

SUCTION BUCKET INSTALLATION: RISKS DURING THE INSTALLATION PROCESS

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ABSTRACT

Future offshore wind farm projects are likely to be built further offshore in deeper water with larger wind turbine generators leading to increased foundation loads. Furthermore, in some regions, foundations must be installed without exceeding strict regulatory requirements on underwater noise. Thus, traditional foundation solutions are being pushed to their limits and there is a need for innovative foundation concepts. The suction bucket jacket (SBJ) is one such foundation solution which may address these challenges. SBJs are unique in that their geotechnical design may be governed by either installation or in place requirements. Therefore, understanding the installation process is crucial for an efficient and cost effective suction bucket foundation design. In addition to understanding the ground conditions and the expected resistance during the suction bucket installation, installation risks must also be considered. To this end, this paper examines installation data from twenty suction bucket jacket foundations installed in the German sector of the North Sea. The paper provides insight into the risks which may be encountered during the suction bucket installation process such as the effect of the installation process on the internal plug, the inclination of the structure during installation and the difficulties associated with real time monitoring of the installation process.

Keywords: suction bucket, installation risk, suction installation

INTRODUCTION AND BACKGROUND

With the advancement of offshore wind farm (OWF) projects towards deeper waters and larger wind turbine generators (WTGs), foundation solutions other than the monopile have received increasing attention over the past 5 years. Monopiles (MPs) are the most commonly used foundation solution for offshore wind turbines, with 82% of offshore wind turbines in European waters founded on MPs foundation (EWEA, 2019). However, 2018 saw a record number of suction bucket jacket (SBJ) structures, which consist of a three legged jacket supported by a suction bucket at each leg (as shown in Figure 2), installed for offshore wind applications. SBJs have now been installed successfully at the Borkum Riffgrund 1 (2014; one position, Ørsted), Borkum Riffgrund 2 (2018; 20 positions, Ørsted, as shown in Figure 1) and Aberdeen Bay (2018; 11 positions, Vattenfall) offshore windfarms.

Suction installed foundations, referred to as suction buckets (in this paper), suction caissons, suction piles or suction anchors, have been widely used in the offshore industry since the early 1980's for a range of offshore applications, predominantly as anchors for floating offshore structures, where they are "the most widely used anchor types for deep-water mooring applications" (McCarron, 2011). Suction buckets, installed using pumps which generate suction forces by creating a pressure difference between the inside and outside of the bucket, allows for the installation to be undertaken with minimal noise and without the use of any impact forces. 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

and installation specific risks (for example, soil stratification with significant differences in permeability) may have a direct influence on the dimensions of the foundation.

Whilst the number of SBJs installed for offshore wind applications has increased significantly in recent years, the installation process for SBJ structures is yet to become standard practice and is considerably more complicated than the installation process for monopiles. This paper provides a brief background to the use of SBJs as a foundation solution for WTGs and examines data from recently installed full scale suction buckets to provide insights into the risks which may be encountered during the suction bucket installation process.



Figure 1 Photos of the Borkum Riffgrund 2 suction bucket jacket installation

BACKGROUND TO THE CASE STUDIES

The Borkum Riffgrund 2 offshore wind farm (BKR02) is located approximately 40 km north of the island of Borkum off Germany's North Sea coast. The BKR02 wind farm comprises 56 8.0 MW WTGs, of which 20 are supported by SBJ foundations and 36 are supported by MP foundations. Figure 3 shows the location of the BKR02 wind farm relative to other German windfarms and the German coastline.

At BKR02, the suction buckets and jacket structures were identical for all 20 locations. The suction buckets had a diameter of 10 m and a skirt length of 7 m, with a minimum required embedded length of 5.5 m. The bucket dimensions were governed by in place criteria, as the installation process was not expected to be critical. However, additional skirt length commonly referred to as 'stick up', was required to allow for the plug heave which was expected to occur during the installation. Figure 1 shows photos of the SBJs being installed at BRK02.

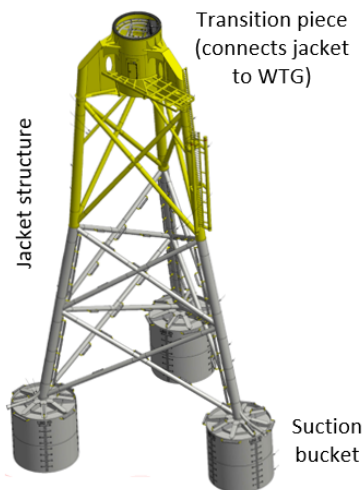


Figure 2 Suction bucket jacket structure

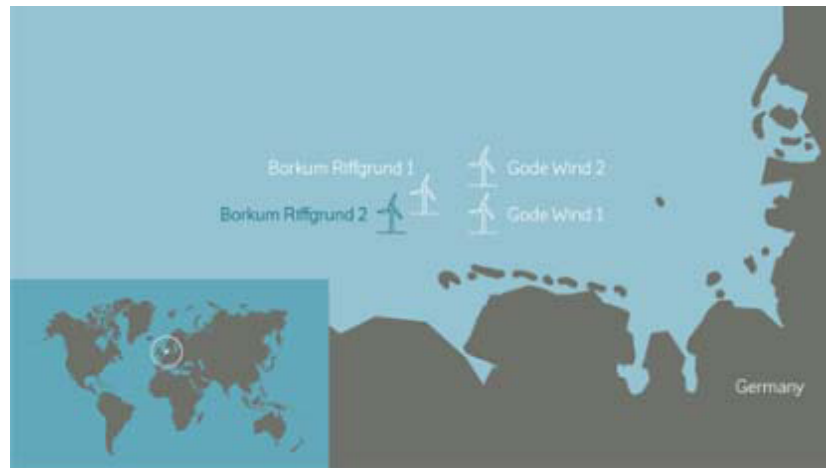


Figure 3 Location of the BKR02 offshore wind farm

The ground conditions at BKR02 are typical of German Bight North Sea conditions, with predominantly granular materials dominating the upper 10 – 20 m of the soil profile. As per the soil profile identified at Borkum Riffgrund 1 (BKR01) offshore wind farm (Shonberg et al, 2017), some silt layers were also identified across the site. Table 1 provides a summary of the relevant soil units for the suction bucket installations. The soil unit ‘Sand SS’ was observed at all 20 SBJ locations. Interbedded silt layers, between 0.2 m and 2.0 m thick, were common across the site, with the ‘Silt’ soil unit encountered at 15 WTG locations. The particle size distribution for the soil samples defined as ‘Sand’ is shown in Figure 4, indicating that the sandy soil is generally a poorly graded, fine to medium dense sand, with some silt particles.

Table 1 Typical properties of BKR02 units found in the upper soil profile

Unit	Description	Relative density (%)	Fines content (%)	Number of locations
Sand (SS)	Clean to slightly silty, dense to very dense, fine to medium grained.	90 - 100	0 – 5	20
Sand (VS)	Silty to very silty, medium to dense, medium to fine grained.	60 - 80	10 - 20	9
Silt	Medium dense, fine grained.	50 - 70	> 20	15

A 3D ultra high resolution survey (UHRS) was carried out at each SBJ location to assess the potential hazards that could affect the suction bucket installation. The 3D UHRS, an example of which is shown in Figure 5, was undertaken to assess the likely presence of boulders and the presence of silt layers which might affect the flow conditions around the bucket during installation. The 3D UHRS process is further described by Harte et al (2019) for an OWF where similar risks were identified.

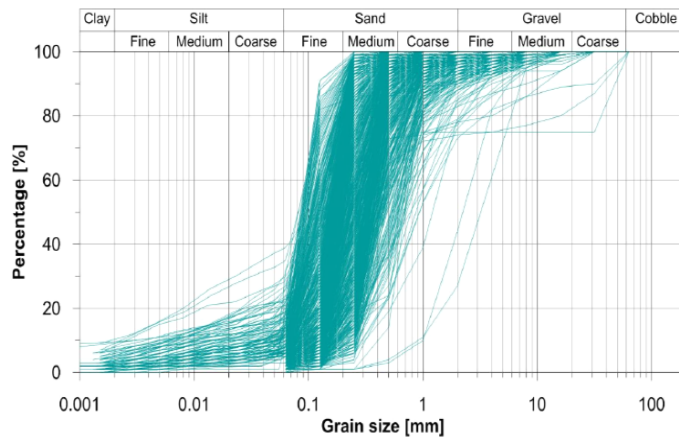


Figure 4. Sieve and hydrometer analyses results for coarse grained materials

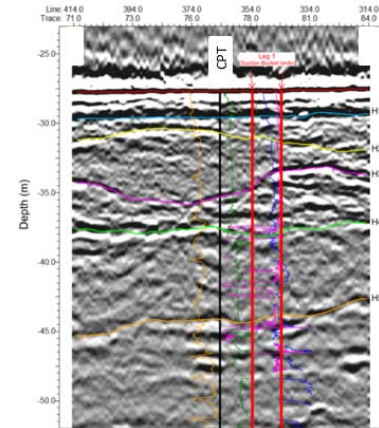


Figure 5 Example 3D UHS output for a BKR02 location

INSTALLATION THEORY

The installation of suction buckets, particularly in coarse grained materials, has been studied extensively for more than 30 years. Research into the installation process was undertaken for oil and gas application in the North Sea (Tjelta et al, 1986; Bye et al, 1995; Erbrich and Tjelta, 1999) and since then, significant research efforts have focused on laboratory scale experiments (Tran, 2005; Bienen et al, 2018), large scale experiments and field trials (Houlsby et al, 2006; Ibsen, 2008, Tjelta, 2014) and finite element modelling (Klinkvort et al, 2019). This has led to both CPT based prediction methodologies (DNV, 1992; Senders & Randolph, 2009) and bearing capacity based prediction methodologies (Houlsby & Byrne, 2005; Andersen et al, 2008). The available methods for predicting the required suction pressures for suction bucket installations in sand and the risks associated with these installations are well summarised by Offshore Wind Accelerator (2019) and Sturm (2017).

Most bearing capacity methods, and some CPT based methods such as Senders & Randolph (2009), take into account the effect of flow around the skirt tip caused by the differential pressure between the inside and outside of the bucket, which leads to a reduction in vertical effective stresses at the skirt tip and inside the bucket skirt. Numerous numerical modelling studies (Erbrich and Tjelta, 1999; Andersen et al, 2008; Klinkvort et al, 2019) show similar results regarding the expected equipotential lines in and around the bucket during steady state flow conditions as shown in Figure 6 (where k_f refers to the soil permeability).

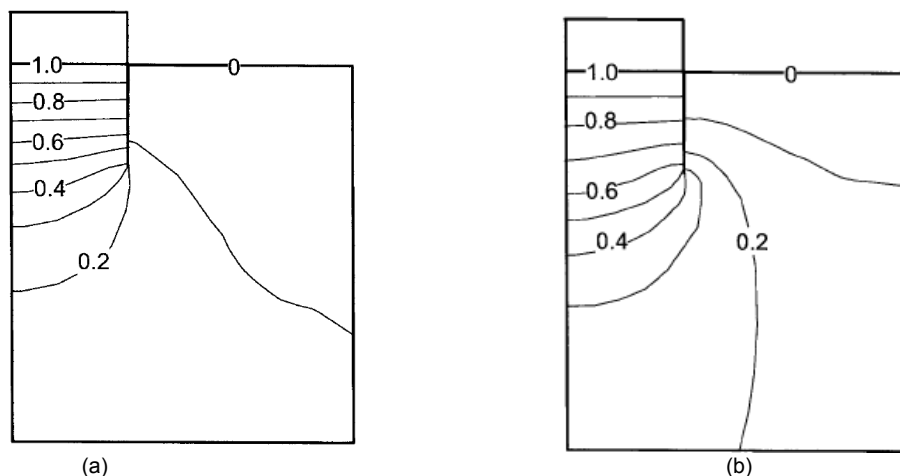


Figure 6 Equipotential lines for cylindrical anchors with $z/D=0.45$ from finite-element analyses; (a) $k_f = 1.0$; (b) $k_f = 2.5$ (where $k_f = k_{inside} / k_{outside}$) from Andersen et al, 2008

FIELD OBSERVATIONS

All 20 SBJ foundations at BKR02 were installed successfully over a period of two months during the summer of 2018. All 20 installations achieved the required installation embedment and the required inclination tolerances as defined by Ørsted. Of the 20 SBJ installations, the vast majority did not encounter any geotechnical challenges and the installations proceeded as predicted. The following sections describe some interesting observations from the SBJ installations at BKR02.

Monitoring system

Key to the success of the suction bucket installations at BKR02 was the ability to review, in real time, the main installation parameters. Some basic installation parameters which should be accessible in real time during the installation are the suction bucket 'depths' ('internal' and 'external'), differential pressures, inclinations and flow of water through the pump. These parameters, all of which were available for each of the three suction buckets, are described in detail in Offshore Wind Accelerator (2019). Unrecoverable instrumentation, placed on the suction buckets or the jacket, should be avoided due to the excessive costs and delays to the fabrication process. Therefore, as much instrumentation as possible should be mounted on the suction pump such that it can be reused for each installation. For BKR02, the majority of monitoring equipment was placed on the suction pump, with a notable exception being the skirt tip pressure measurement, which required a permanent installation on each bucket.

A diagrammatic representation of the measurement system installed for the BKR02 SBJ installations is shown in Figure 7, from which the following should be noted:

- The suction pumps are eccentrically placed on the bucket lid to avoid the jacket leg
- The embedment depth (PENout) is calculated from the pressure difference between the outside of the suction pump (PTout) and at a reference unit located on the seabed (PTref).
- The internal 'depth' (PENin) is measured using an echosounder, which is prone to erroneous readings when turbidity is high due to reflections from suspended particles.
- Differential pressure (DP) is measured as the pressure difference between the inside of the bucket cavity (PTin) and the pressure on the outside of the suction pump (PTout).
- Skirt tip pressure differential is measured as the pressure difference between the skirt tip pressure (PTtip) and a pressure sensor on the outside of the suction pump (PTout).

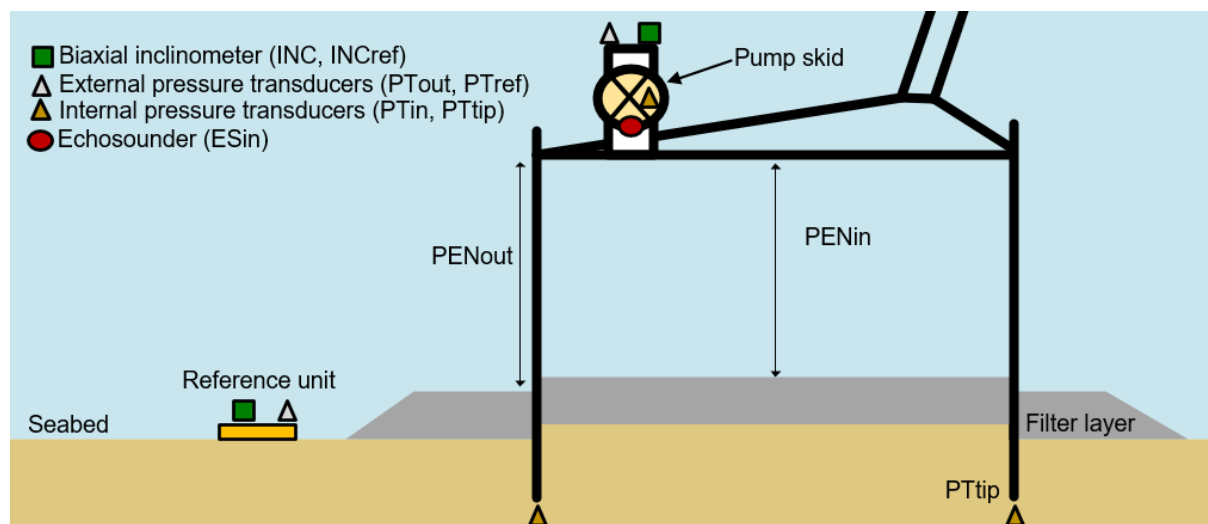


Figure 7 Diagrammatic representation of the measurements system for each suction bucket

Pore pressure distribution

A key risk for suction bucket installations is that extended installation durations could lead to excessive loosening of the internal plug, which can be assessed by monitoring the pore pressure factor. Houlsby and Byrne (2005) define the pore pressure factor, a , as the ratio between the pore pressure at the skirt tip and bucket lid (both of which were measured, as shown on Figure 7). From Figure 6, this ratio is expected to be between approximately 0.2 - 0.4 for $k_f = 1$ and 0.3 - 0.5 for $k_f = 2.5$ (depending where on the skirt tip the measurement is taken). Higher values of ' a ', especially values of ' a ' which increase during the installation process, may therefore indicate increased loosening of the internal soil plug and therefore increased plug heave. The BKR02 installations offered a unique opportunity to assess the pore pressure distribution around the bucket skirt.

Figure 8 shows that during the initial stages of the installation, prior to the setup of a steady state flow regime, the pore pressure factor tends towards 1, but as the flow regime develops, it tends towards values predicted in the literature. Figure 8 (which includes plots of the predicted ' a ' values from Houlsby and Byrne, 2005, denoted 'H&B') shows that as the installation proceeds past $h/D \sim 0.5$, ' a ' increases from the predicted value for $k_f = 1$ towards the predicted value for $k_f = 2$, indicating that the soil permeability (k_f) inside the bucket is increasing with increasing installation depth. As shown in Figure 6, higher k_f values would lead to an increased pore pressure factor and this should be expected as the installation duration increases. Therefore, monitoring the pore pressure factor provides an indication of the change in permeability of the soil and may be used to quantify the loosening of the soil plug in real time.

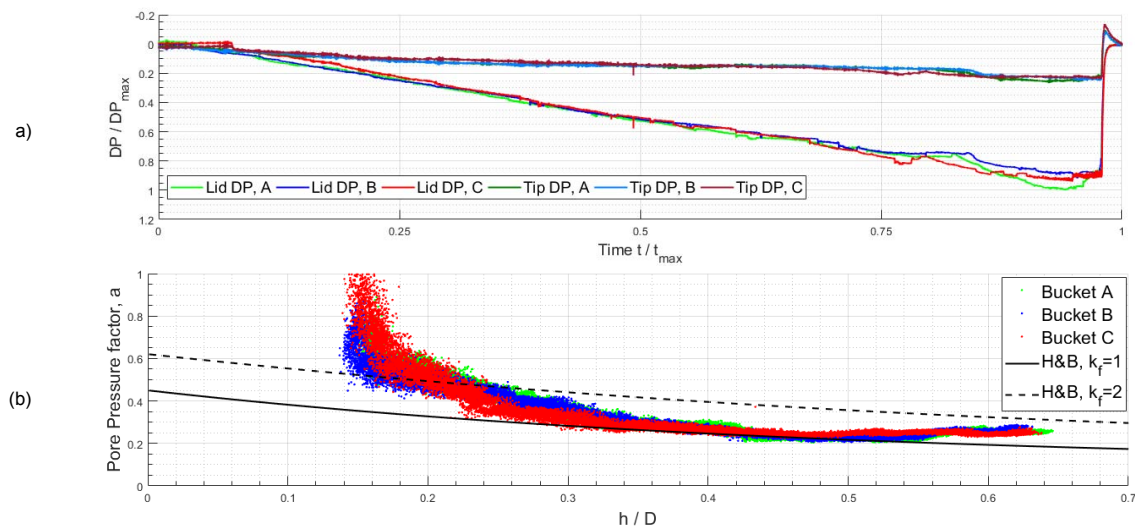


Figure 8 Example BKR02 SBJ installation (a) suction pressure and (b) pore pressure factor

Internal plug heave

Internal plug heave refers to the difference in height between the soil inside the bucket and the original seabed level, as indicated on Figure 7 (the difference between PEN_{out} and PEN_{in}) and Figure 9. The change in height of the soil inside the bucket, due to an apparent volumetric expansion of the internal soil plug caused by the installation process, is commonly observed to occur for suction bucket installations which may be due to:

1. Insertion of a volume of steel into the ground (with preferential volumetric soil displacement towards the inside of the bucket due to the flow of water and pressure gradient)
2. Loosening of the soil due to the flow of water (in coarse grained soil profiles only)
3. Dilation of the materials at the interface between the bucket skirt and the soil

A number of studies show the measurement of plug heave in the field (Senpere and Auvergne, 1982; Tjelta, 1995) and in the laboratory (Tran, 2005; Kim et al, 2016). From the database collected by Akeme et al (2018), almost all suction bucket installations in coarse grained

materials faced challenges associated with plug heave. In practice, the measurement of plug heave simplifies a complex three dimensional problem of the change in height of a surface within the bucket into a single value (i.e. 'plug heave') which is generally measured at one point on the soil surface. Numerous authors (Ragni 2018; Tran 2005) have analysed this problem in the laboratory using particle image velocimetry (PIV) techniques which show that the soil surface is variable across the bucket footprint during laboratory scale installations.

The absolute soil plug heave measured at BKR02 was taken as the difference between PEN_{in} , measured by the internal echosounder at a point directly under the suction pump (see Figure 9), and PEN_{out} , measured via differential pressure. As the measurement of PEN_{out} can be made with a high degree of confidence, the plug heave measurement is highly reliant on the variability of the soil surface level directly under the suction pump. Relative plug heave, H_{plug} , is calculated by normalising the absolute soil plug heave by the embedment (PEN_{out}).

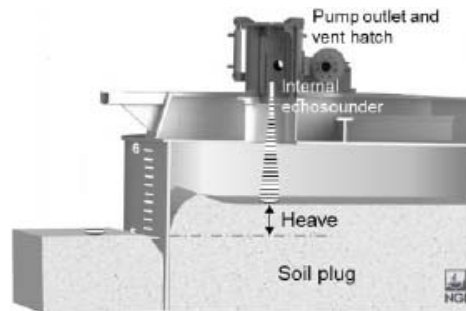


Figure 9 Illustration of the internal heave measured by an internal echosounder (from Sparrevik & Strout, 2015)

Figure 10 shows the measured H_{plug} for a SBJ installation at BKR02. For the majority of the installation, the plug heave progressed as expected with 1-2% plug heave observed but near the end of the installation the plug heave rapidly increases in Bucket C and rapidly decreases in Bucket A. Whilst plug lift could explain the rapid increase in relative plug heave in Bucket C, there is no obvious global mechanism which could explain the rapid decrease (and subsequent increase) in plug heave in Bucket A. This phenomenon was observed in some, but not all, of the BKR02 installations. For reference, Figure 11 shows a different installation where relative plug heave was not observed to vary significantly near the end of the installation. Both examples exhibit similar penetration trends yet the plug heave response is evidently different, particularly near the end of the installation process.

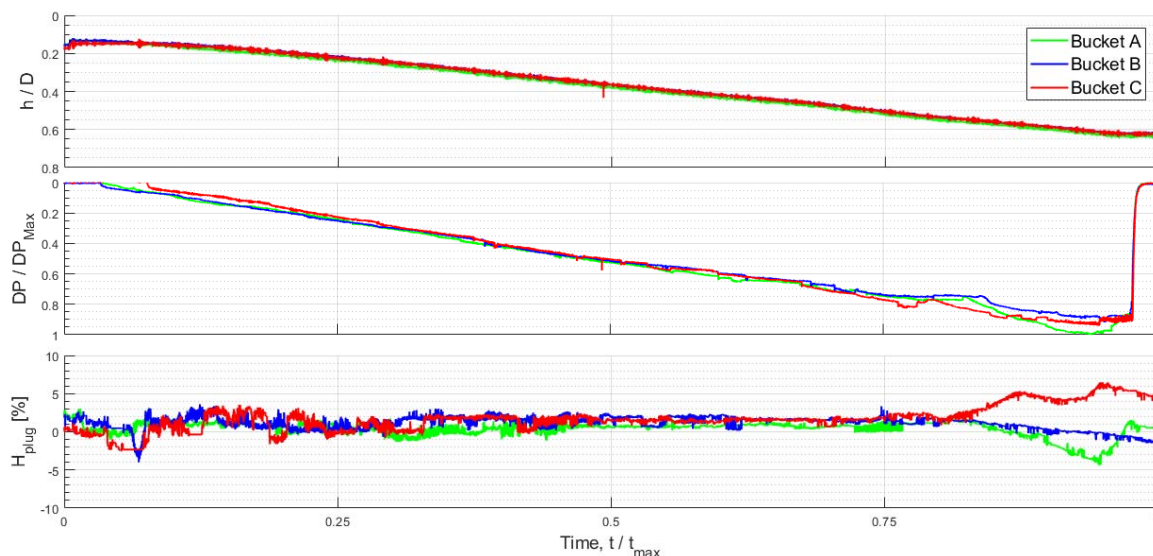


Figure 10 Relative plug heave for an example SBJ installation with plug height variation

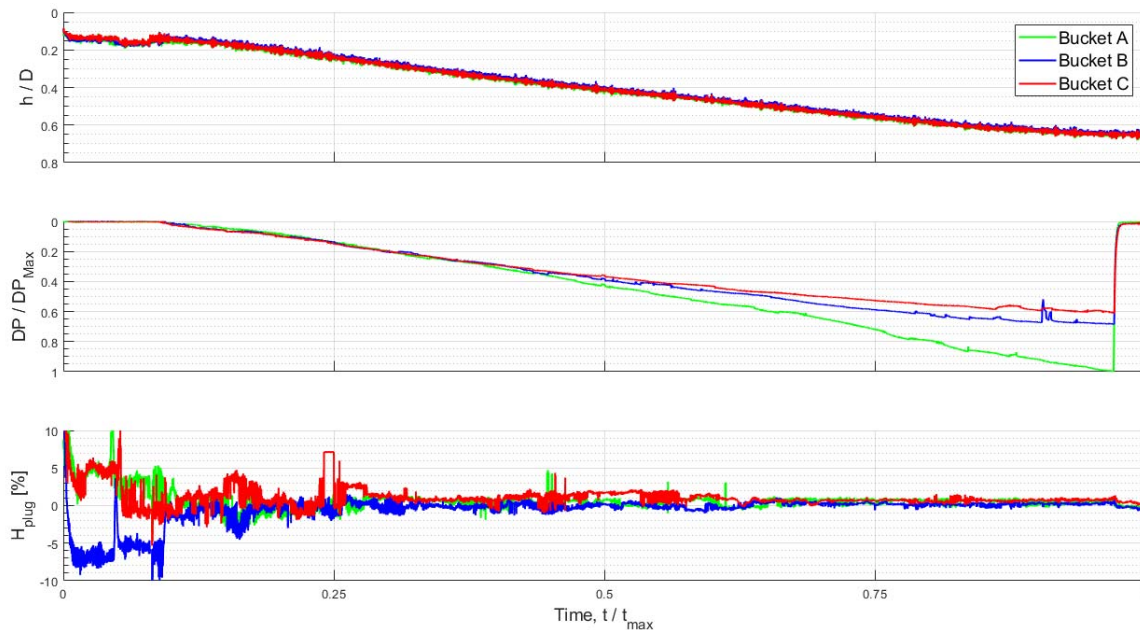


Figure 11 Relative plug heave for an example SBJ installation with little plug height variation

A potential reason for the observed plug height behavior of Bucket A in Figure 10 is that the soil under the pump is being removed (i.e. scoured) due to the effects of the pumping itself. Additional monitoring data is therefore required to fully understand the change in shape of the plug surface and how the monitoring system interacts with this 3D problem. If not monitored appropriately, and enough headroom is not allowed for, relative plug heave could lead to significant installation issues.

Inclination during installation

Inclination of the jacket structure, both during and after installation, is a key concern for the installation process. Although mounting inclinometers on the suction pumps is highly advantageous from a cost perspective, previous industry experience has indicated that monitoring of the inclination using inclinometers directly mounted on the suction bucket lids may be misleading as these measurements may be affected by suction pressure and subsequent lid deformation during installation. The pressure difference applied to the lid during installation is a significant force, which may even be governing for the structural design of the lid itself. Therefore, the stiffness of the lid, which as shown by Shonberg et al (2017) is not rigid, plays a key role in the live measurement of individual suction bucket tilt.

Measuring the inclination of each bucket is often a key measurement, as this potentially removes the requirement for an inclinometer to be attached to the superstructure. It may also be required to confirm that structural limits relating to the relative inclination between the suction bucket and the jacket leg are not exceeded. Figure 12 shows a SBJ installation at BKR02 where individual suction bucket inclinations (denoted Bucket A, Bucket B and Bucket C) and the global SBJ inclination (denoted SBJ Tilt) were monitored. Figure 12 shows that the SBJ experiences an initial increase in inclination after ‘touch down’ as the buckets penetrate the upper soil under their own weight. After the initial inclination is rectified, the installation continues where it can subsequently be observed that increasing suction pressures lead to apparent increases in the inclination of each suction bucket. Meanwhile, the inclination of the SBJ structure does not appear to vary significantly. Furthermore, when the suction installation was completed and the pumps were turned off such that the differential pressure reduced to zero, there is a significant reduction in apparent suction bucket inclination. This shows that suction bucket mounted inclinometers are significantly affected by bending of the lid and that alternative measurements of the inclination which are not affected by the suction pressures

should be taken. Solely relying on inclination data from the suction bucket lids is unlikely to be representative of the structure's overall inclination. If the individual suction bucket inclination values were the only inclination measurements available, the monitoring of these parameters in real time could lead to incorrect assumptions regarding the inclination of the overall structure.

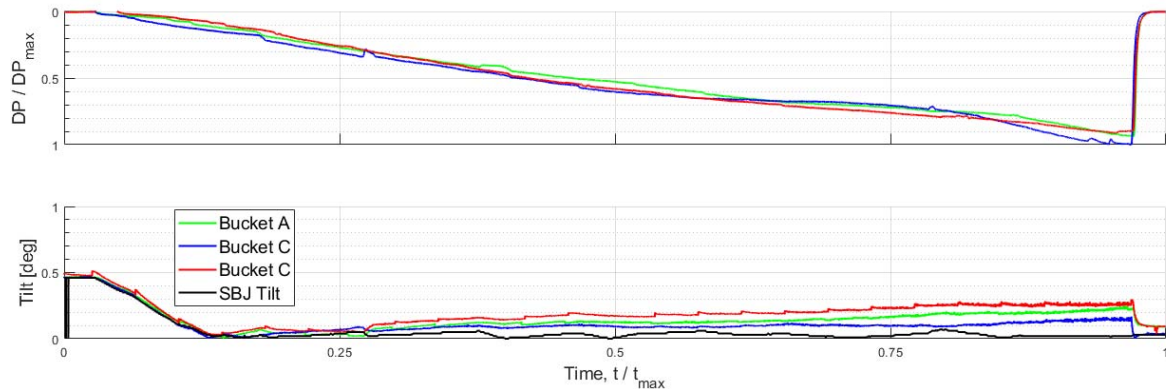


Figure 12 Individual suction bucket tilt during an installation of an SBJ at BKR02

SUMMARY

In 2018, Ørsted successfully installed 20 SBJ structures to support offshore wind turbine generators at the BKR02 offshore windfarm. These structures, which were installed into a predominantly granular soil profile, utilised a state-of-the-art monitoring system to aid the installation procedure. Using monitoring data from these installations, a number of risks to the installation process have been identified and discussed, including distribution of pressure around the suction bucket skirt, variability of the plug heave and suction bucket inclinations. Real time monitoring of these parameters is critical for ensuring successful suction bucket installations for future projects where SBJs are chosen as the foundation solution.

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