary geotechnical risks prior to desk study

Design parameter	Geotechnical risks
None	Unknown site constraints
	Unknown design constraints
	Unknown construction constraints

Following completion of a desk study which includes a review of geological information, design requirements and possible foundation types and construction considerations,

geotechnical design information is available and project specific geotechnical risks can be identified, as shown in Table 2. At this point the design parameters have been selected based on geological memoirs and nearby site investigations. The undrained shear strength of the main clay unit has been used as an example to show how the design inputs change as more information is collected.

Table 2. Design undrained shear strength of main clay unit and primary geotechnical risks following desk study

Design parameter	Geotechnical risks
125 to 350 kPa	No wind farm specific ground information
	Presence of regional geohazards
	Several foundation types possible

The design information and project risks are reviewed at this stage. Referring to Figure 2, this level of design information and risk may be acceptable to some clients, in which case the design and construction risks will be managed with a conservative and uncertain design, or passed onto a third party with large financial consequences. However in this case, to confirm the ground conditions and add confidence to the design, site investigation works were specified.

4.3 Geophysical survey

A site wide sub-bottom geophysical survey was carried out. The primary objectives were to: identify the geological units present; identify any unexpected geological features; and, collect information to allow preliminary geotechnical boreholes to be positioned.

4.4 Preliminary geotechnical survey

A preliminary geotechnical survey consisting of seabed CPT and composite CPT and sampling boreholes was carried out. The primary objectives were to: validate the desk study and geophysical survey; collect information for ground model development including in situ testing and sampling in the primary units; and, identify unexpected ground conditions and risks.

Following completion of the preliminary geotechnical site investigation, the results were interpreted and a ground model produced.

4.5 Ground model development

The ground model was developed using a collaborative geophysical and geotechnical approach. The engineering units were identified and geotechnical parameters selected using the CPT and laboratory testing results. Wind farm specific ground information is now known, and the regional geohazards understood, allowing preliminary design to commence. The design parameters and risks (Table 3) have been refined, resulting in a more efficient foundation.

Table 3. Design undrained shear strength of main clay unit and primary geotechnical risks following preliminary site investigation and ground model development

Design parameter	Geotechnical risks
Low: 145 kPa	Local variation in site geology
Mean: 240 kPa	Advanced design parameters unknown
High: 325 kPa	

4.6 Design team and stakeholder review

The confidence and expected accuracy of the geotechnical interpretation and risks were reviewed by the design team and stakeholders. It was decided that there was sufficient knowledge

of the site to progress the design and construction planning and manage the geotechnical risks.

Some of the project infrastructure will be designed and developed by others. There is now sufficient knowledge of the site to be able to define a contract ground model baseline, and enable the risk to third parties of unknown ground conditions to be appropriately handled.

4.7 Future geotechnical survey

The residual project risks are not acceptable for the finalisation of detailed design. To obtain this information, a small number of sampling boreholes (to obtain samples for advanced laboratory testing) complemented by one CPT to the expected foundation depth (to identify local variability and confirm the units present) will be carried out. Subsequent investigation may be required depending on the results of this investigation and the developer's acceptable risk.

5 CONCLUSIONS

Offshore wind projects in their early stages present considerable challenges to engineers managing the geotechnical hazards given the large complexity, cost and time scale of the projects.

A review of the site investigations undertaken for various projects highlights repeated mistakes leading to inefficient site investigations; namely the site investigations not being planned to mitigate project specific geotechnical hazards and surveys not being specified by the foundation designers.

Lessons must be learnt from the wider construction industry, including: the need for formal approaches to the management of geotechnical risk; acceptance that a staged site investigation will deliver the most cost effective results; and, considering a contracting structure that brings the detailed designer onto the project from a very early stage.

The authors have proposed an engineer led approach for managing geotechnical risks, where the design team and stakeholders are actively involved in assessing and mitigating the geotechnical risks, allowing the geotechnical foundation design and site investigation to develop with the project and ensuring that survey work is specified to directly control project risks.

These principles are being applied to the first project of the Hornsea Round 3 development area, where design and construction risks are being mitigated early with a relatively small amount of site investigation works.

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