Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Field observations from large scale Suction Bucket Jacket installation for an offshore wind farm in East China Sea

C. Brandolini*
Geowynd, Milan, Italy

C. Piatti, L. Zuccarino
Geowynd, Milan, Italy

**cab@geowynd.com*

ABSTRACT: Suction Bucket Jacket (SBJ) has become a valid alternative to monopile foundations for offshore wind turbines and the number of Offshore Wind Farms (OWF) founded on SBJ is expected to increase significantly across the globe in the coming years. However, the existing literature and design guidelines related to SBJ installation are still quite limited. Available field experience on SBJ installation is mainly associated to North Sea where first SBJ applications to OWF occurred. Very limited field information is available for SBJ installation in lithologies different from typical heavily over-consolidated North Sea soils. This paper presents experience gained and key observations from the installation of n.52 tripod SBJs (156 suction buckets) for an offshore wind farm in the East China Sea. Soil stratigraphy comprises mainly normally consolidated extremely low to low strength clay and lightly over-consolidated low to high strength silty clays. Key observations from installation are discussed, including self-weight penetrations, suction pressures, penetration rates and set-up factors. Detailed discussion on the commonly used CPT-based method approach and its suitability to our case study is provided. Field observations show tendency of recommended DNV predictions to significantly overestimate the installation resistances and, therefore, the need of a thorough back analysis of the field data. Recommendations for a robust back-analysis framework are given based on lessons learnt on the specific case study.

Keywords: Offshore Wind Farm; Suction Bucket Jacket; East China Sea; CPT-based method; back-analysis

1 INTRODUCTION

Suction Bucket Jacket (SBJ) can be a valid alternative to monopile foundation solution for offshore wind turbines, especially for future deeper water developments. However, very few SBJ installation field datasets have been published in literature to date (Jones, L. and Harding, A., 2020; Zuccarino et al., 2024). In common industry practice, SBJ installation predictions rely on the CPT-based method (DNV-RP-C212, 2019a) which links the soil resistance during installation to cone tip resistance q_c by means of two empirical coefficients, k_p and k_f, related to the end-bearing and shaft friction resistance, respectively. The DNV coefficients are calibrated by full scale data from installations of gravity base platforms, mainly in sands and in over-consolidated clays, typical of North Sea conditions. However, uncertainties remain regarding the conversion from skirt penetration resistance and cone penetration resistance, for example due to effects of different rates of penetration and due to excess pore pressures developing during cone penetration testing (DNV-RP-C212, 2019a). In addition, installation resistances in different soil conditions to the North Sea are poorly addressed. It is evident the need for extensive field data investigation and sea trials installations to develop consistent set of correlations between various types of penetration resistance and allow reliable SBJ installation predictions.

A recent attempt to derive k_p and k_f by back-analysis of SBJ field data measurements was carried out for an Offshore Wind Farm (OWF) in the East China Sea soft soil conditions (Zuccarino et al., 2024). The study demonstrated that coefficients from DNV (DNV-RP-C212, 2019a) can lead to significant installation resistance overpredictions. As a companion study, the present work further explores the East China Sea OWF SBJ installation field dataset (Zuccarino et al., 2024) providing useful observations and recommendations for robust back-analysis. The paper also highlights how poor quality input data could pose limitations and uncertainty into the k_p and k_f assessment. Lessons learnt are discussed in this paper, in order to share experience and improve the reliability of the installation back-analysis for SBJs.

2 CASE STUDY

2.1 Installation Field Data

The dataset includes 52 SBJ installation field measurements from an OWF in the East China Sea, in water depths ranging from 36.5 to 47.2 m below the seafloor (bsf). SBJs are 3-legged jacket structures founded on suction buckets and support 8 MW and 10 MW wind turbine generators. Suction bucket diameter (D) ranges from 10 m to 13.5 m and total length (L) from 19 m to 26 m, depending on specific locations, with L/D ranging from 1.4 to 2.6. The input data include the recorded Self-Weight Penetration (SWP) for each SBJ leg, applied suction pressure, crane load and the timing. Additionally, the dataset includes CPT data for only one of the three SBJ legs, conducted at each location at the centre of the northern suction bucket. More detailed information can be found in (Zuccarino et al., 2024).

2.2 Soil Conditions

Soil stratigraphy comprises shallow very soft to soft normally consolidated clay (Unit 1) followed by lightly over-consolidated (OC) to OC silty clay (Unit 2a). Locally, a layer of loose to medium dense silty sand (Unit 2b) is found between Unit 1 and Unit 2a. Medium to dense silty sand (Unit 3b) is found below Unit 2a down to the maximum investigated penetration (approximately 30 m bsf). Soil unit depth ranges are summarized in Table 1. Additional details on soil properties are given in (Zuccarino et al., 2024). It shall be emphasised that such soil units are significantly different from the North Sea typical conditions considered in the DNV regulation (DNV-RP-C212, 2019a), as presented in Figure 1. This comparison based on cone tip resistance (q_c) highlights the remarkably soft soil conditions characteristic of the East China Sea case study site in contrast to a typical CPT from the North Sea region, which generally consists of layers of very dense sands and overconsolidated clays.

Table 1: Soil unit description and depth ranges

Unit	Description	Top [m bsf]	Bottom [m bsf]	Thickness [m bsf]
1	Very soft to soft CLAY	0.0	6.1-15.0	6.1-15.0
2a	Firm to stiff silty CLAY	6.5-15.6	17.5-25.7	4.0-17.7
2b	Loose to medium dense silty SAND	6.1-22.7	8.0-23.5	0.6-6.9
3b	Medium dense to dense silty SAND	16.0-24.9	19.0-25.7	0.5-3.5

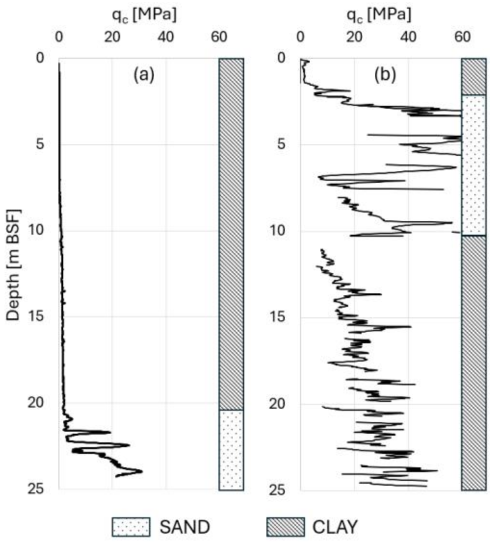

Figure 1: Typical CPTs from East China Sea case study (a) and North Sea region (b)

2.3 Site-Specific k_p and k_f Coefficients

Back-analysed site specific calibrated empirical k_p and k_f coefficients are summarized in Table 2 and Table 3 (Zuccarino et al., 2024). Coefficients were obtained by trial and error methodology by fitting the installation field measurements available for each SBJ location. Values are provided for both SWP and the suction-aided phase, and differentiated for each soil unit. Low Estimate (LE) and High Estimate (HE) values of the coefficients were determined to cover the range of measured values between the three legs for each installed SBJ. The selected combinations of k_p and k_f were chosen to achieve the best engineering fit valid for all the 52 installed SBJ foundations. Field observations including challenges, limitations, and potential improvements to the coefficients depending on the specificity and accuracy of the provided dataset will be further discussed in this paper in Section 3.

Table 2: Site-specific coefficients for the SWP phase

Self-Weight Penetration phase					
Soil type	**Soil unit**	**LE**		**HE**	
		k_p	k_f	k_p	k_f
Clay	Unit 1	0.3	0.009	0.3	0.012
	Unit 2a	0.1	0.007	0.1	0.010
Sand	Unit 2b & 3b	0.2	0.002	0.3	0.002

Table 3: Site-specific coefficients for the suction phase

Suction-aided phase					
Soil type	**Soil unit**	**LE**		**HE**	
		k_p	k_f	k_p	k_f
Clay	Unit 1	0.3	0.011	0.4	0.022
	Unit 2a	0.2	0.009	0.3	0.018
Sand	Unit 2b & 3b	0.3	0.003	0.4	0.004

Installation prediction comparison between DNV and site-specific coefficients in terms of suction pressures for a representative SBJ location is given as example in Figure 2, showing the good fit of site-specific coefficients for predicting the installation measurements. It is worth noting that the unitisation at Location 29 does not include Unit 3b, which is present in the stratigraphy of 24 out of 52 SBJ locations up to the target penetration depth.

Suction pressures represent the underpressure applied through a pump inside the suction buckets to allow their penetration to a specified target depth. Suction pressures are exerted when the submerged weight of the structure balances the soil resistance during penetration, thus reaching the SWP depth, and increasing with soil resistance as per Eq. 1 (DNV-RP-E303, 2019b):

$$\Delta u = \frac{R - W'}{A_{in}} \quad (1)$$

where Δu is the suction pressure [kPa], R is the soil resistance [kN], W' is the submerged weight acting on each leg [kN] and A_{in} is the cross-sectional area where underpressure is applied [m^2].

Suction pressure measurements in Figure 2 begin at the SWP measured depth for each of the three SBJ legs at Location 29, ranging between 12 m and 13 m, and continue until the target penetration depth at about 21 m is reached. It can be observed that the predicted SWPs reach values of approximately 7.5 m and 9.5 m, respectively, with the highest expected and most probable coefficients from DNV. Additionally, the suction pressures required indicate that using the DNV coefficients result in significant overestimates of the installation soil resistance when compared to field measurements.

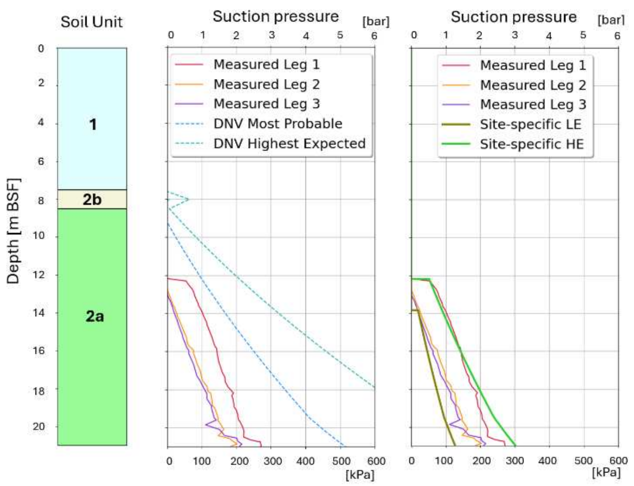

Figure 2: Example of DNV (DNV-RP-C212, 2019a) vs site-specific predictions for SBJ location 29

3 FIELD OBSERVATIONS

Key factors to be taken into account for a robust back-analysis of coefficients k_p and k_f are discussed in this section. While these empirical coefficients were already defined in Zuccarino et al. (2024), the following sections aim to highlight the lesson learnt from the previous study, including valuable field observations as well as challenges, limitations and potential improvements to the back-analysis carried out for this specific case study. Ensuring that all relevant field measurements are available during the SBJ installation process is essential for enhancing the accuracy of back-analysis and improving soil resistance predictions.

3.1 Penetration rates

Penetration depth and time were recorded during the installation at each leg of the SBJ, allowing for calculation of penetration rates. The available measurement depth intervals are not constant in depth and across the different locations. Derived penetration rates for all SBJ locations during SWP and suction-aided phase are shown in Figure 3. Values are reported in cm/s to appreciate the differences with the typical CPT penetration rate of 2 cm/s. The penetration rate emerged to be a crucial factor to describe the installation response. Indeed, coefficients k_p and k_f had been differentiated for SWP and suction aided phases due to the significant penetration rate differences (Zuccarino et al., 2024). In particular, as shown in Figure 3, the SWP phase resulted in consistently faster penetration rates compared to suction-aided phase. By averaging the penetration rates in m/h for each location, the mean penetration rate across the 52 SBJ locations varies from 8.2 m/h to 25.8 m/h during the SWP phase and from 0.5 m/h to 5.8 m/h during the suction-aided phase.

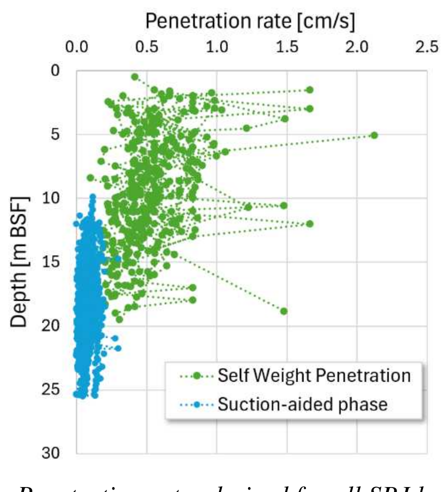

Figure 3: Penetration rates derived for all SBJ locations for SWP (green) and suction phase (light blue)

The penetration rates during suction-aided phase derived for all SBJ locations are further analysed and presented as depth average penetration rate intervals in m/h in Figure 4. Case study average penetration rates during the suction phase are compared with available literature data from the SBJ installations at Seagreen OWF, located in the North Sea off the coast of Scotland (Hamdan, et al., 2023). It can be noted that the majority of the case study suction phase penetration rates is generally in line with Seagreen OWF values (Figure 4). No detailed information is available about SWP penetration rates at Seagreen (Hamdan et al., 2023). It is worth noting that Seagreen and current case study present strong differences in terms of SWP depth (less than 2 m versus up to 21 m), overall maximum target penetration (11 m versus 26 m) and bucket geometry (L/D of about 1 versus up to 2.6).

Further research is currently ongoing to develop a novel approach aimed at estimating k_p and k_f for each measurement depth and allow deeper investigation of the dependence of the two coefficients on the penetration rate.

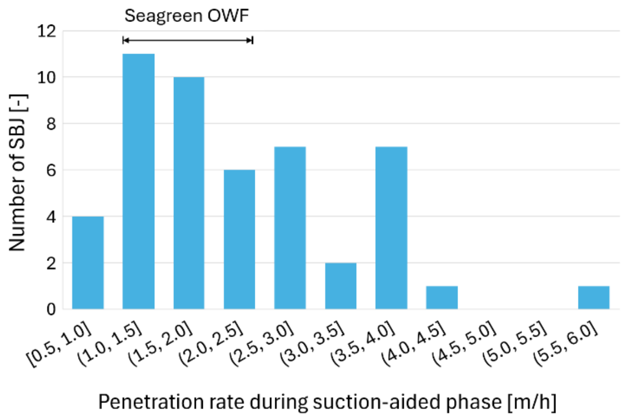

Figure 4: Depth average penetration rates for the case study (suction-phase) compared to typical ranges for the SBJ installed at Seagreen OWF (Hamdan et al., 2023)

3.2 Self-Weight Penetration (SWP)

Once the foundation has landed on the seabed, SBJ penetrates under its own self-weight until downward force is balanced out by soil resistance. Recorded SWP penetrations range significantly across the site, from 9.2 m to 21.4 m (Figure 5**Erreur ! Source du renvoi introuvable.**). The reason of such wide range can be found in the stratigraphic lateral thickness variability of soil unit at site (see Table 1). Figure 5 presents the SWP depth related to the thickness of the shallow very soft to soft clay (Unit 1) for each location, showing that greater SWPs are usually found at locations where Unit 1 is thicker. In other words the SWP seems to be controlled by the thickness of Unit 1.

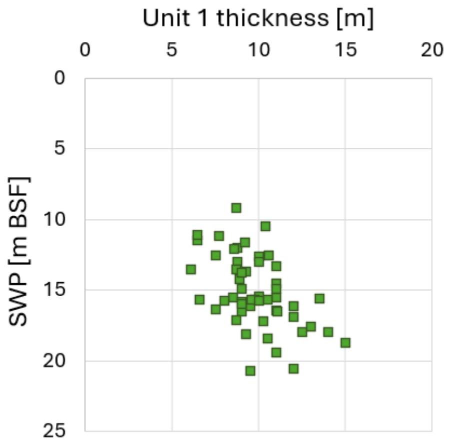

Figure 5: SWP vs Unit 1 thickness

3.3 Installation Data Variability within SBJ Footprint

It was found that at some locations the recorded installation measurements at the three legs of the same SBJ footprint could be significantly different. Figure 6 presents the field-measured suction pressures for each SBJ leg at WTG Locations 12 and 38. Suction pressures begin to be applied upon reaching the SWP depth and continue until the target penetration depth, which is 25.5 m at Location 12 and 21 m at Location 38. Regarding the data variability within the SBJ footprint, significant differences in SWP between the three legs for these two locations can be noted in Figure 6, as summarised in Table 4.

Table 4: Delta SWP within the SBJ footprint

Location	Delta SWP between SBJ legs [m]		
	Legs |1-2|	Legs |1-3|	Legs |2-3|
12	2.7	3.2	0.5
38	2.8	2.7	0.1

As reported above, the differences between minimum and maximum measured SWP at the three legs reach 3.2 m at Location 12 and 2.8 m at Location 38. Variability is also found in the suction pressures applied per leg. Such differences could be attributed to various factors, including installation operations and tilt corrections, but typically they can reflect lateral soil variability between the three legs of the jacket. As mentioned in Section 2.1, a single CPT was performed for only one of the three SBJ legs at each location. Lack of geotechnical data (CPT and/or soil sampling) at each leg as well as geophysical data did not allow for a clear understanding of such behaviour. It is, therefore, of paramount importance to plan and perform a detailed site investigation across the jacket footprint which should enhance both the design and the installation analyses of the suction buckets and to remove the uncertainties in case of back-analysis. CPT data at each suction bucket location and geotechnical samples at the jacket centre are recommended (Offshore Wind Accelerator, 2019), especially in case of expected high variability at site. Both jacket legs and CPT coordinates should be made available in order to match the field measurements with the corresponding geotechnical and geophysical information in order to properly address soil variability.

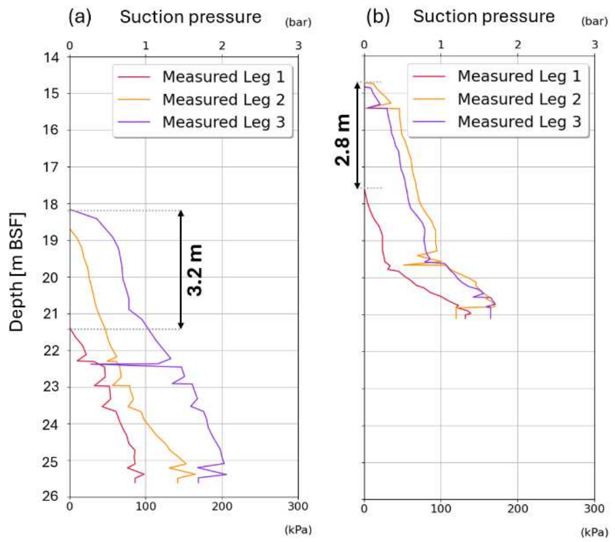

Figure 6: Example of field measurement variability within SBJ footprints: Location 12 (a) and Location 38 (b)

3.4 Crane loads

A crane load is usually applied to the SBJ during installation. Crane loads reduce the effective weight acting on the single leg and, therefore, they influence the soil resistance calculation and back-analysis. In the present study, crane load measurements were mostly not available or unreliable in the SWP phase, while during the suction phase there was no crane load applied. For locations where crane loads were deemed reliable, a sensitivity check was performed including crane loads and showing negligible influence on the estimated SWP. Anyway, it is highly recommended to record and report on the installation data sheet the crane load values throughout the installation since they can provide a better picture of the operations at site and be used to highlight or explain any differences between locations.

3.5 Out of verticality

The tilt of the SBJ foundations during the installation phase represents another important parameter to be monitored in field. Tilting corrections are typically made by acting on the single leg suction pressures and regulating the penetration rates. These adjustments could be necessary during installation where lateral soil variability occurs within the SBJ footprint. No tilt measurement were available in the dataset. However, very low values of suction pressure were observed immediately at the start of the suction phase at some SBJ locations. Although lacking detailed information, these values are believed to be related to tilt corrections accumulated during the SWP phase to ensure the stability of the foundation. It would be highly valuable to include tilt data during the installation process, as this could help explaining potential differences in field measurements between the three SBJ legs (see Figure 6) and further elaborate on the lateral variability at site.

3.6 Set-up factor

At four SBJ locations, the installation was interrupted during the suction phase and then resumed after time for various reasons, including adverse weather conditions. As an example, Figure 7 presents the case of Location 18, where the application of suction pressures for the three SBJ legs was stopped at around 20 m, and then restarted until the target penetration depth of 21 m. It is noted that higher peaks in suction pressures are found at the installation restart for Location 18, corresponding to increments of about 166%, 194% and 134% for SBJ legs 1, 2 and 3, respectively. Once the penetration is onset, the required suction pressure decreases and slowly converges to the pre-stoppage trend.

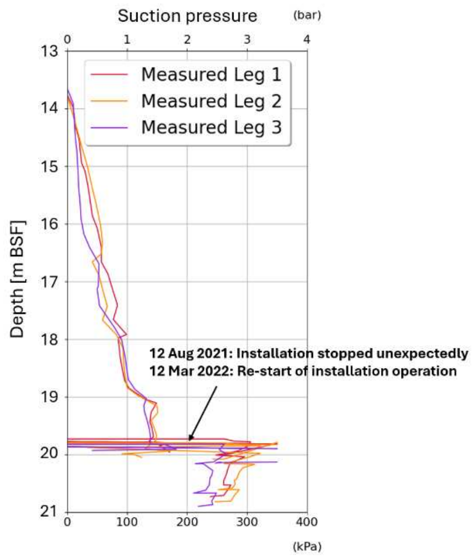

Figure 7: Example of installation stop and re-start effects for Location 18

Set-up factors α for these four SBJ locations were determined as the ratio between the average soil resistance at the installation restart ($R_{restart}$) and immediately before the installation break ($R_{pre-stop}$):

$$\alpha = \frac{R_{restart}}{R_{pre-stop}} \quad (2)$$

The calculated set-up factors as function of the operational restart time for each SBJ location are plotted in Figure 8, along with recommended values by DNV for low plasticity normally consolidated clays (PI < 30 %) (DNV-RP-E303, 2019b). The back-analysed set-up factors align with the trend suggested by DNV of low plasticity clays in line with the clay properties at site (summarized in Table 5).

Table 5: Site-specific sensitivity and plasticity index values

Unit	S_t [-]	PI [%]
1	2.0	18
2a	3.2	13

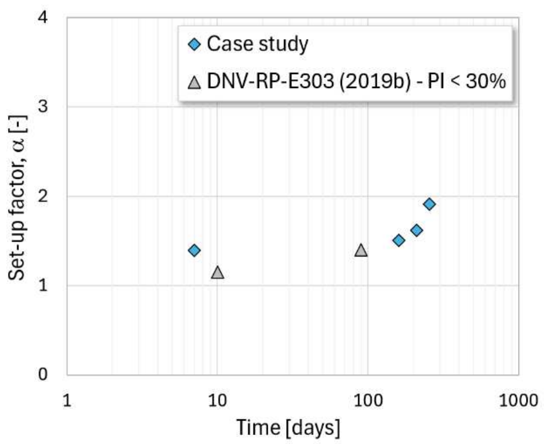

Figure 8: Set-up factor versus time

4 CONCLUSIONS

SBJ installation analyses in common industry practice make use of the well-know DNV CPT-based installation method. The study complements the results of back-analysed k_p and k_f values from a large scale SBJ installation campaign for an OWF in East China in soft soil conditions (Zuccarino et al., 2024) with valuable field observations, highlighting challenges, limitations and possible improvements. In particular, penetration rate played a crucial role in differentiating the coefficients k_p and k_f between the two main installation phases, highlighting its importance as a key parameter to be derived from installation measurements. A correlation was observed between the thickness of Unit 1 and the SWP depth across all SBJ locations, with greater SWP depths typically recorded at locations where Unit 1 is thicker. Furthermore, differences in field measurements within the same foundation were investigated highlighting the importance of properly assessing the lateral soil variability. More comprehensive site investigations, including CPTs at each leg and geophysical surveys, are recommended. Also, during the installation operations it would be highly valuable to record in detail possible SBJ tilt corrections and crane loads, in order to possibly improve back-analysis accuracy. Future research should focus on improving field data collection and refining empirical coefficient models to minimize uncertainties and enhance the optimization of SBJ installation predictions for foundation design.

AUTHOR CONTRIBUTION STATEMENT

Carlo Brandolini: Data curation, Formal Analysis, Writing- Original draft. **Claudio Piatti**: Software, Methodology, Supervision. **Lorenzo Zuccarino**: Conceptualization, Supervision, Writing- Reviewing and Editing.

ACKNOWLEDGEMENTS

The authors are grateful to SPT Offshore for the valuable installation dataset provided.

REFERENCES

DNV (2019a). DNV-RP-C212 Offshore soil mechanics and geotechnical engineering, Edition September 2019.

DNV (2019b). DNV-RP-E303 Geotechnical design and installation in suction anchors in clay, Edition April 2017, Amended November 2019.

Hamdan, N., Powell, T. A., Grace, D., MacBeath, M., Jones, L., Thumann, V. (2023). Suction caissons installation in layered soils – observations from installations, In: *Proceedings of the Offshore Site Investigation and Geotechnics (OSIG) Conference,* London, United Kingdom, pp. 1749-1756. https://doi.org/10.3723/PBKH8958

Offshore Wind Accelerator. (2019). *Suction Installed Caisson Foundations for Offshore Wind: Design Guidelines.*

Jones, L., Harding, A. (2020). Experience from Full-Scale Suction Caisson Trial Installations at the Seagreen Offshore Wind Farm, In: *Proceedings of the International Symposium on Frontiers in Offshore Geotechnics (ISFOG) Conference,* Austin, Texas, USA, pp. 725-735.

Zuccarino, L., Brandolini, C., Piatti, C. (2024). New Site Specific CPT-based Suction Bucket Jacket Installation Coefficients from Field Measurements, In: *Proceedings of International Ocean and Polar Engineering Conference (ISOPE),* Rhodes, Greece, pp. 79-86.