



Applying the Observational Method to Anchoring of Floating Offshore Wind Turbines

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ABSTRACT: The principles of the observational method and its use for onshore geotechnical engineering are introduced; it is a continuous process of design with monitoring and review to enable appropriate modification to be taken during or after construction. The observational method is seldom acknowledged as a principle in offshore design standards but on some occasions is put into practice with significant benefit to a project and on other occasions the adoption of an observational approach can be problematic. Effective implementation of the observational method requires the various parties within a project to acknowledge that it is being implemented and what their responsibilities are. Some example applications are described including anchor design and installation, scour, and site investigation with a review on good practice and potential pitfalls of an observational approach through the design & construction process and in-service asset management.

Into the future, floating offshore renewable developments may come to rely on the observational method whereby anchor design can be optimised through the installation of a wind farm as experience of the seabed and soil conditions within a site develops. The paper looks at how the observational method may be implemented for anchoring and how it interacts with other requirements such as site investigation, anchor selection and anchor installation.

Keywords: Observational Method, Offshore Floating Wind, Anchors, Site Investigation

1 INTRODUCTION

This paper gives an overview of the Observational Method (OM). It then follows on to introduce some examples where an observational type approach is commonly adopted offshore without formal recognition. Following from this some applications of the Observational Method to floating offshore wind are discussed and a summary of useful principles is given. These include application of OM to offshore site investigation and anchor sizing.

2 OBSERVATIONAL METHOD

2.1 Overview

The Observational Method was developed by Peck in the 1960s and these days as suggested by Biscontin (2019) is more often seen as a best way-out process to deal with unforeseen issues. However, when used deliberately within the project design process the Observational Method can also provide a formal means to make design more economical or efficient than it would be otherwise. The original principles of

the observational method have been incorporated into Eurocode 7 and they are:

- Limits of acceptability of the values of certain quantities representative of the behaviour of the structure-soil complex must be established;
- It must be shown that the chosen solution is acceptable with respect to these limits;
- Alternative solutions (if the stated limits are assumed to be achieved), congruent with the project, must be provided, and their economic burdens defined;
- Adequate in-progress monitoring system, with associated control plans, must be established such that one of the planned alternative solutions can be adopted in a timely manner if the stated limits are reached.

The observational method has found extensive application onshore where it is well suited to a wide variety of situations. This is mainly because onshore engineering often has a greater ability to inspect and modify designs at the time of installation and to monitor and remediate during service life. On the other hand, an observational approach is often implemented

on a formal and informal basis offshore and offshore engineering in general would benefit from adopting a formal framework so that all parties are aware it is being implemented and that it is done in a way that the risks of such an approach can be managed.

Practice for the observational method applied in onshore geotechnical engineering is described by Patel in ICE (2012). DNV (2021) is one of the few offshore design standards that acknowledges the potential role of the observational method and it is likely that the observational method could bring further benefit to the offshore industry if it were more widely codified, including in ISO 19901-4. It may be difficult to apply to certain situations such as conventional foundation types including driven piles or gravity base foundations.

3 OFFSHORE EXAMPLES

The observational method has yet to gain formal recognition in offshore engineering, though at times it is often put into practice without being recognised as such. Similar to onshore practice, application offshore is often hindered by contractual issues such as how to manage to the costs, the practicalities of remediation, monitoring of a situation, lack of code or standard definition. The examples below describe some offshore scenarios where an observational type approach has been, or may be, adopted. In some cases

it was done as Biscontin (2019) suggests as a measure of last resort. In other cases, the process is more familiar to those involved and the observational approach was planned up front with appropriate measures and controls being in place. Some typical applications offshore are outlined in Table 1 and further explanation is provided in the following sections. The financial aspect of applying the observational method offshore could be highly significant (into 10's of millions for some projects) where it can result in cost savings in steel, optimisation of design or accepting structures that may otherwise require remedial work. Furthermore, application of the observational method offshore would require more recognition in codes & standards, project procedures for doing so, measurement of cost benefit and definition through contracts. Without these measures being in place it may not be effective to apply OM on a regular basis.

3.1 Scour

Scour is a commonly encountered hazard for offshore structures including anchors and is the phenomenon whereby the soil surrounding a structure is removed principally by a combination of seabed current and wave action. Scour can occur soon after installation, or there have been scenarios where scour has occurred for the first time many years after installation. Scour is

Table 1: Typical applications of the observational method offshore

Application	Acceptable Performance	Solution for adverse behaviour	Monitoring
Scour design allowance	Scour remains within acceptable limits	Install scour protection to remediate scour hole and prevent further scour	Scour inspection – periodic or event triggered
Jackup spudcan penetration	Rapid penetration does not occur	Minimum airgap to reduce consequences of rapid penetration. Retrieve spudcans and reposition or redesign for site	Monitor jackup performance during spudcan penetration
Drag anchor installation	Anchor test load passes and anchor embedment achieved	Retrieve and reposition anchor; adjust fluke angle Resize anchor	Test load procedure Inspection to ensure minimum burial achieved (e.g. for scour)
Driven pile refusal (measures of last resort as not fully anticipated prior to driving)	Piles are driven to target penetration	Drilling out to reduce resistance. Reassessment of pile capacity or loads and adjustment of remaining pile lengths.	Blow counts and penetration.

often recognised as an issue assessed within the design process with the result being a prediction of scour susceptibility, magnitude depth and extent and an associated timeframe. Where scour is predicted to be significant then its impact can be handled in design by making a design allowance or by the use of scour protection to minimise occurrence or limit impact on the structure in question. Structures or anchors may then be subject to inspection to demonstrate that actual scour remains within design limits; or that the scour protection is providing sufficient protection to the integrity of the foundation or anchor. However, scour can be rather unpredictable, and it may be the case that a structure or anchor can go through the design life without scour ever occurring. In this case inclusion of scour protection or use of design limits may increase the cost (or capex) of the development significantly. On the other hand, the author has experience of a structure that was a significant way through design life and, without a clear event or trigger, large amounts of problematic scour occurred. An alternative to scour protection or design allowances is to use inspection and ensure that remediation is possible before the integrity of the structure is impacted by scour. In this sense the issue of scour easily lends itself to an observational type of approach on the basis that inspection and remediation can be implemented before scour has an impact on foundation integrity.

3.2 Driven Piles

Driven piles are an example of where an observational type of approach has been adopted offshore in order to remediate an unexpected event. The author has encountered a significant number of projects where pile driving refusal has occurred and 'late adjustments' were made to acceptable pile penetration. In some cases, a deliberate underdrive allowance was made in the pile design and the design of the grouted connection allowed for premature pile refusal. In other cases leg piles were used for the jackets (often for non-geotechnical reasons) and the leg pile arrangement allowed for a reassessment of pile capacity (sometimes with support of pile monitoring and restrike tests) to demonstrate that the achieved pile penetration was indeed acceptable. In the case of acceptance, the leg piles were cut and jacket installation was completed. A further example is for a wind farm where it was realised that certain strata had more driving resistance than anticipated. A late examination of pile loads indicated that there was scope for optimisation of pile lengths prior to pile installation commencing. In the case of pile driving the 'late adjustment' to pile capacity often came with uncertainty on mobilisation of offshore vessels and

with other consequences such as uncertainty on jacket completion and sensitivity to weather (e.g. pile grippers not being activated, or the grouted connection being completed in the expected period). The observational approach was manageable but with undesirable uncertainty or consequences.

3.3 Jack-ups

Offshore jack-ups are an area where an observational approach is used on a regular basis during installation and in-service. During the jack-up spudcan preloading process there is sometimes a risk of rapid penetration or punch through where a layer of stronger soil exists over a layer of significantly weaker soil. In scenarios where the risk of rapid penetration may occur it is often difficult to predict the exact risk. In this case, spudcan installation and preloading can take place but with punch through precautions being used including pre-loading at minimum air gap and with appropriate monitoring in place, so that in the event there are signs of rapid penetration action can be taken to try and prevent it.

For jack-ups that are on location and in-service and observational type approach is often used to manage scour or spudcan settlement. Scour has previously been discussed and for jack-ups can be monitored by use of jack-up systems to measure tilt or leg loads. In the case scour occurs corrective measures can be taken such as use of rock, further pre-loading or even withdrawal of the unit from the location. Leg settlement can be managed in a similar manner to scour for a jack-up. For jack-up units in general the scenarios where an observational approach can be used are well recognised, remediation measures are understood and well-practiced and the contractual relationships between the jack-up unit owner and the client are able to handle the different possibilities.

4 FLOATING OFFSHORE WIND

4.1 Site Investigation

Site investigation does necessarily fall within the observational method approach as Peck (1960) considered it. However, for a large wind farm the site investigations are often performed in phases which then lend themselves to adjustment and optimisation based upon the results of previous phases. In this sense the observational method can be applied on the basis that site investigation is often performed using a series of investigations or that the scope of the site investigation can be adjusted within a phase.

Decision points can be introduced, within or after phases, to evaluate whether the available data is

Table 2: Factors that influence the amount of geotechnical data required for a location

Decreased requirement for geotechnical data	Factor	Increased requirement for geotechnical data
Concept relatively insensitive to geotechnical conditions Example Drag embedment anchors require less complex data	Complexity of anchor behaviour and sensitivity to uncertainty in geotechnical conditions	Anchor concept has sensitivity to geotechnical conditions Example Suction installed piles might be sensitive to layer changes or PSD
Extensive experience in the area with numerous previous developments adopting similar concepts Example Central North Sea	Experience in the area with the soil behaviours important to the anchor type	Limited to no experience in the area and none with the anchor concept(s) under consideration. Example Undeveloped frontier area
Anchor capacity confirmed during installation process and can be reconfigured Example Drag anchors	Confirmation of anchor capacity during installation coupled with ability to reconfigure design during installation	Anchor configuration fixed at design stage – very limited ability to change after manufacturing Example Driven piles
Ground modelling able to define soil layering at a location and parameters can be assigned from site wide data with sufficient confidence for design	Ability of ground modelling to understand ground conditions at a location with tolerable uncertainty	Ground modelling is unable to give confident understanding of layering at a location

sufficient, more data needs to be collected, or particular focus is needed on certain aspects. Definition of geotechnical parameters for design is often associated with an uncertainty; however, it can also be useful to consider the impact of obtaining more data on the end design – for example, whether further data collection will enable optimisation of the design or further data is unlikely to benefit the design process.

This application of the observational method would be strengthened by use of a ground modelling approach and in combination with technologies, such as artificial intelligence or geostatistical modelling. The following paragraphs discuss site investigations for anchor design to consider the application of the observational method in context.

Site investigation of a floating offshore wind farm will seek to understand the conditions at locations within a wind farm site where interaction with the seabed is expected. This includes anchor locations, dynamic cables or other fixed assets such as substations, inter array or export cables. What defines understanding the site conditions depends largely upon the complexity of the site or the sensitivity of the engineering activities to uncertainty on understanding of the site. For example, the knowledge required for drag anchor design can be relatively simple when

compared to suction anchor design. This is mostly a combination of the anchor sizing methodology being based upon empirical charts, the installation test load giving significant proof of capacity (as well as ensuring proper embedment and orientation); whereas suction pile sizing is more dependent on soil properties (e.g. strength parameters are an input) and. post installation loading is limited to the extent needed to ensure cut in of the anchor line or chain. It should be noted that more sophisticated assessment of drag anchors can be performed – for example to investigate performance under cyclic loading.

One of the main points with floating offshore wind development is to consider the extent to which data is required. As shown in Figure 1, anchor configuration can vary significantly and this affects the behaviour of the anchor and in turn, this affects the amount and type of data that is required. Geophysical data will always be a requirement to map seabed features and to determine if there are any hazards that need to be considered when selecting locations for development within a wind farm; or to account for potential hazards in the design of anchors. The extent to which geotechnical ground truthing is required depends upon:

- Complexity of the anchor design and sensitivity to uncertainty in geotechnical conditions,
- Experience of conditions in the area.
- Ability to demonstrate anchor Capacity through post-installation test loading or measurement of anchor installation performance coupled with the ability to reconfigure the design at installation stage. Note: Possible degradation of anchor capacity or performance in service needs to be considered (e.g. due to seismic loading or cyclic degradation).
- Use of ground modelling techniques to determine geotechnical conditions based upon geophysical data within an acceptable range of uncertainty.
- Anchorage areas are an example where perhaps centuries of empirical experience have been gained and they are used on a temporary basis. Vessels are able to relocate in the event of adverse weather (i.e. limits of holding capacity might be reached) and are therefore able to accept limited data and apply the principles of the observational method.
- A step down from this, in terms of site knowledge and experience, are areas offshore that have been extensively developed through the oil & gas industry with a significant body of knowledge on the seabed features and hazards and the soil types likely to be encountered to the likely depth of interest. An example of this is the Central North Sea where there are many oil & gas assets such as platforms and subsea developments. These have required site investigations, and a significant amount of experience has been gained on the performance of different foundation types and for engineering of these areas.
- On the other hand, some areas have yet to be developed, or oil and gas presence is more limited (e.g. off the North Coast of the UK). Going further still, there are areas of the seabed where little oil & gas has been found to be present, or there is an absence of other offshore development (e.g. cables, subsea mining etc). These might be considered frontier areas where significant effort might be required to gain a

Site investigation for floating wind may lend itself to greater application of the observational method approach than fixed offshore wind has typically allowed. Table 2 shows some schematic examples on the different levels of data or ground model knowledge that may be required to develop a site. As described above the amount of site investigation data required is interrelated to the seabed conditions at the site, the anchor type and flexibility of anchor configuration at the time of installation.

The concept of site knowledge and experience is explained through the simplified examples of different sites below (note there are many variations on understanding of a site):

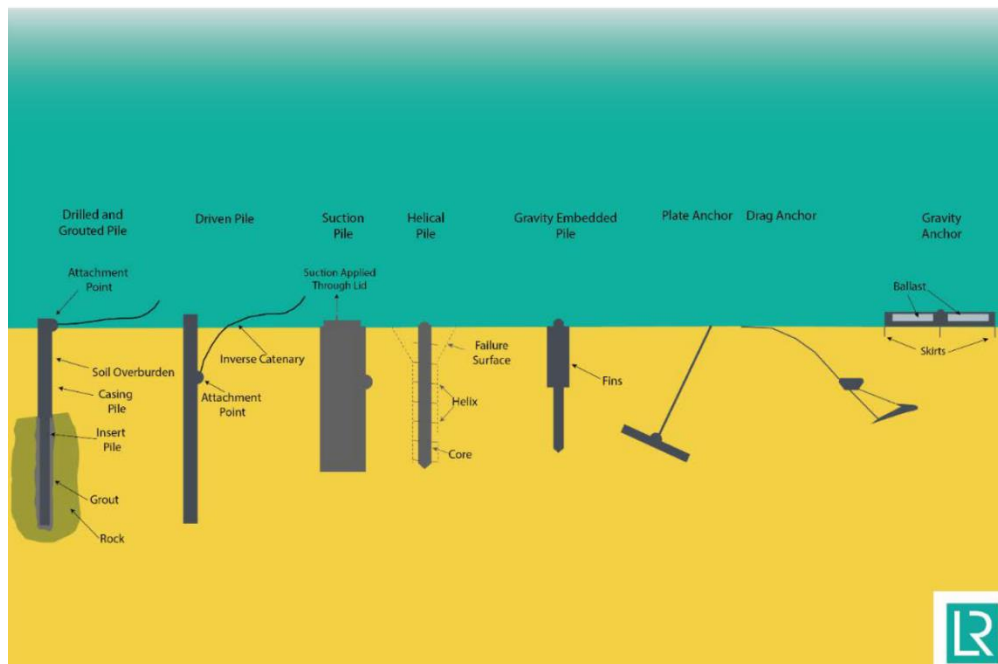


Figure 1. Different anchor types that may be applied for floating offshore wind turbines, reproduced from LR (2024)

sufficient understanding to develop a floating wind farm.

LR (2023) and SUT (2022) provide further recommended practice and guidance for site investigation of floating offshore wind farms. This includes coverage and type of data, type of equipment and other considerations for defining and specifying site investigations

4.2 Anchor Sizing

The growth of floating offshore wind will increase the amount of anchoring required vastly beyond the oil & gas industry, but also brings pressure for increased design optimisation at the same time as high supply chain demands. As such, during the construction of a wind farm experience of anchor performance may be gained through the monitoring of installation characteristics and where post-installation test loading is performed.

Anchor piles and suction piles are typically pre-sized and acceptance depends upon achieving the design penetration and location during installation. On the other hand, drag embedment anchors are subject to post-installation test loading and therefore the capacity is subject to some site-specific demonstration of capacity and performance. In this sense an observational type approach may be used to optimise the selection of anchors during wind farm construction, although this would depend on the supply chain being able to adapt. Drag anchors may also be retrieved and reinstalled if the first installation is not successful and the authors have experience of one site with seabed variability where the installation of many anchors was unsuccessful on the first attempt, but retrieval and repositioning led to successful installation test loading being concluded. In this sense, perhaps drag anchors are most adaptable to an observational approach as they are less sensitive to site parameters and can be reconfigured and repositioning easily. Other anchor types, such as piles, are often not designed to be tested to failure as their structural integrity may be compromised during such a process.

Further, some anchor types like screw piles or other concepts that may be adjustable during the installation with extra anchors or anchor sections added until a certain anchor performance is achieved. The sizing of the anchor is more real-time in nature and therefore an observational approach may find more application if there is confidence the anchor sizing can be adapted to react to soil conditions or installation performance (e.g. applied torque). Future developments of anchor types that are less sensitive to conditions, some form of proof during installation and the ability to reconfigure may readily lend themselves to an

observational approach being adopted and the optimisation that can be achieved with this approach.

5 CONCLUSIONS

The observational method is already being regularly applied offshore; and in many cases this is without explicit recognition – especially for those outside of the offshore geotechnical profession. The observational method could be used to optimise design and manage uncertain situations provided the steps required to make OM applicable and feasible offshore are in place and recognised appropriately between the different project stakeholders. To make the observational method more applicable some industry guidelines and wider consideration in industry standards may help provide better application. OM could also be combined with other techniques such as geostatistical modelling and artificial intelligence to lead to even great benefit by combining these techniques.

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Neil Morgan: Planning and Writing of the paper;
Francesca Ciavaglia and Clara Casanovas: Reviewing and contribution to final manuscript.

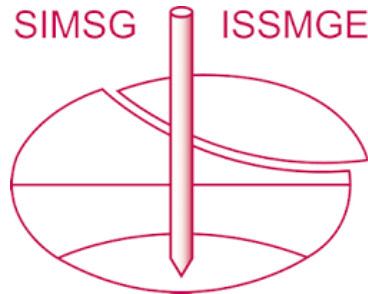
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