Our experience with suction bucket jacket foundations

Ørsted

1. Introduction

Monopiles (MPs) are currently the most commonly used foundation solution for offshore wind turbines with 82% of offshore wind turbines in European waters founded on MPs at the end of 2018 (EWEA, 2019). Where site conditions do not allow for an efficient or practical MP design, a number of alternative foundation solutions are available, including the suction bucket jacket (SBJ), piled jacket, gravity base or even a floating solution. Therefore, the SBJ is one of a range of alternative foundation solutions to the more commonly used monopile foundation solution for locations where the MP solution is not appropriate. All of the above listed foundation solutions have successfully been used to support offshore wind turbine generators (WTGs), with the choice of foundation solution often dependent on site-specific conditions such as water depth, ground conditions and country specific requirements.

In general, there is limited industry experience in the design, fabrication and installation of SBJs compared to the more common MP foundation solution. Installing monopiles is a complicated undertaking, but due to the high degree of experience gained with this foundation type, the complexity has become well understood and manageable in practice.

In contrast, the installation process for SBJ structures is yet to become standard practice and is thus considerably more complicated in practice than the installation process of monopiles.

The SBJ was first used as a foundation solution for a WTG in 2014 at the German Borkum Riffgrund 1 offshore wind farm (developed by Ørsted) where a single SBJ foundation was installed. In 2018, Ørsted installed a further 20 SBJs at the German Borkum Riffgrund 2 offshore wind farm, bringing the total amount of installed SBJs to only 21 out of more than 1,100 foundations installed in total by Ørsted.

This memorandum provides a brief background to the use of SBJs as a foundation solution for WTGs. It provides a brief description of suction buckets for windfarm applications, the limitations for the use of suction buckets and a summary of Ørsted's experience with suction buckets as a foundation solution.

2. Brief description of suction buckets for windfarm applications

Suction installed foundations, referred to as suction buckets, suction caissons, suction piles or suction anchors, have been widely used in the offshore industry since the early 1980's for a range of applications. These foundations, normally made from steel or concrete, are installed using the principles of suction whereby the pressure difference generated between the inside of the bucket and the water surrounding it (at the seabed) leads to the structure being installed without any use of mechanical force. Therefore, a key difference between suction installed foundations and other foundation types is that the installation design, which must consider the soil type, soil strength, installation specific risks (for example, the presence of boulders or other hard inclusions) and the installation process (for example, the speed of installation), have a direct influence on the dimensions of the foundation.

Since suction bucket technology was developed in 1970's, suction buckets have predominantly been used as anchors for floating offshore structures, where they are "the most widely used anchor types for deep-water mooring applications" (McCarron, 2011), or for seabed installations supporting oil and gas infrastructure in deep water. This is due to the difficulty associated with installing other foundation types at locations with deep or very deep water (for example, in the Gulf of Mexico, where water depths may be greater than 1,500m). For these applications, suction buckets are generally installed into soft clay material

For a small number of fixed base structures, such as the Sleipner T (Bye et al, 1995) and Draupner E (Erbrich and Tjelta, 1999) oil production platforms in the North Sea, suction buckets were also used as a foundation solution for supporting the superstructures (images of these structures are shown in Figure 1). More recently, suction buckets have been deployed in the offshore wind sector with installations taking place at the Borkum Riffgrund 1 (2014; one position; as shown in Figure 2), Borkum Riffgrund 2 (2018; 20 positions) and Aberdeen Bay (2018; 11 positions) offshore windfarms. For this application, three suction buckets are used to support a 'jacket' structure, most commonly referred to as a 'suction bucket jacket' (SBJ).

SBJs for windfarm applications differ significantly from typical oil and gas suction assisted installations (such as suction anchors) as they:

- are connected rigidly to a structure (such as a jacket)
- are installed in relatively shallow waters (less than 100m water depth),
- predominantly carry vertical loads (and relatively small moment and horizontal loads) which results in the behaviour being very similar to a shallow foundation, and
- have a large overall footprint[1] and a low suction bucket 'length to diameter' ratio (L/D ratio), meaning that they generally cover a large spatial area whilst maintaining a small embedment into the underlying soil (very short 'skirt' lengths).

Figure 1: A) The Sleipner T Statoil platform (installed 1995) and B) the Draupner Statoil platform (installed in the Norwegian part of the North Sea 1994)

[1] Footprint refers to the maximum plan area of the jacket structure. For the Borkum Riffgrund 1 SBJ, the footprint was approximately 30m in diameter.

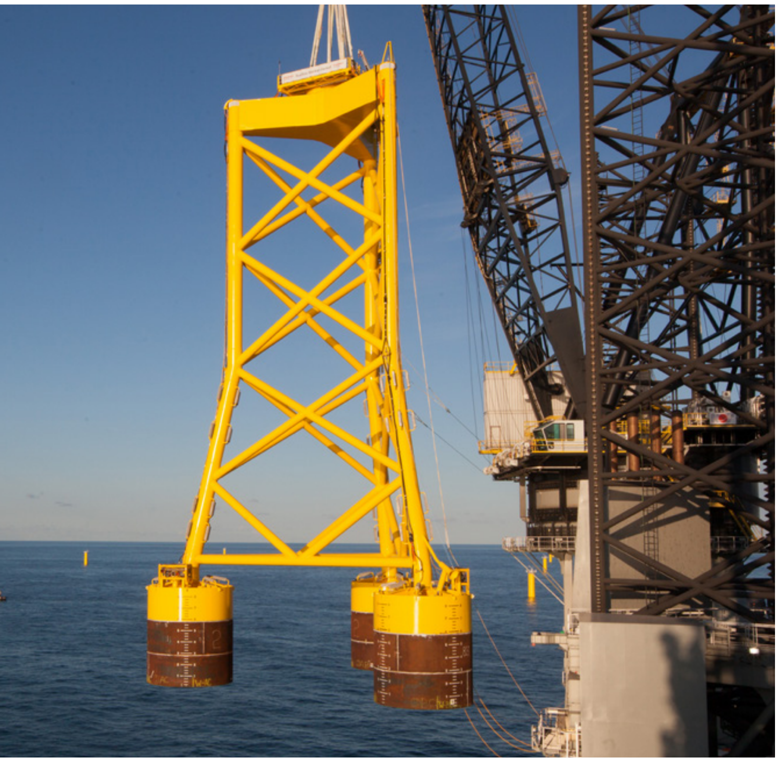

Figure 2: The three-legged SBJ installed at Borkum Riffgrund 1 by Ørsted

There are two key reasons for windfarm suction buckets having a large footprint and shallow seabed embedment compared to other foundations types (including typical deep-water oil and gas applications and also monopile foundations):

1. Loading conditions relevant to an offshore WTG. As shown in Figure 3, an offshore WTG experiences a significant lateral load (due to the wind and waves) which is transferred to the foundations via the jacket as a 'push-pull' mechanism, resulting in predominantly vertical foundation loads (Shonberg et al, 2017). Therefore, the load transferred to the ground is a function of the distance between the suction buckets such that increasing the footprint of the jacket reduces the load on the foundations. In order to transfer the loads into the ground, individual suction buckets must also therefore have a large area over which to spread the large vertical loads, which results in the suction buckets having low embedment compared to suction caissons used for deep-water applications.

2. Shallow waters restrict the installation pressure which can be applied during the installation process. As described by Houlsby and Byrne (2005), the maximum suction pressure is limited by the water depth. Therefore, if the water is shallow and the soil resistance is high (e.g. if stiff clays are expected to be present), the suction bucket diameter must be increased in order to increase the installation driving force such that the suction bucket can be installed to the required depth.

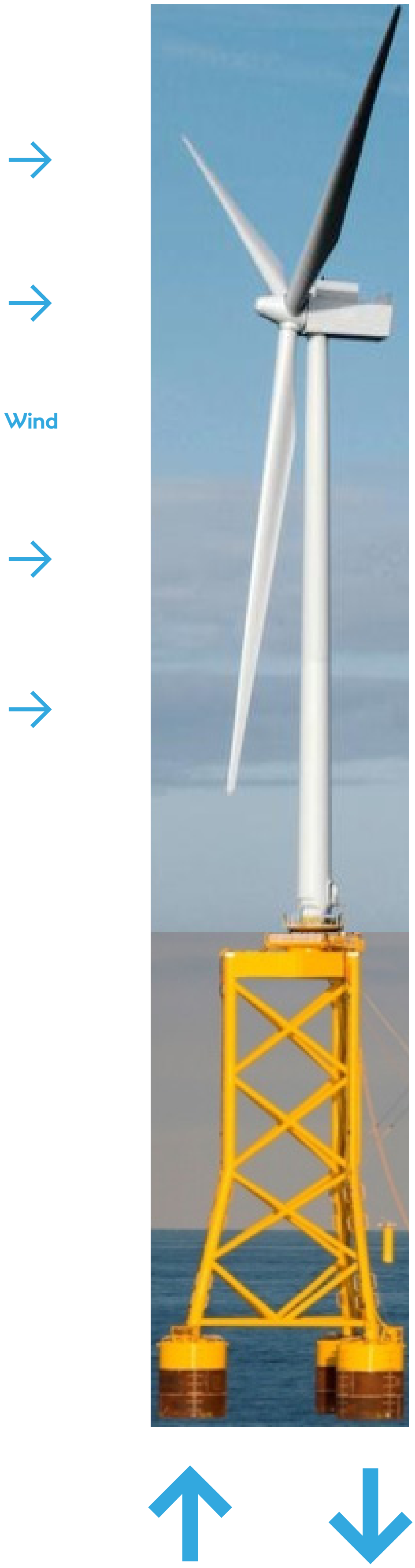

Figure 3 Idealised SBJ loading.

3. Limitations

3.1 Geotechnical limitations

Suction buckets are generally able to be installed in all soil materials, including silts, sands and clays, which are commonly found at the seabed surface in the offshore environment. However, a number of geotechnical limitations do exist meaning that the technology is not applicable everywhere.

As previously described, the installation design is a key step in the design process and is considered a key risk for any suction bucket design. This is predominantly due to the unknowns associated with the underlying soil conditions which are likely to vary with depth and vary laterally. It has been noted in the literature that there have been a number of difficult suction bucket installations over the years which has led to further investigations on this topic, in particular, a joint industry project led by the Carbon Trust Offshore Wind Accelerator program (Tjelta, 2014).

In general, suction buckets cannot be installed into rock. However, where rock is encountered deeper than 10m below seabed level, suction buckets are potentially a viable foundation solution (i.e. the suction buckets can be installed in the soil material above the rock). Large boulders, or other 'hard inclusions' (such as cemented layers or coral outcrops) can also be problematic for suction bucket installation. Where large boulders or hard inclusions are present, suction buckets can be 'micro-sited' (position shifted laterally by 5-10m) to ensure that the bucket does not come into contact with the boulder, or if practical, the boulder could be removed prior to suction bucket installation.

Furthermore, a key limitation to suction bucket installation is a shallow seabed (limited water depth). As suction bucket installation is a function of water depth[2] (Houlsby and Byrne, 2005), shallow waters restrict the amount of driving force available for suction bucket installations and therefore, water depths less than 15-20m may not be suitable for suction bucket installations.

3.2 Installation limitations

To date, a total of 32 SBJs have successfully been installed to support offshore WTG structures at Borkum Riffgrund 1 and 2 (Ørsted) and Aberdeen Bay (Vattenfall). Therefore, it is generally considered that there is limited experience in the installation of three-legged SBJ structures (when compared with monopile installations). The recent projects Borkum Riffgrund 2 and Aberdeen Bay projects where markedly different soil profiles were encountered, has however increased the knowledge regarding SBJ-installation significantly.

The entire SBJ installation operation, including lowering, 'touch down', self weight penetration and the suction installation process, all have unique risks which must be considered in the design. A limited number of companies, perhaps only a few, currently have extensive experience with this procedure. Furthermore, the suction installation procedure is technically very different from piling in that soil variability may significantly impact the installation, mitigation measures are limited and extensive 'real time' monitoring of the suction installation process is required.

3.3 Manufacturing limitations

Monopiles are by far the most commonly used foundation technology in the offshore wind industry with jackets only accounting for approximately 7% of all installed offshore wind foundations (EWEA, 2019). The limited experience with serial production of jackets and the additional complexity in the jacket manufacturing process limits the scalability of the use of SBJs. Though manufacturing increasingly larger monopiles is a challenging discipline, manufacturing of jackets is much more complex and as such, the industry is yet to see manufacturers with serial production capabilities to compete at competitive cost and time schedule levels.

3.4 Limitations summary

As the monopile is the most common foundation solution for supporting offshore WTGs, comparisons are often made between these two foundation solutions. In brief, the SBJ's limitations when compared to the monopile are that:

- they have a significantly larger footprint (approximately 30-40m in diameter) and require more scour protection (although scour protection may not be required for all structures in appropriate ground conditions),
- there are installation challenges in shallow water (less than 20m),
- the installation process is highly dependent on soil type and soil strength,
- the installation process is potentially riskier due to the larger volume of soil in contact with the structure (leading to a higher risk of ground variability, hitting a boulder or encountering a 'hard inclusion') and a lack of available proven mitigation options, although it is expected that this risk could be mitigated during the design process,
- installation experience is limited,
- manufacturing experience and scale is limited; and
- the overall cost may be higher.

[2] Due to the critical suction limit in sandy materials or cavitation limit in clayey materials

4. Ørsted experience with suction buckets

Suction bucket technology was originally developed in the early 1980's for offshore oil and gas applications and has now been identified as a foundation solution for the offshore wind industry. Whilst there is limited offshore wind industry experience relating to the design and installation of SBJs, Ørsted has been an industry leader in the development of SBJ technology for application in the offshore wind environment. Ørsted's development of the SBJ foundation solution aims to provide flexibility in choosing the right foundation solution for any given offshore wind farm development.

Within this context, Ørsted installed the world's first SBJ for an offshore WTG at the Borkum Riffgrund 1 offshore windfarm in Germany in 2014. The SBJ installed at Borkum Riffgrund 1 was designed by Ramboll (structural jacket design) and NGI (geotechnical design).

The Borkum Riffgrund 1 SBJ was outfitted with an extensive monitoring system to provide measurements of the geotechnical and structural response of the structure during installation and operation. The most comprehensive study of the recorded data relating to the geotechnical behavior of the Borkum Riffgrund 1 suction buckets has been published by Shonberg et al (2017).

Furthermore, Ørsted (then DONG Energy) entered into a 3 year collaboration with Leibnitz University of Hannover (LuH) and BAM (Bundesanstalt für Materialforschung und -prüfung, or German Federal Institute for Materials Research and Testing) whereby a number of researchers were provided access to the monitoring data. This project is currently being concluded (results are yet to be published). The lessons learned from back analysis of the monitoring data collected from the Borkum Riffgrund 1 SBJ will be required to ensure cost effective SBJ structures for any future Ørsted project utilising this as a foundation solution.

Since the installation of the Borkum Riffgrund 1 SBJ, Ørsted has been involved in the design and installation of SBJs at the Borkum Riffgrund 2 and the design for Hornsea 1 offshore wind farms. At Hornsea, 1 overall project timeline considerations and limitations of serial production capacities, precluded the use of SBJs, and therefore the project chose an alternative foundation type. The Borkum Riffgrund 2 SBJs, installed in 2018, were designed by Ramboll and NGI (Norwegian Geotechnical Institute). All of Ørsted's SBJ scheme designs have been certified by the certifying body Det Norske Veritas (DNV-GL).

4.1 Summary

A range of foundation solutions exist for supporting offshore wind farm WTGs. Monopiles are the most common foundation solution but other solutions, such as the SBJ, piled jacket, gravity base and floating, have all successfully been installed at offshore windfarms in Europe.

Suction installed foundations, which are able to be installed without the need for any mechanical force, have most commonly been used as anchors for deepwater oil and gas applications. They are generally able to be installed in all soil materials, including silts, sands and clays, but are unsuitable for locations with a rocky seabed or locations with shallow water (less than 20m). The installation design of suction buckets is key to their use and introduces a risk due to the uncertainties associated with the site specific ground variability.

The SBJs utilised for offshore wind applications are considerably different to oil and gas focused structures as they are required to transfer predominantly vertical loads (created by the combination of wind and waves) and they are also installed in much shallower waters. Compared with monopiles, SBJs have a much larger footprint and potentially have a higher installation risk to the potential presence of subsurface 'hard inclusions' such as boulders.

To date, 32 SBJs have been installed to support offshore WTG (installed at Borkum Riffgrund 1 in 2014 and Borkum Riffgrund 2 and Aberdeen Bay in 2018) and in general, there is limited offshore wind industry experience relating to the design, manufacturing and installation of SBJs for this purpose. It is within this context that Ørsted has been an industry leader in the development of SBJ technology, through research and partnerships, to ensure a range of foundation solutions are able to be considered for each project.

5. References

5.1 Ørsted publications

A significant volume of published information is available in the literature relating to suction buckets.

The published information relates to both the installation of suction buckets and the behavior of suction buckets under different loading conditions. Initial research focused on the use of suction buckets for oil and gas applications (for example, Bye et al, 1995 and Erbrich & Tjelta, 1999), but more recently, the focus of the research has been targeted towards the use of suction buckets for offshore wind applications (for example, DTI, 2005, Houlsby and Byrne, 2005, Achmus et al, 2013, Tjelta, 2014 and Shonberg et al, 2017).

The following publication relating to SBJs authored by Ørsted employees (or those directly associated with Ørsted) have been published over the past two years:

Harte, M., Shonberg, A. (2018)
"Reliability based installation design of a suction caisson in clay" Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering (Energy and Geotechnics), 1-3 November 2018, Hanoi, Vietnam (submitted, under review)

Shonberg, A., Harte, M., Aghakouchak, A., Andrade, M.P., Brown, C.S.D., Liingaard, M.A. (2017) *"Suction bucket jackets for offshore wind turbines: applications from in situ observations"*, Proceedings of the TC209 Workshop at the 19th International Conference on Soil Mechanics and Geotechnical Engineering, 20 September 2017. Seoul, South Korea.

Shonberg, A., Anusic, A., Harte, M., Schupp, J., Meissl, S., Liingaard, M. A (2017) *"Comparison of Self Weight Penetration Prediction Methods for Large Diameter Monopiles in North Sea Soils"*, OTC-27763-MS. Proceedings of the Offshore Technology Conference, 2 – 5 May, 2017, Houston, Texas.

Surysentana, S., Byrne, B. W., Burd, H. J., Shonberg, A. (2017)
"Weighting functions for the stiffness of circular surface footings on multi-layered non-homogeneous elastic half-spaces under general loading" Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, 17 - 21 September 2017, Seoul, South Korea.

Suryasentana, S., Dunne, H., Martin, C., Byrne, B. W., Burd, H. J., Shonberg, A. (2018) *"Assessment of numerical methods for determination of shallow foundation failure envelopes"*, Geotechnique (submitted for review).

Surysentana, S., Byrne, B. W., Burd, H. J., Shonberg, A. (2017)
"An elastoplastic 1D Winkler model for suction caisson foundations under combined loading" Proceedings of the 9th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE), 25 - 27 June 2018, Porto, Portugal.

Surysentana, S., Byrne, B. W., Burd, H. J., Shonberg, A. (2017)
"Simplified model for the stiffness of suction caisson foundations under 6 DOF loading" Proceedings of the SUT OSIG Conference, 12 - 14 September 2017, London, UK.

5.2 Other publications

NGI (Sturm, Sparrevik, Andersen), Oxford University (Houlsby, Byrne), the University of Western Australia (Randolph, Gourvenec, Senders, Doherty, Deeks) and a number of other practitioners (Tjelta, Erbrich, Bye) have all provided a significant additions to the understanding of suction bucket behaviour (including both installation and in place behavior) over the past 20-30 years. Some selected references are presented below.

Achmus, M., C. T. Akdag and K. Thieken, 2013.
Load-bearing behaviour of suction bucket foundations in sand.
Applied Ocean Research 43, 157-165.

Bye, A., Erbrich, C., Rognlien, B. and Tjelta, T.I., 1995.
Geotechnical design of bucket foundations.
Offshore Technology Conference. Houston, Texas, USA, May 1-4, 1995.

DTI (Danish Technological Institute), 2005.
The application of suction caisson foundations to offshore wind turbines,
Contract No. W/62/00604/00/00, URN No. 15/1691.

Erbrich, C. T., and T. I. Tjelta, 1999.
Installation of bucket foundations and suction caissons in sand-geotechnical performance. Offshore Technology Conference, Houston, Texas, May 3-6, 1999.

European Wind Energy Association (EWEA), 2019.
The European Offshore Wind Industry - Key Trends And Statistics 2018.
Web. 19 Feb. 2019.

Houlsby, G. T. and Byrne, B. W. 2005.
Design procedures for installation of suction caissons in clay and other materials, in: Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 158, April 2005 Issue GE2, Pages 75–82.

McCarron, W. O., 2011, *Deepwater Foundations and Pipeline Geomechanics*, J. Ross Publishing, 2011.

Shonberg, A., Harte, M., Aghakouchak, A., Andrade, M.P., Brown, C.S.D., Liingaard, M.A., 2017. *Suction bucket jackets for offshore wind turbines: applications from in situ observations,* in: Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering. Seoul, Korea, September 24-27, 2017.

Tjelta, T. I., 2014. *Installation of suction caissons for offshore wind turbines.* Danish Geotechnical Society Seminar, Gentofte, Copenhagen, Denmark, 1st April, 2014. Web. Accessed 15 March 2018. http://www.danskgeotekniskforening.dk/sites/ default/files/pdf/pdf2014/ Moede%202/ Session%204%20-%20Presentation%201%20-%20T%20 Tjelta%20-%20Statoil%20-%20Installation%20of%20suction%20caissons%20for%20OWT's%20-%20DGF%20Seminar%202014-04-01.pdf