Scoping Appropriate Feasibility Level Geophysical and Geotechnical Survey for Offshore Wind – Offsetting Cost against Knowledge Gain

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ABSTRACT:

In order to carry out preliminary design activities and project cost estimation for offshore wind projects, it is necessary to undertake feasibility level geophysical and geotechnical survey. Due to the nature of the timings of these surveys prior to consent, they may be considered ‘at risk’ expenditure and, as a result, financial constraints are likely to be considerable. However, in order to facilitate conceptual design, generate reliable CAPEX models and reduce seabed risk to an appropriate level, the scope of the survey must be sufficient. It is this balance that we must strive to achieve. But what constitutes an ‘appropriate’ scope? As might be expected, the drivers for this level of survey are many and varied. The principal considerations for this and any survey are ‘How much do we need to know?’ and ‘How much will the survey cost?’

This paper will identify the key objectives that need to be met by survey works at this stage of a project. Such a survey should facilitate conceptual design and so should also investigate the full range of seabed geology anticipated within a development area. The survey scope should be developed through close involvement and co-operation between the appointed geoscience specialist, environmental consultant and the developer’s project team. This ensures that the survey is ‘fit for purpose’ and achieves the engineering and environmental expectations of the project development team whilst identifying key seabed risks and constraints.

1 INTRODUCTION

Conceptual design engineering is a significant milestone in the development of an offshore wind project in order to provide sufficient definition to CAPEX and OPEX models which in turn determines project debt levels, debt serviceability and project investability. Feasibility geophysical and geotechnical surveys are an essential precursor to generating reliable and accurate project financial models as these surveys determine developable areas and substructure selection.

This paper considers the factors and considerations present within typical offshore wind projects which govern the design of appropriate survey and identify the key competing constraints and objectives which define preliminary survey scope. Accordingly, guidance is given as to what may constitute an appropriate survey scope as a function of the anticipated geological conditions and the acceptable geotechnical risk.

As documented in this paper, there are a considerable number of variables particular to any given offshore wind farm site which determine the nature of an appropriate survey scope. Hence, whilst the recommendations in this paper strive to be quantitative and specific, some generalities are necessary in order to enable this discussion to be applied to the bespoke nature of offshore surveys.

2 EXISTING GUIDANCE

There are a number of guidance documents available to the offshore industry for the design of offshore surveys and many of these in recent times have been tailored for offshore renewable energy projects. These guidance notes are, however, largely tailored towards detailed survey stages when project uncertainty is significantly lower, contain qualitative guidance and do not consider the project constraints influencing survey scope.

A selection of commonly consulted guidance documents are discussed in this section, excerpts provided and their respective guidance discussed for survey scoping.
This DNV document provides an offshore standard for the design, construction and inspection of offshore wind turbines. Section 3G specifically concerns investigation of soils and the acquisition of data but is written specifically to provide guidance on the requirements to inform detailed design.

With specific reference to geophysical survey, the guidance recommends:

‘The line spacing of the seismic survey at the selected location should be sufficiently small to detect all soil strata of significance for the design and installation of the wind turbine structures. Special concern should be given to the possibility of buried erosion channels with soft infill material.’

At preliminary survey stage a degree of risk may be accepted that not all occurrences of a given formation have been detected within a development area, provided that this is not to the excessive detriment of conceptual design. The author does recommend, however, that the survey is scoped in order to substantially limit the risk of a given significant geological strata not being detected within a development area at all.

With specific reference to geotechnical survey, the guidance recommends:

‘For wind turbine structures in a wind farm, a tentative minimum soil investigation program may contain one CPT per foundation in combination with one soil boring to sufficient depth in each corner of the area covered by the wind farm for recovery of soil samples for laboratory testing. An additional soil boring in the middle of the area will provide additional information about possible non-homogeneities over the area.’

For the purposes of conceptual design, it is sufficient that each geological stratum is intersected and sufficient spatial coverage of the wind farm development area is obtained. The level to which multiple investigations are undertaken within a single stratum to address issues of heterogeneity should be subject to the scrutiny of an experienced geotechnical engineer.

This DNV guidance document provides guidance for the survey and subsequent geotechnical design of fixed offshore structures. The guidance was intended for offshore oil and gas developments and was published prior to the advent of offshore wind in Northern Europe. Nevertheless, the note does contain relevant guidance and makes specific reference to staged survey approaches and the requirements for preliminary investigation which may be adopted for the scoping of preliminary survey for offshore wind farm developments:

‘The required amount of information with respect to soil properties normally changes during a field development. At an early stage the gathered data should be sufficiently detailed to demonstrate the feasibility of a given concept. Also, the information available at this stage facilitates the selection of the location for the structure within the development area. At a final stage the soil investigation should provide all necessary data for a detailed design of a specific structure at the specific location.’

With regards to geotechnical survey scope, the API guidance refers to the need to tailor the scope to suit the type of foundation structure and the degree of heterogeneity of the seabed geology which this paper advocates:

‘If practical, the soil sampling and testing program should be defined after a review of the geophysical results. On-site soil investigation should include one or more soil borings to provide samples suitable for engineering property testing, and a means to perform in-situ testing, if required. The number and depth of borings will depend on the soil variability in the vicinity of the site and the platform configuration. Likewise, the degree of sophistication of soil sampling and preservation techniques, required laboratory testing, and the need for in-situ property testing are a function of the platform design requirements and the adopted design philosophy.’
As this guidance has been developed for the detailed engineering design of individual oil and gas platforms (minimum of one borehole per structure), the suggested guidance of a single borehole for a wind farm development over 10’s of km’s would not be valid.

2.4 BOEMRE

BOEMRE have produced guidelines\(^5\) for the specification and scoping of geophysical and geotechnical survey for offshore wind projects. Whilst there is not a statutory requirement to comply with the recommendations given by BOEMRE and the recommendations leave considerable room for manoeuvre, a clear onus is placed upon the offshore wind developer to justify the survey mobilised and to provide the information that BOEMRE require to process the developers Site Assessment, Construction and Operations and General Activities plans.

The recommendations are, as in many of the other guidance and standards available to industry, written in the context of providing information for detailed infrastructure planning and design.

The BOEMRE guidance document provides very detailed and specific guidance for geophysical survey which almost constitute a scope and specification for survey. BOEMRE recommend that:

‘The geophysical survey grid for the project area should include bathymetric charting, hazards assessments, and archaeological resources assessments. These should be oriented with respect to the bathymetry, geologic structure, and renewable energy structure locations whenever possible. The grid pattern for each survey should cover the project area including areas of all anticipated physical disturbances.’

BOEMRE further recommend that:
- Survey line spacing should not exceed 150m for side scan sonar and sub-bottom profiling
- Survey line spacing for multi-beam echo sounders and side scan sonars should enable the detection of discrete targets 0.5-1.0m in diameter
- Tie-lines should be perpendicular to track lines and should not exceed a line spacing of 150m
- Line spacing for archaeological resource assessments should not exceed 30m in areas where the seafloor will be disturbed by any activities

Whilst such prescriptive guidance may reduce ambiguity in detailed survey, conceptual design may not require the resolution of seabed strata associated with 150m sub-bottom profiler line spacing. As preliminary survey is not intended to provide a full suite of data for the purposes of BOEMRE approval, a more pragmatic approach may be taken.

BOEMRE’s recommendations for geotechnical investigation are somewhat less prescriptive but clear objectives are given for detailed geotechnical survey:

‘Sampling/testing protocols generally use one or more of the following: soil borings, cone penetrometers, and vibracores to elucidate the geotechnical (and geological) aspects of soils and sediments. BOEMRE should be provided with a detailed geotechnical evaluation of the structure’s foundation(s) based on analysis of soil borings and cone penetrometers at the site. The results of the tests should allow for a thorough investigation of the stratigraphic and geoengeering properties of the sediment that may affect the foundations or anchoring systems of the structure(s). There should also be sufficient geological/geotechnical sampling and testing of foundation soils to thoroughly categorize engineering conditions within the proposed transmission cable corridor.’

‘The principal purposes of the tests are to: (1) assess the suitability of shallow foundation soils to support the renewable energy structure or associated transmission cable under extreme operational and environmental conditions that might be encountered; and (2) document soil characteristics necessary for design and installation of all structures and transmission cables.’

BOEMRE further recommend that:
- Completion of a minimum of one deep (>10m below foundation termination depth) boring at each edge of the project area and within the area as required
- It may be necessary, should the seabed conditions be particularly complex, to obtain an investigation at each foundation location

The guidance provided by BOEMRE, therefore, is very closely aligned to that of DNV. The statistical variance of soils and cost-benefit of undertaking geotechnical investigation at each turbine location has been investigated by Stuysts et al\(^6\) for detailed geotechnical survey and may be used to justify a given approach to BOEMRE. For preliminary investigation, however, such as detailed approach is not required and is in fact
impossible, largely due to the constraints described in 3.5. A preliminary survey may, however, begin the process of compliance with BOEMRE guidelines through the completion of sufficiently deep peripheral boreholes (5.2.3).

2.5 BSH

In order to gain approval for offshore wind developments in the German sector of the North Sea, compliance with the BSH standards is mandatory. These standards have been developed specifically for the planning, design and construction of offshore wind farms and present a prescriptive methodology for the survey and interpretation of offshore wind development sites. The standard[7] is very prescriptive with respect to geotechnical investigation but less so with regards to geophysical survey. Generally:

‘The basis of the ground investigations is geological and geotechnical field and laboratory tests. It shall be carried out taking into account the planned foundation concept, with adequate consideration of the difficulties of foundation design, on the one hand, and of soil properties and other conditions, on the other hand. Their scope shall be such that all soil properties that are relevant to planning are determined well before the installation of the structures.’

And with specific regard to geophysical survey:

‘Geological reconnaissance to assess the general suitability of an area, which allows a detailed geological interpretation of a planned wind farm area on the basis of a sufficient number of survey transects. Conditions at all planned locations of offshore wind farm components shall be investigated in order to identify unfavourable local soil conditions and, if necessary, change or optimise individual locations’

And with specific regard to geotechnical survey:

‘For preliminary investigations one borehole shall be drilled and cone penetration test shall be made at each corner of the wind farm area and in its centre, but at least at 10% of all turbine sites, unless different points appear more suitable for testing on the basis of the results of the geophysical reconnaissance or in view of the special geometry of the wind farm area.’

The BSH standards therefore require the designer of offshore survey to know, in advance of site survey, the planned location of offshore wind farm infrastructure. Whilst probable locations for infrastructure can be assumed for the purposes of designing survey, it is highly probable that these locations would substantially change following detailed wind resource modelling, constraints analysis and interpretation of survey data. Such an eventuality would then call into question the validity of the preliminary surveys should the infrastructure locations be subject to substantial modification. A more pragmatic approach may be taken to preliminary survey.

2.6 NORSOK G-001

NORSOK standard G-001[8] provides specific guidelines and requirements for geotechnical investigation techniques and may be used as a base specification for geotechnical investigations within a survey contract. As such, the guidance contained within the document regarding survey scope is limited but the document does make the following relevant general statement:

‘The level and extent of a soil investigation should be a function of several factors including, but not limited to, geology of the area, local soil conditions, project requirements, availability of previous investigations, accessibility, environmental conditions and any limitations related to budget and time available.’

2.7 OSIG

Developed specifically for offshore renewable energy projects, these guidance notes[9] provide a pragmatic assessment of survey requirements and a critical appraisal of existing survey design guidance. In a similar manner to the DNV guidance, the OSIG document states:

‘The required level of information will vary during the development of the project. At project conception, the data available should be sufficient to demonstrate the feasibility and suitability of the preferred foundation design concepts and selected cable route corridors. As the project progresses towards detailed design and construction, the data should be sufficiently detailed and robust for design purposes and to allow contractors to provide optimised pricing for supply and installation contracts.’
The document also makes quantitative recommendations regarding the scope of geophysical and geotechnical surveys although the recommendations relate to acquiring data for detailed design. The following scope statements are provided for geophysical and geotechnical survey respectively:

‘Final survey design will depend upon the requirements of the survey, water depths and any other physical restrictions. Typically for an echo sounder, side scan sonar, and a sub bottom profiler data should be recorded along survey lines spaced at 50m intervals with cross lines every 250m. Swathe data should be recorded along lines spaced no less than 3 times water depth. It is also advised that magnetic, resistivity and electromagnetic data be recorded along lines as closely spaced as is feasibly possible.’

‘The geotechnical survey should provide all the necessary seafloor data to allow detailed design of the project including foundations and cable routing, burial and protection. To add maximum value to the seafloor risk management process the geotechnical survey data should be correlated with the preliminary site assessment and the findings of the geophysical survey. The aim of the survey is to confirm the geological / geophysical model for the site, determine the vertical and lateral variation in seafloor conditions and to provide the relevant geotechnical data for design.....

.........The spacing of sampling and testing locations will depend on the lateral variability in ground conditions revealed by the desk study and geophysical survey phases. The number, depth and position of investigation locations should be a product of a rational engineering exercise, incorporating the owners / developers risk acceptance criteria, the robustness of the design and the degree of homogeneity anticipated across the site.’

3 PROJECT DEVELOPMENT CONSTRAINTS TO SURVEY SCOPE

Aspects of the project development generate the key constraints to feasibility survey scope as opposed to aspects of the natural environment. Many of these constraints are cost related whilst technical constraints relating to project planning also play a significant role. This section will present these constraints and the particular associated influence on survey scope.

3.1 Project Finance

Feasibility surveys occur during a high-risk phase of the development of an offshore wind project. The surveys are undertaken pre-permit and before financial close and as such are an ‘at risk’ cost. Significant financial pressures therefore exist for the geoscience consultant and developer when scoping surveys in order to reduce the financial risk to the project. Conversely, without the risk-reducing influence of these surveys, it is impossible to plan and design the infrastructure which defines the eventual CAPEX models. Figure 1 below presents a qualitative project finance curve with respect to various project development milestones.

Figure 1 Offshore wind project finance curve versus development milestones
The timing of survey spend illustrated in Figure 1 is the primary factor requiring the offset of knowledge gain against cost to which this paper refers.

3.2 Local Supply Chain

Whilst in certain parts of the world, for example, major oil and gas development areas such as the North Sea, a substantial supply chain exists to service offshore projects, frontier areas such as the eastern seaboard of the United States may be inadequately equipped to undertake offshore survey in a ‘best practice’ manner or to provide a suite of contractors for the purpose of competitive tendering.

Accordingly, prior to scoping survey, it is important that the survey designer understands the local supply chain to ensure that the scope design is deliverable. Alternatively, the survey designer and the offshore wind developer need to understand the potential cost implications of long-distance mobilisations of specialist contractors.

3.3 Metocean and Bathymetric Conditions

The cost of undertaking preliminary survey is primarily as a result of vessel cost. Due to the acute budgetary pressures presented in 3.1, there is a strong tendency to under-specify the survey vessel required to undertake the work. Whilst this approach results in attractive figures for board approval, the resultant survey is likely to incur onerous quantities of downtime due to adverse weather conditions. Rather than considering the absolute pre-weather cost of a survey, likely weather contingency costs should be included which encourages the concept of ‘value for money’ rather than ‘cheapness’ of survey.

Areas such as the eastern seaboard of the United States can be highly onerous in terms of productive survey time due to high wind and swell conditions constraints created by Nor’easters, southerly tropical storms and easterly Atlantic swells.

The selection of an appropriate survey vessel is subject to a number of practicalities:

- Operational distance from shore
- Accommodation capacity and victualling
- Vessel endurance and duration of operations
- Shift working – 12 or 24 hours
- Seakeeping capabilities
- Available working / equipment deployment areas

Geophysical survey operations are particularly sensitive to metocean conditions and so it is essential that the selected vessel is not more weather sensitive than the towed arrays. Such a scenario would result in unnecessarily low survey availability and further constraint to survey (Figure 2).

Figure 2 The benefit of a large, stable geophysical survey vessel should not be underestimated
A key constraint for the selection of an appropriate geotechnical vessel is site bathymetry. Dynamically positioned vessels are preferable in terms of flexibility and weather tolerance (Figure 3) but encounter positioning problems in water depths of less than 20m (Figure 4). Small jackup vessels suitable for undertaking geotechnical investigation are commonly deployed in water depths up to 30m, provided significant leg penetration into seabed is not anticipated (Figure 5).

Figure 3 The sensitivity of a particular vessel type to metocean conditions is an important factor when considering survey efficiency.

Figure 4 A typical dynamically positioned geotechnical survey vessel.
The selection of survey vessel is also likely to be influenced by anticipated offshore working practices and survey techniques. Efficient geophysical survey is often achieved with single-pass survey whereby all of the mobilised geophysical sources and sensors are deployed simultaneously. Such an approach generally requires a larger vessel with an associated higher day-rate and so the selection of vessel may be defined by a cost benefit of total days at sea versus day-rate costs. Metocean considerations should also be borne in mind, however, as small survey vessels performing multiple passes will be significantly more weather sensitive.

The selection of geotechnical survey techniques can have a decisive impact and constraint upon vessel selection. If monopiles are considered to be the most viable foundation solution, such infrastructure benefits greatly from an understanding of lateral soil pressures and radial soil stiffness due to the manner in which a monopile deflects and strains the seabed soils. Such an understanding is best gained through the deployment of down-hole driven or drilled pressuremeters which can only be deployed from a jackup vessel and so the anticipated infrastructure can also constrain the selection of survey vessel.

### 3.4 Preferred Development Areas

The area of ocean bounded by a development zone boundary is unlikely to be entirely suited to economic development. Even after public and statutory body consultation, the designated development zone is likely to encompass areas of sensitive or conflicted seabed less suitable for the development of wind turbine generators.

Potential ‘soft’ constraints such as these may comprise:
- Areas of excessive bathymetry
- Areas of ecologically sensitive but non-designated seabed
- Areas of ocean with large seabird populations
- Areas of ocean subject to recreational use
- Areas of unacceptable visual impact
- Areas associated with radar and navigation interference
- Areas used for fishing
Whereas most constraints act to impede survey scope, the soft constraints detailed above enable areas of a development to be discounted. It is highly advantageous, therefore, for these potential constraints on development to be quantified, in so far as possible, prior to the deployment of preliminary survey. This allows the survey to be more intensively focussed with less wasted survey effort on areas with fewer constraints which are most likely to be utilised for development. This approach is dependent upon an open dialogue between the regulatory body, developer, environmental consultant and geoscience expert and benefits greatly from the integration of the developer’s consultants into the project team.

3.5 Project Infrastructure

The consideration of anticipated project infrastructure encompasses a diverse range of key components that constitute an offshore wind farm:

- Turbine size and type
- Substations
- Meteorological masts
- Substructures
- Foundations
- Subsea cables – inter-array and export

At the point of developing a feasibility survey scope, a well-planned geotechnical risk mitigation strategy requires the completion of a site suitability assessment and foundation optioneering exercise. This is utilised in conjunction with a detailed desk study in order to inform the scoping process. These studies will enable the feasibility surveys to be significantly more targeted and efficient.

These studies are, however, unlikely to resolve all of the geohazards and geotechnical risks into a single foundation and substructure option for which a survey may be designed. Even in cases where the particular seabed conditions at a site are such that only a single foundation option is likely to be feasible, for example hard rock at seabed, a prudent offshore wind developer will seek to maintain redundancy in the permitting process by continuing to consider more than one foundation option. Thus, the survey scope must be such that a given range of foundation and substructure possibilities may be accommodated.

The foundation and substructure options under consideration have the principal impact of determining the depth below seabed to which a geophysical or geotechnical survey must investigate. Whereas a gravity base foundation founded on hard rock at seabed might require shallow investigation of 10-20m, a piled solution founded within soils may reasonably require investigation to depths of 50m or more below seabed.

A given certainty at this stage of any offshore wind farm project is that turbine locations will not be finalised, indeed this may not have been considered at all. The only spatial constraints to feasibility survey likely to be present at this stage of development are the overall development zone boundary and any preferential development areas within this identified by site suitability exercises. As a further consenting risk mitigation strategy, the offshore wind developer may choose not to discount any areas for survey but focus particular effort on those areas identified as being more suitable.

Whilst the lack of spatial constraint is less of an issue for preliminary geophysical survey for which total survey coverage should always be considered (justification and arguments for this are presented later in this paper), geotechnical survey benefits greatly from being deployed in a spatially targeted manner. The lack of planned infrastructure locations requires the preliminary geotechnical survey to be located according to anticipated site characteristics and to facilitate general coverage.

3.6 Survey Design Basis

Preliminary surveys should be designed and deployed as part of a planned geohazard and geotechnical risk mitigation strategy such as that outlined by OSIG\textsuperscript{[9]}. Such a strategy seeks to progressively reduce geotechnical risk and address geohazards by managing, mitigating, avoiding or allowing for those hazards and risks.

Whilst these surveys are the first quantitative step in achieving the objectives of a risk mitigation strategy, the information preceding the surveys upon which they are scoped may be incomplete, inaccurate or flawed which creates a constraint on the scope of the surveys.

The unavailability of geotechnical data at research stage can also have significant implications for the geotechnical risk associated with survey. The safe emplacement of jackup vessels depends upon an adequate understanding of seabed soils and thus the extent of leg penetration and risk of punch through failure.
Any inaccuracy or lack of information may be expressed as a geotechnical risk which should be addressed by survey. Clearly, a comprehensive and well executed desk based study can mitigate a lack of information and reduce geotechnical risk.

An example of this is geological mapping of the seabed available from the United States Geological Survey. Such offshore information is commonly based upon widely spaced regional geophysical transects that, whilst being highly valued as a source of regional geological information, can easily miss smaller scale features such as palaeochannels (Figure 6) which are an important consideration for geotechnical design of offshore structures.

Figure 6 Palaeochannels such as this example may contain more recent and less well consolidated soils which, depending upon foundation type this may be advantageous or disadvantageous

As part of a geotechnical desk study, it is essential that these desk research derived resources are critically appraised and their limitations expressed.
4 SURVEY SCOPE DRIVERS

The objectives of preliminary surveys act to diversify and increase survey scopes. Due to the level of uncertainty at the preliminary stages of a project, there may be a tendency to attempt to investigate all anticipated geohazards and address all geotechnical risk which should be avoided as this is likely to result in abortive survey effort and expenditure. A preliminary survey should seek to be fit-for-purpose and to permit sufficient reduction of risk to achieve the necessary CAPEX model definition. The surveys must also sufficiently constrain the potential infrastructure options to undertake focussed license and permit activities.

This section of the paper presents the various primary drivers that must be addressed in order to achieve successful conceptual design and permitting.

4.1 CAPEX Modelling

In order to gain board consent and to raise finance for construction of an offshore wind farm, it is imperative that accurate cost forecasting and CAPEX models are available prior to financial close. Clearly, given the timing of preliminary surveys, the accuracy of such models relies heavily upon the raw and interpreted data gathered by such surveys.

This financial driver behind survey scope directly opposes that of the financial constraint to confine ‘at-risk’ survey cost (3.1).

The scope of preliminary surveys is driven by the degree of accuracy required in these CAPEX models prior to financial close. Such a parameter will vary between developments and between offshore wind developers but is most commonly expressed as a +/- % of total CAPEX cost. Clearly, such accuracy in CAPEX is related to the potential permutations in design which in turn is related to the level of uncertainty in base data acquired by survey. Assessments in the potential variance in CAPEX cost as a result of the level of detail acquired by preliminary survey can either be undertaken empirically and qualitatively through experience or quantitatively by investigating and budgeting design scenarios.

4.2 Regulatory Requirements

Federal and State bodies impose requirements on survey campaigns, particularly geophysical survey, to enable the quantified assessment of seabed ecology, environment and natural processes such as sediment mobility (Figure 7). In addition to these requirements, the offshore wind developer should seek to gain sufficient seafloor data at preliminary stages to de-risk the site environmentally and ecologically and to provide a comparative data set for later survey in order to assess seabed change and mobility.

Such assessments of the seafloor are very likely to require 100% insonification of the seabed within areas to be developed in order to guarantee that the marine habitat has been properly investigated and to permit comparison with later surveys[5]. From a technical standpoint, total coverage of the seabed is highly desirable in order to determine seabed change and sediment mobility. Long term sediment mobility is a risk to submarine cables due to de-burial and also, if of a sufficient magnitude, to the stability of substructures and foundations.

Figure 7 Sand wave and associated megaripples investigated with high resolution multi-beam echo sounder

[5] Source: This figure displays a high-resolution multi-beam echo-sounder survey of a sand wave and associated megaripples, indicating the kind of data that is essential for understanding seabed dynamics and ecological impacts.
In addition to the technical content of surveys, regulatory bodies may also stipulate the timing of surveys. Fishing seasons, migrations of marine mammals and birds and fish spawning seasons can all cause regulatory bodies to consider specifying restrictions on survey mobilisations.

### 4.3 Anticipated Infrastructure

The anticipated foundation and substructure to be utilised within an offshore wind development is one of the principal governing factors for the scoping of survey quantities and survey techniques. Since the advent of offshore wind power in Northern Europe, offshore wind development sites have moved further from shore into deeper waters which have necessitated a diversification in potential foundation technologies to address the changes in metocean environment. Therefore, when scoping preliminary survey, a wide range of potential foundation systems should be considered in order to avoid the need for expensive survey re-mobilisation to gather more data at a later date.

The most commonly considered foundation and substructure options to date are:

- Monopiles
- Gravity Base Structures
- Piled Jackets and Tripods
- Suction Caissons

Each foundation option interacts with the seabed in different ways but all foundation options impart loads to the seabed strata to a considerable distance beyond their own physical extent. Figure 8 below illustrates how survey penetration to the termination depth of a foundation structure is not sufficient to permit its design.

![Figure 8 FE Analysis of a suction caisson foundation illustrates the zone of soil mobilised by the foundation](image)

For piled foundations, empirical and conservative work has suggested that the zone of pile influence extends to approximately 2.5-3.0 times the pile diameter below the base of the pile which can be used to specify the depth of penetration for survey\(^{3,4}\). For other foundation systems, the particular seabed strata and foundation loadings should be examined to determine the likely foundation influence depth and therefore the required depth of penetration of survey.
Many of these assessments and calculations will be based upon desk based research and may, therefore, not be particularly accurate. Where experienced geotechnical engineers are available to undertake the offshore management of geotechnical surveys, consideration may be given to performing conservative real-time foundation capacity calculations during the progression of boreholes to ensure a sufficient depth below seabed is reached.

In addition to foundation and substructure systems, preliminary survey may also be undertaken for subsea cabling. Whilst subsea cabling is less onerous in terms of survey scoping and design, it is important to establish likely cable routing, cable risk and burial depths at an early stage in order to properly scope survey\textsuperscript{[10]}.

4.4 Geological Complexity

Foundation and substructure conceptual design is heavily dependent upon the seabed information available. To maximise value from conceptual design, it is essential that all of the geological conditions anticipated to be present within a development area are investigated to ensure the applicability of the conceptual design to the site.

This implies that a more geologically complex site will require a greater scope of survey than a site with little geological complexity. Indeed, compared to the relatively simple fluvio-deltaic homogenous sands of the German Bight, past-glaciated terrains such as those present offshore the north-east of the US and along the eastern coast of the UK require greater survey scopes at preliminary stages.

The level of geological complexity present within a development area should be repeatedly assessed after each new stage of data gathering or survey. The geological complexity of a site should be expressed as geological provinces (Figure 9) where a single geological province is a spatially constrained area of similar geology. In this way the geology of a site may be visually summarized and used to guide the scoping of surveys. When spatially constraining areas of similar geology it is important to consider the following factors:

- Geomorphology
- Stratification
- Geological significance (very thin / infrequent strata may not be considered)
- Potential infrastructure (provinces may be tailored to present foundation suitability)

A further consideration with regards to geological complexity may be given to the likely geological, and hence geotechnical, variability within single geological strata. Whilst basal till deposits may be relatively chaotic and homogenous, flooded palaeochannel and palaeo-delta deposits associated with glacial outwash and subsequent marine regression at the end of the last glacial maxima may vary in composition significantly. Such a geological unit may typically comprise fluvial braided palaeochannel deposits such as sands and gravels at the base overlain by tidal estuarine silts and clays which are subject to marine reworking near the top of the unit due to marine regression.

Such complexity within a single geological unit may result in the need for sub-provinces to properly express geological complexity for the purposes of survey scoping. Such a unit is also likely to warrant more detailed investigation with survey such as closer geophysical survey line spacing or multiple geotechnical sample locations.
4.5 Anticipated Geological Strata

The anticipated geological strata present within a site are the foremost driver in selection of survey techniques in conjunction with the considerations of survey penetration discussed in 4.3. Accordingly, an offshore wind development utilising suction caissons in soft cohesive soils will require substantially different sub-bottom profiling techniques to that of a site utilising gravity bases upon a rocky seabed.

In soft seabed soils, sufficient geophysical penetration and resolution may be achieved with pinger-boomer combinations whereas sites with sub cropping or outcropping rock will require higher powered techniques such as towed sparker or mini-airgun arrays.

The structure and geomorphology of soils and rocks present at or below seabed are also important considerations. Geophysical survey in the English Channel, for example, should consider the ability to detect karst voids within seabed limestone.

Similar considerations exist for geotechnical survey. Soft soils are likely to be very well suited to traditional composite borehole techniques of thin wall push sampling and low thrust down-hole CPT. If such a survey spread were to be deployed to investigate hard soils or rocky substrates, equipment damage, lack of data recovery and significant vessel down-time would result.

4.6 Subsequent Work

All surveys, preliminary or otherwise, should be scoped with a forward-looking perspective in order to ensure their suitability to inform future workscopes.

Consequently, a preliminary geophysical survey should be scoped to inform the following:

- Preliminary geological reporting and modelling
Refinement of preferred development areas
Preliminary geotechnical survey scoping
Coastal process and sediment mobility modelling
EIS and EIA
Conceptual design

Preliminary geotechnical survey should be scoped to inform the following:
- Data integration and re-interpretation (ground-truthing) of geophysical data
- Refinement of preferred development areas
- Geological reporting and refined modelling
- Coastal process and sediment mobility modelling
- Geotechnical design basis for Conceptual design

In order to ensure that the deployed surveys are fit-for-purpose, it is essential that the scope is developed by personnel with experience of design activities and data interpretation who understand the end use of acquired data.

5 SURVEY SCOPE OPTIMISATION

This section of the paper aims to present means of scoping efficient survey which permits cost to be offset against knowledge gain without inappropriate sacrifices being made to the quantity or quality of the data acquired. The discussion in this section is based upon recent experience of survey design and management in Northern Europe and subsequent integration and interpretation of acquired data.

5.1 Geophysical Survey

In both preliminary and detailed geophysical surveys, a number of items of equipment may be considered as ‘standard’ in order to acquire the necessary data sets for infrastructure planning and design. Efficiencies in survey may be attained through the intelligent deployment of the various techniques or through the deployment of state-of-the-art or novel equipment.

The following constitutes a typically deployed geophysical survey spread for offshore wind farm survey:
- Single-beam Echo Sounder
- Multi-beam Echo Sounder
- Side Scan Sonar
- Magnetometer
- Sub-bottom profilers
  - Pinger
  - Boomer
  - Sparker or Mini-Airgun

Depending on the size of the survey vessel, the spread may be deployed simultaneously or in separate passes.

5.1.1 Survey Management and Planning

Effective survey management by an experienced client representative offshore is an essential component in the effort to deliver efficient and cost effective survey. The client representative (a single representative suffices for geophysical survey), who should be a geophysicist preferably with a geological background, should be empowered by the developer to vary the survey scope of work and specification in real-time within given contractual and financial bounds.

The real-time variation of the survey enables the operation of the geophysical tools and the planned survey lines to be tailored to the conditions encountered offshore. This substantially de-risks the reliance upon desk based information upon which the original survey scope was defined.

Survey planning should be undertaken well in advance of anticipated mobilisation dates. By consulting the contracting supply chain in this manner, lower survey prices may be secured and the risk to the development timeline substantially reduced. This approach may also enable developers to ‘join-forces’ in order to share mobilisation costs between offshore wind developments and to encourage specialist contractors to mobilise to frontier areas with poor supply chain.
5.1.2 Advances in Equipment Design

The field of geophysical survey tools is subject to constant improvement and optimisation. Specifying state-of-the-art tools can achieve significant cost and time savings. Recent improvements to side scan sonar design, such as the multipulse technology of the Edgetech 4200 towed fish (Figure 10), are an example of this. This sonar is capable of operating at significantly higher survey speeds than its predecessors whilst retaining data resolution and conforming to typical 1m dimension detection criteria. As the remainder of a typically deployed survey spread is less sensitive to survey speeds, the survey vessel may operate at greater survey speeds than may otherwise be possible. This reduces the required productive survey time and exposure to adverse weather risk offshore.

Figure 10 Edgetech 4200 Side Scan Sonar Fish

Similar advancements in sparker technology have led to virtually maintenance free sparker tips which remove the need for daily tip maintenance, trimming and replacement, all of which require vessel downtime. Currently available sparker systems are also sufficiently powerful to attain adequate penetration into a variety of seabed conditions at excellent resolutions (Figure 11), thus removing the need to deploy more maintenance intensive mini-airgun solutions.
The prevalence and concern surrounding marine mammals along the eastern seaboard of the United States makes the replacement of mini-airgun arrays, whose water column sound and pressure waves can cause bodily damage to marine mammals, highly desirable.

5.1.3 Engineering Geophysics

Conventional industry knowledge establishes that geophysical survey data cannot provide specific information on soil types or actual geotechnical parameters. Advances in the design of geophysical survey techniques do have the potential to alter this viewpoint. A new geophysical discipline is emerging, commonly referred to as ‘Engineering Geophysics’.

Engineering geophysics utilises various survey tools which utilise refraction rather than reflection, surface waves and resistivity to sense the seabed which enables geophysical data to be interpreted to generate geotechnical parameters such as dynamic and static stiffness modulii. These techniques also have the potential to investigate geological features such as weathering profiles and fracture densities. Engineering geophysics techniques, therefore, permit the continuous and rapid acquisition of data which can be utilised in geotechnical design and to provide greater detail on the characteristics of sub-seabed soils.

However, the notion of ‘ground-truthing’ with geotechnical survey remains. Engineering geophysics will always depend upon the correlation of geophysical data to actual geotechnical parameters derived through in-situ or laboratory testing which requires site specific geotechnical survey. The discipline of engineering geophysics does, however, potentially offer the opportunity to reduce the amount of geotechnical survey effort required to facilitate effective conceptual and detailed design. The discipline must, however, first gain industry acceptance.

5.1.4 Selective Equipment Deployment

There is a sound basis for total geophysical survey coverage of the seabed for offshore wind developments (4.2). Due to the nature of conceptual design, however, it may be possible if the site conditions permit, to only deploy sub-bottom profilers on selected geophysical transects (Figure 12). This decision is not to be taken lightly however as complex geological conditions may be missed by wide transect spacings. It is important, in particular, that if this approach is adopted, the main survey lines are oriented perpendicularly to any anticipated linear features such as buried palaeochannels in order to maximise the chances of their detection which requires a detailed understanding of the geomorphology and palaeo-environmental aspects of deposition.

Such an approach can dramatically reduce total survey effort, particularly on small vessel deployments where it is not possible to deploy the entire required geophysical array simultaneously. If a large vessel is utilised with the potential to deploy the entire spread simultaneously, any cost savings by reducing the number of sub-bottom profiling lines would only be realised if the sub-bottom profiling is the most weather sensitive aspect of the operation, thus improving survey availability.
Figure 12 Selective deployment of sub-bottom profiling may dramatically reduce total survey effort. The intervening minor survey lines may be surveyed with sub-bottom profilers at a later date prior to detailed design.
5.2 Geotechnical Survey

Whereas there exists a strong argument for certain aspects of geophysical survey scope to be quite prescriptively recommended for offshore wind developments, the scoping of geotechnical survey is much more subjective and dependent upon prevailing site conditions. However, there are in a similar manner to geophysical survey, a standard suite of offshore geotechnical techniques that may be considered for mobilisation:

- **Standard Onshore Shell and Auger drilling**
  - Suitable for jackup deployment but therefore limited in deeper water and workable metocean conditions
  - Traditional and accepted drilling technique
  - Possible to obtain relatively undisturbed U4 samples
  - Possible to undertake *in-situ* Standard Penetration Testing (SPT)
  - Possible to undertake advanced *in-situ* testing such as dilatometers and down-hole geophysical logging easily
  - Possible to mobilise rotary follow-on for rock

- **API String Composite Drilling**
  - Suitable for vessel deployment but therefore limited in shallow water but weather resilient
  - Oil and gas industry established standard
  - Very high quality samples from push tubes
  - *In-situ* high quality Cone Penetration Test (CPT) data
  - Rapid borehole progress rates
  - Possible to mobilise rotary follow-on for rock

- **Geobore-S Triple-Tube Type Drilling**
  - Rotary drilling suited for coring of rock
  - Excellent core quality
  - Difficult to sample or test soils without modification of the bottom hole assembly
  - Wireline technique enabling rapid borehole completion without removal of borehole string

Other less common seabed sampling techniques are available such as jumbo piston cores and box cores but are highly specialist in nature and suited to very particular soil conditions.

5.2.1 Survey Management and Planning

Client representation for geotechnical survey is at least as important as for geophysical survey (5.1.1). Two client representatives are required for geotechnical survey to provide the necessary oversight, both of whom should be geotechnical engineers, preferably with design experience.

In addition to the recommendations in 4.3, the offshore client representatives should be enabled to vary the downhole sampling and testing regime and the offshore laboratory testing to suit the encountered conditions. Client representatives may also be empowered to vary the location of boreholes to suit the encountered seabed conditions although this should be within the stipulated regulatory body requirements.

Advanced planning for geotechnical survey carries with it all of the benefits and risk reduction as that for geophysical survey (5.1.1). The positive effects of this planning is, however, likely to be leveraged due to the significantly more restrictive supply chain available for geotechnical investigation. It should also be considered that if survey contractors are able to long-term forecast possible opportunities then the local and national survey supply chain will improve.

5.2.2 Seabed Frame CPTs

The seabed frame CPT comprises a submersible frame containing all of the necessary equipment to undertake a CPT test that is connected and controlled via an umbilical to the survey vessel (Figure 13). Such a system may either be deployed over the side or stern of a vessel with an A-frame or through a sufficiently large moonpool.

Seabed frame CPTs are available in a variety of push capacities depending upon the self-weight and therefore reaction force capacity of the particular equipment. Whereas smaller 4 tonne push-capacity CPTs are used and have been available for cable route surveys for a number of years, much larger 20 tonne push capacity units are now becoming more widely available and more commonly deployed.

Because of the substantial push capacity of 20 tonne seabed frame units, it is possible to penetrate the seabed to considerable distances before the capacity of the unit is reached. Even in past-glaciated terrains with very stiff and hard clays, penetrations in excess of 15m below seabed are attainable. In softer cohesive and cohesionless soils, penetrations in excess of 30m are attainable.
The advantage of seabed frame CPTs lies in their rate of completion and therefore the ability to rapidly gain excellent coverage of an offshore wind development area. From a dynamically positioned vessel, it is possible to complete 8-10 locations in 24 hours compared to a single borehole over a similar timeframe. Seabed frame CPT operations are also significantly less weather dependent. Seabed frame CPTs are also being rapidly adopted in Northern Europe due to advances in pile design techniques that utilise CPT data[11].

Seabed frame CPT’s do, however, require borehole derived geotechnical data to calibrate against. The application of seabed frame CPTs is also limited by the ability to overcome obstructions below seabed. Whilst a CPT cone is likely to be able to push past an obstruction of pebble or small cobble in size, it will refuse on an obstruction of a boulder size or at unweathered rockhead.

Figure 13 A moonpool deployed 20 Tonne seabed frame CPT unit

5.2.3 Selective Equipment Deployment

Efficient and cost-effective preliminary geotechnical survey may be attained through the targeted deployment of seabed frame CPTs in conjunction with geotechnical boreholes (Figure 14). Following the interpretation and 3D geological modelling of geophysical data, investigation locations should be assigned on a geotechnical risk basis.

Geotechnical boreholes provide the highest quality data with the opportunity to obtain physical samples and so should be deployed within areas of greatest known geotechnical risk or greatest perceived geological variability. Geotechnical boreholes should also be scheduled at the perimeter of an offshore wind development zone to spatially constrain the site geological conditions with high-quality data, thus reducing uncertainty. Seabed frame CPTs should be deployed to provide spatial coverage within a site perimeter to permit the reduction in geological interpretation required between known points and to provide spatially frequent ground-truthing of geophysical data. Consideration should also be given to which particular geological units the seabed frame CPTs are deployed within to reduce the risk of early refusal.
Figure 14 Preliminary geotechnical survey may take the form of an efficient and optimised mix of geotechnical boreholes and seabed frame CPTs.

5.2.4 3D Geological Modelling

All survey scopes are constrained by the knowledge base upon which they are established. Although not a direct technique to improve the cost-effectiveness of geotechnical survey, detailed 3D GIS modelling of geophysical data and assignation of geological provinces can greatly improve the efficiency of geotechnical survey (Figure 15).

In combination with desk-based research, GIS based modelling greatly improves the understanding of the spatial distribution and morphology of geology within an offshore wind development area. This improved understanding of geological occurrences permits an enhanced level of understanding of geotechnical risk and therefore targeting of geotechnical survey.
CONCLUSIONS

This paper has reviewed the state-of-play in the offshore industry with regards survey scoping and the development model for offshore wind farms. A number of significant pressures have been identified to act upon the scope of feasibility level surveys which conflict with the need to acquire sufficient quality and quantities of data to inform conceptual design.

Whilst the pressures to reduce preliminary survey scope are great, the guidance available to industry is predominantly written for the purposes of informing detailed design and thus presents onerously high levels of survey scope. Means of achieving optimised survey scopes are, however, available to enable survey cost targets to be met whilst permitting the objectives of conceptual design to be achieved. The following sections summarise each survey scope constraint and potential means of mitigation.

6.1 Survey Cost

The following measures may be taken to reduce survey cost whilst achieving a sound engineering basis for conceptual design:
- Early consultation of supply chain
- Refined analysis of site suitability to permit concentrated survey effort
- Selective deployment of techniques to achieve survey that is ‘fit-for-purpose’
- Deployment of state-of-the-art techniques and equipment to improve survey efficiency
6.2 Supply Chain

The following actions may be taken to de-risk feasibility survey with respect to the supply chain of survey contractors:

- Research and understand local supply chain
- If possible, tailor survey scopes to suit local availability
- Consult the supply chain early to allow for planned, lower cost mobilisations
- Encourage the growth of local supply chain

6.3 Survey Area and Infrastructure

In order to ensure the completion of relevant and non-abortive survey the following should be achieved:

- Undertake a detailed constraints and consultation exercise to define the areas most suited for development from an environmental perspective
- Undertake foundation optioneering studies to understand the most likely infrastructure options and therefore likely locations for emplacement

6.4 Survey Design Basis

The design of a survey campaign is entirely dependent upon the desk-based research preceding it. Efficient and relevant survey scopes can be developed by:

- Undertaking detailed and diligent desk based research into the likely seabed conditions, geohazards and geotechnical risks
- Produce 3D geological models as early as possible to enhance understanding of spatial distribution of strata and geomorphology
- Empower experienced and suitably qualified offshore client representatives to vary the survey scope

7 REFERENCES

2. Det Norske Veritas (DNV), Classification Note 30.4, February 1992