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# Evaluating calculation methods for suction-assisted installation techniques in sand: A comparative study

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**ABSTRACT:** The use of suction caissons as a foundation for offshore wind energy converters is increasing due to their low-noise installation, reduced installation time and adaptability to a wide range of site conditions. As the size of support structures for modern, high-capacity turbines increases, so does the required size for their foundations, which is challenging for cost-effective design. The suction installation process contributes to overcome soil penetration resistances. Nevertheless, unforeseen events such as interrupting installation due to technical issues or penetration refusal due to challenging soil conditions, may demand contingency measures to achieve the desired embedded depth. Their impact on both the installation procedure and the caisson's bearing capacity demands further detailed investigations. To explore these effects, geotechnical tests at various scales have been conducted as part of the ProBucket research project. This paper presents and analyses the results of suction installation tests of a fully instrumented suction caisson in homogeneous sand. The installations involved a test specimen with a diameter of 1.60 m and a skirt length of 1.42 m, which was installed a.) continuously, b.) with downtime, and c.) with pressure cycles. By comparing the experimental installation curves with predictive calculations, the suitability of established calculation methods for suction assisted installation in sand is assessed. The findings indicate that current methods for estimating suction pressure require further evaluation, especially for cases with varying penetration rates or alternative installation techniques. Based on these findings, recommendations for future work are given.

**Keywords:** large-scale testing; suction-assisted installation; suction caissons; sand; physical modelling

## 1 INTRODUCTION

Suction caissons are increasingly being used as foundations for offshore wind turbines due to their rapid, low-noise installation and adaptability to various site conditions. The use of suction caissons as foundation element for jacket structures can offer cost and environmental advantages by comparing with pin piles. A crucial aspect in their design is the installation process. In suction installation, it is typical to estimate the required best and high suction pressure needed to overcome different soil penetration resistances. Methods are available that either use a mechanism-based approach as Houlsby & Byrne (2005) or derive the suction pressure directly from the CPT data as Andersen et al. (2008) or Senders & Randolph (2009). Bienen et al. (2018) compared the predictions of these methods with experimental results from centrifuge tests. For each approach, a set of input parameters was found that gave good agreement with the applied suction. However, the lack of a consistent parameter set complicates the application of these methods under offshore conditions.

Unexpected events, such as installation disruptions or tough ground conditions may create challenges that demand adapting the installation method in the field. In OWA (2019) reactive mitigation measures that require preliminary engineering studies are mentioned. These include pausing the installation process, cyclic installation or ballasting suction caissons. Risks in the installation process must be anticipated and mitigated through appropriate installation procedures and contingency plans for any residual risks (OWA 2019).

Joseph et al. (2023) reported on the successful use of cyclic installation in an offshore installation trial. By using two-way-cycles, the suction pressure was reduced, and a larger installation depth was achieved. However, the implementation of such measures can affect both the installation process and the subsequent bearing capacity of the foundations.

Due to the insufficient publicly available data, following questions are raised:

- Do the methods for predicting the suction pressure allow for consistent application?
- What are the effects of reactive mitigation measures on caisson installation?
- Can the prediction methods consider such effects?

As part of the ProBucket project, suction assisted installation tests were carried out at various scales in homogeneous, nearly dense sand. These tests aimed to evaluate the effectiveness and reliability of suction caisson foundations under controlled conditions in a geotechnical pit. This paper presents findings from four large-scale suction assisted installation tests, including continuous, interrupted and cyclic installation scenarios. The measurement data are compared with predictions from existing calculation methods, and the results are then discussed in relation to the research questions.

The detailed analysis presented in this paper aim to provide a deeper understanding of the installation challenges and offer practical solutions for future offshore applications.

## 2 CALCULATION PROCEDURES

The conventional installation of a suction caisson is executed in two steps. Initially, the caisson is released on the mudline and an initial penetration occurs due to the self-weight penetration. Afterwards, a force that is generated by creating a negative differential pressure (suction) beneath the lid enables the caisson to penetrate further into the soil. To calculate the required suction [Eq. (1)] for a certain depth, all load and resistance components must be considered:

$$V' + s * A = F_i(s) + F_o(s) + R_{tip}(s) \quad (1)$$

where $V'$is the effective vertical load, $s$ and $A$ are the applied suction and the area of the caisson lid, respectively. $F_i(s)$ and $F_o(s)$ are the resistance forces caused by the friction inside and outside the caisson and $R_{tip}(s)$ is the resistance at the caisson tip (see Figure 2). During installation, the flow-induced change in effective stress leads to a significant reduction in penetration resistance. While the external skirt friction is slightly increased, the internal friction and tip resistance are significantly reduced. Failure of a suction caisson installation can result from the critical hydraulic gradient at critical suction $s_{crit}$, particularly in highly permeable soils. Excessive suction may reduce the effective stress inside the caisson to zero, leading to hydraulic failure or to piping channels. To prevent these issues, the applied suction pressure should be kept below a critical value known as the critical suction pressure. For the calculation of the resistance forces, two main approaches have been established.

### 2.1 Mechanism-based method

Houlsby & Byrne (2005) developed an equation for predicting caisson penetration and sand, which is based on earth pressure theory and the soil state parameters: friction angle $\varphi'$ and effective unit weight $\gamma'$ . Assumptions for the horizontal earth pressure coefficient $K$ and the interface friction angle $\delta$ are necessary, since hard data for these parameters is uncommon. This method accounts for specific effects occurring during installation, such as variations in permeability $k_r = k_i/k_o$ both inside and outside the caisson, as well as changes in effective stresses due to the induced flow.

### 2.2 CPT-based method

Senders & Randolph (2009) provide an equation where the friction terms inside and outside of the caisson are calculated by integrating the cone tip resistance $q_c$ over the penetration depth $L$ [Eq. (2)]. In addition, an empirical friction coefficient $k_f$ is used as a multiplier.

$$F_{i/o} = \pi D_{i/o} k_f \int_0^L q_c(z) dz \quad (2)$$

Where $D_{i/o}$ are the inner or outer diameter and $z$ is the vertical coordinate describing the depth below mudline.

The caisson tip resistance $R_{tip}$ results from multiplying $q_c$ at the tip depth with the tip area $A_{tip}$ [Eq. (3)]. Similarly, an end-bearing coefficient $k_p$ is used in this approach.

$$R_{tip} = A_{tip} k_p q_c(L) \quad (3)$$

In this method, both the inner friction and tip resistance are influenced by a factor $(1 - s/s_{crit})$, where $s_{crit}$ describes a critical suction. There are several definitions for $s_{crit}$. Feld (2001) provides an approach based on geometric parameters and Houlsby & Byrne (2005) incorporate the permeability ratio $k_r$ in the calculation of $s_{crit}$.

The CPT-based method described in Andersenet al. (2008) provides a calculation procedure that considers several of the aforementioned effects related to suction assisted penetration. This method is based on diagrams linking the interaction of critical suction, penetration resistance with and without suction and permeability ratio. All of them are derived from prototypes and model tests as well as assumptions from literature.

# 3 LARGE-SCALE EXPERIMENTS

## 3.1 Test setup

The test specimen detailed in this paper is a model caisson with a diameter of 1.60 m, a skirt length of 1.42 m ($L/D$ = 0.89) and a wall thickness of 8 mm (see Figure 2Figure 2). It represents a fictitious prototype caisson of a jacket structure for an offshore wind turbine (OWT) at a scale of 1:6.

The large-scale geotechnical model tests were carried out in the geotechnical foundation test pit of the Test Centre for Support Structures in Hannover (TTH). The pit was filled with a uniformly graded siliceous sand, referred to as Rohsand 3152, which was compacted in layers of approximately 25 cm. The final height of the compacted soil sample was 9.25 m. The preparation of the soil sample in layers enabled the placement of earth pressure sensors vertically and horizontally as well as pore water pressure sensors at different depths. During the soil filling process, soil core samples were taken from each sand layer. The relative density ($D_R$) averaged 0.64, indicating nearly dense sand condition. The water level was gradually increased from bottom to top, ensuring substantially saturated conditions. Table 1 shows the physical properties of the model sand used.

*Table 1. Physical properties of the test sand Rohsand 3152*

| Properties | Unit | Value |
|---|---|---|
| Maximum void ratio, $e_{max}$ | - | 0.82 |
| Minimum void ratio, $e_{min}$ | - | 0.41 |
| Specific gravity, $G_S$ | g/cm³ | 2.61 |
| Coefficient of uniformity, $C_u$ | - | 1.82 |
| Coefficient of curvature, $C_c$ | - | 0.96 |
| Grain diameter to 60% passing material, $d_{60}$ | mm | 0.40 |
| Hydraulic conductivity, $k$ | m/s | 1.09E-04 |

Following the soil preparation phase, cone penetration tests (CPT) were executed to assess the quality of the compaction and verify the homogeneity of the soil sample. Figure 1 shows a representative CPT profile, which reflects the average of the measurements. The zigzag-shaped curve indicates the layered preparation method of the model sand. Cone resistance values reach up to 10 MPa at depth of 1.30 m.

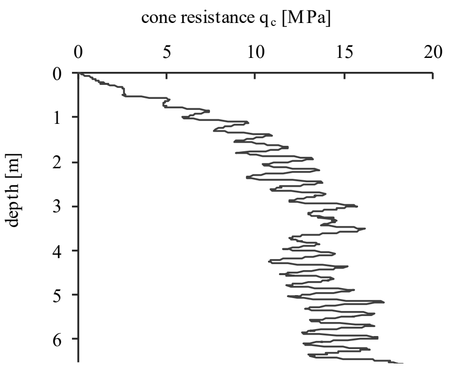


*Figure 1 – Averaged CPT-Profile of prepared soil in the geotechnical test pit of the TTH*

To estimate the friction angle for the model sand, four distinct CPT-correlations were used. The mean values over the final penetration depth reached ranged from 35.2° (correlation for shallow layers) to approximately 40°.

Alternatively, according to Andersen et al. (2008), the bearing capacity can be estimated using the plane strain friction angle, which may be up to 10 % higher than the friction angle from triaxial tests. It is stated that the displacement pattern around the skirt tip is closer to plane strain. Based on this, plane strain friction angles would range from 38.8° to 42.2°, resulting in a mean value of 40°, which is used for the back-calculations.

## 3.2 Description of the test campaign

The suction caissons were installed in three steps: initially, self-weight penetration, followed by two steps of suction, termed air phase and water phase. During the air phase, air was evacuated from the caisson using a vacuum pump, with a vacuum tank acting as a reservoir. Once the caisson reached a depth of approximately one meter, the air phase ended, and the water phase began, with water flowing into the vacuum tank. Due to technical constraints, at some point, the extracted water needed to be discharged from the vacuum tank, resulting in a short-term decrease of the suction pressure.

The installation process was controlled by regulating the suction pressure and referencing a predicted suction curve to maintain optimal conditions throughout the installation.

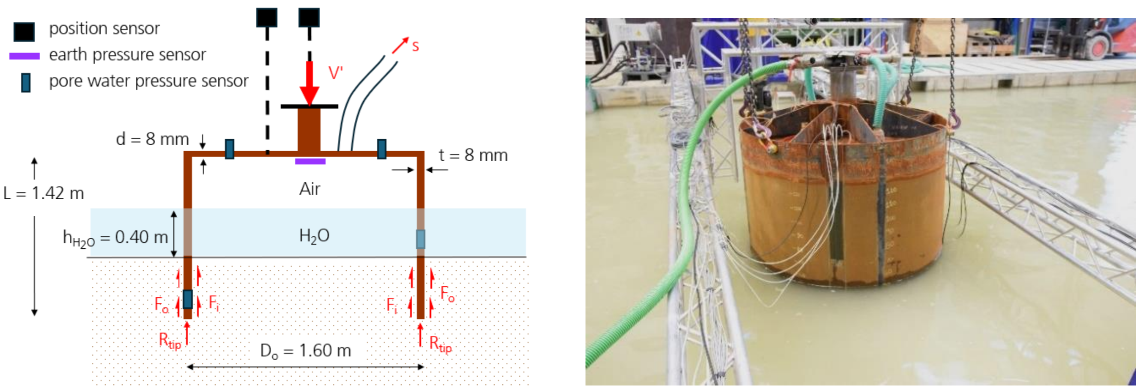


*Figure 2 – Overview of experimental setup: Sensors applied and forces acting on a caisson during suction installation (left). Installation of the suction caisson with D = 1.60 m and L = 1.42 m in the geotechnical test pit of the TTH (right)*

Two pore water pressure sensors placed below the caisson lid measured the pressure applied during installation. An earth pressure sensor was attached to the lid invert to measure contact stresses at the end of installation. Eight additional pore water pressure sensors were mounted on the skirt, positioned at the midpoint of its length and at the tip level, enabling measurements both inside and outside the skirt.

Four installation tests were conducted to evaluate the influence of the installation procedure on suction pressure. Three test scenarios were examined: scenario 1 involved continuous installation, with two variations in penetration rates. Scenario 2 represented cyclic installation, while scenario 3 consisted of an installation with downtime. These are summarized below.

### 3.2.1 Continuous installation

In absence of technical or soil-related issues, continuous installation is the conventional and preferred method for installing suction caissons. Exemplary penetration rates registered during offshore installations are provided in Jones and Harding (2020). Based on this, two comparable installation rates ($v_{mean}$) of 0.91 mm/s and 0.43 mm/s were implemented in the two continuous installations described in this paper. To accommodate variations in installation rates, the flow rate was adjusted accordingly throughout the process.

### 3.2.2 Installation with pressure cycling

Pressure cycling is the process of applying the pressure in the caisson periodically. During alternating (two-way) cycling, the negative pressure (suction) will be followed by a transition to positive pressure. If the positive pressure is sufficiently high, the nominal drained tensile capacity will be exceeded, resulting in a slight upward movement. Subsequently, the pressure level will be reduced back to negative pressure, allowing further penetration. With the cyclic installation is intended to reduce the soil strength to facilitate penetration (OWA 2019). Recent research suggests that two-way pressure cycling is generally more effective in reducing installation resistance in clay compared to sandy soils (Joseph et al. 2023). Nonetheless, O'Loughlin et al. (2023) observed in the centrifuge experiments that pressure-cycled installation in sand led to a small but discernible reduction in the required suction pressure over the last ~30 % of skirt embedment depth. This indicates that while the effectiveness of pressure cycling in sand is limited compared to clay, there can be a slight decrease in suction pressure at greater embedment depths.

It can be assumed that the effectiveness of pressure cycling may be influenced by the number of cycles, induced uplift and pressure gradient. In this test campaign, a two-way cyclic installation was implemented exemplarily, with cyclic uplift limited to a maximum of 2 ‰ of the caisson diameter *D*.

### 3.2.3 Installation with downtime

In OWA (2019), pausing installation is recommended as a mitigation measure against the occurrence of piping and soil plug failure. Recent offshore observations in intermediate soils also suggest that pausing installation can reduce suction pressures (Torre et al. 2023). In the present paper, an installation test was performed simulating two pauses in the installation process, each lasting approximately 20 hours. This scenario was designed to model unforeseen technical issues, such as the failure of a suction pump, which may lead to extended downtime.

## 3.3 Results

Figure 3 presents the installation curves of the four conducted installation tests. Table 2 summarizes the results of the installation tests, evaluated at an installation depth of approximately 0.94 m, equivalent to a ratio of $L_i/D = 0.59$. This depth represents a threshold prior to suction pressure decreases minimally, due to unavoidable adjustments to the pumping controlling system by entering the water phase. By comparing the continuous installations SB-D1600-I and SB-D1600-II, it appears that higher penetration rates require lower suction pressures which is also observed in Bienen et al. (2018). The application of alternating pressure cycles in the installation SB-D1600-III effectively reduced the required suction pressure. After seven pressure cycles, a decrease of up to 38 % was measured.

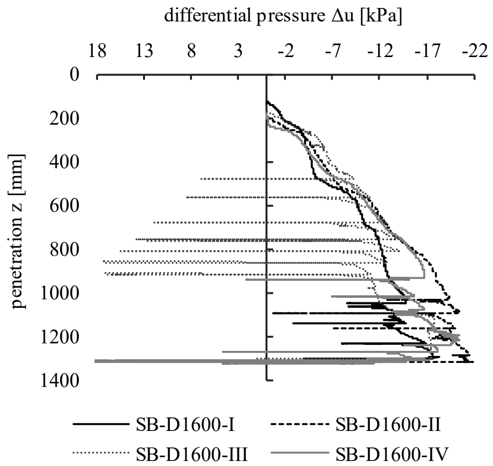


*Figure 3 – Applied pressure in large-scale installation tests.*

The SB-D1600-IV installation test demonstrates that a 20-hour interruption also leads to a reduction of suction pressure upon resuming the installation. Prior to the simulated interruption, this caisson was installed almost at the same penetration rate as the SB-D1600-II and consistently required a similar suction pressure. During the downtime, the built-up soil stresses outside the caisson - caused by the downward flow during suction – gradually decrease, enabling the installation to continue with a lower suction pressure compared to an uninterrupted installation.

In particular, scale effects are associated with low soil stress levels and high dilatancy of the prepared sand, which may influence the direct applicability of the findings from this investigation to real-scale conditions. However, given the relatively large model scale used in this study, along with soil measurements and existing experimental results from a larger model scale test – though not included in this paper – it will be feasible to adequately address potential scale effects in future publications.

## 4 COMPARISON WITH EXISITNG CALCULATION METHODS

The calculation methods described above were used to back-calculate the installation tests. Selecting a consistent parameter set suitable for these methods appears challenging due to the differing data bases and approaches used in their development. However, these methods were not developed to cover resistance-reducing measures. Since preliminary investigations showed a steady trend in the installation curve when installing solely under air conditions and very low water table, no adjustments were made in the back-calculations to match the curve segment below one meter (water phase).

Results are showing that the three established methods are not suitable to reproduce the effects of the alternative installations SB-D1600-III and SB-D1600-IV without fuhrter method modifications. Hence, additional research efforts in this area are necessary. Taking this into account, following analysis focusses only on the experimental installation curves of the tests SB-D1600-I and SB-D1600-II (Figure 3**Erreur ! Source du renvoi introuvable.**). Here, the increase of the required suction during the installation SB-D1600-II is attributed to a lower penetration rate.

*Table 2. Summary of relevant measurements during installation tests at $L_i/D = 0.59$*

| **Name of test specimen** | **Test type** | **Specifications** | **Applied suction (kPa)** | **Change in applied suction (%)** [*1] |
|---|---|---|---|---|
| SB-D1600-I | Continuous | $v_{mean}$ = 0.91 mm/s | -13.15 | -27 |
| SB-D1600-II | Continuous | $v_{mean}$ = 0.43 mm/s | -18.03 | 0: Base case |
| SB-D1600-III | Pressure cycling (7 two-way cycles) | $v_{mean}$ = variable | -11.19 | -38 |
| SB-D1600-IV | Pause installation (20 hours) | $v_{mean}$ = variable | -12.06 | -33 |

[*1] The change in the applied suction force is related to the SB-D1600-II test as a reference.

## 4.1 Houlsby & Byrne (2005)

The back-calculated self-weight penetration depth and suction pressures, determined using the method of Houlsby & Byrne (2005), are also depicted in Figure 4Figure 3, showing **Erreur ! Source du renvoi introuvable.**good agreement with the experimental results. The parameters used for estimating the required suction are listed in Table 3. The interface friction angle between skirt wall and sand was estimated through shear tests on a sandblasted metal plate. The results gave an interface friction angle δ of about 39° under 30 kPa normal stress which is nearly as high as the soil friction angle. However, the authors consider the selection of δ in accordance with Andersen et al. (2008), as $\delta = 0{,}9 * \varphi' = 36°$ to be an appropriate approach for a rough interface.

Houlsby & Byrne (2005) do not consider possible influence of the penetration rate in their methodology. In the present back-calculations, the ratio of permeability was varied for agreement with the two installation curves. However, this approach has to be considered with caution since the phenomenological relationship between penetration rate and ratio of permeabilities is not fully understood at this point. The results of the experimental study by Ragni et al. (2020) show similar behavior, indicating that changes in the permeability are closely associated with variations in penetration rate.

In the present study, based on the comparison of the calculated values and the results of the tests conducted, it seems that halving the penetration rate leads to a doubling of the permeability ratio. The calculated critical suction threshold is reached at a depth of 840 mm for specimen SB-D1600-I and 880 mm for specimen SB-D1600-II. Beyond this depth, the prediction curve follows the critical suction.

*Table 3. Input parameters for penetration implemented in the method proposed by Houlsby & Byrne (2005)*

| **Properties** | **Unit** | **Value** |
|---|---|---|
| Effective unit weight, $\boldsymbol{\gamma'}$ | kN/m³ | 10.2 |
| Effective friction angle, $\boldsymbol{\varphi'}$ | ° | 40 |
| Interface friction angle, $\boldsymbol{\delta}$ | ° | 36 |
| Earth pressure coefficient, $\boldsymbol{K}$ | - | 1.0 |
| Permeability ratio, $\boldsymbol{k_r = k_i/k_o}$ | - | (see Fig. 4) |
| Multiple of diameter over which vertical stress is enhanced, $\boldsymbol{m}$ | - | 1.5 |

## 4.2 Senders & Randolph (2009)

By keeping the same permeability ratios as those assumed in the method by Houlsby & Byrne (2005), a good agreement was achieved between the predictions according to Senders & Randolph (2009) and the experimental results (see Figure 4

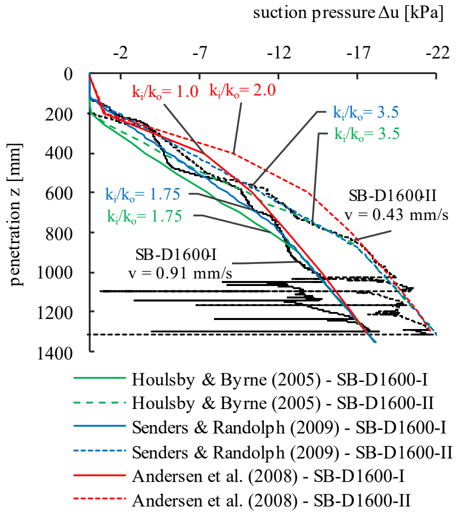


Figure 4). In addition, the definition of the critical suction used was consistent with the one used in the section 4.1 according to Houlsby & Byrne (2005).

*Table 4. Input parameters for prediction using CPT-based approaches.*

| **Properties** | **Unit** | **Value** |
|---|---|---|
| Effective unit weight, $\boldsymbol{\gamma'}$ | kN/m³ | 10.2 |
| End-bearing coefficient, $\boldsymbol{k_p}$ | ° | 0.2 |
| Friction coefficient, $\boldsymbol{k_f}$ | ° | 0.003 |
| Permeability ratio, $\boldsymbol{k_r = k_i/k_o}$ | - | (see Fig. 4) |

The parameters defining the resistance forces for the skirt friction $F(s)$ and end-bearing $R_{tip}(s)$ are calibrated to the suction curves to replicate the self-weight penetration depth and the slope of the initial curve segment. The critical suction is predicted to be reached at a depth of 780 mm for specimen SB-D1600-I and 880 mm for specimen SB-D1600-II.

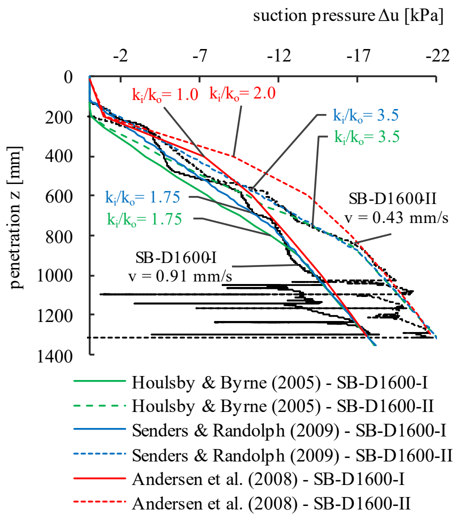

*Figure 4 – Experimental and calculated installation curves using mechanism-based and CPT-based approaches.*

### 4.3 Andersen et al. (2008)

By calculating the required suction according to Andersen et al. (2008), the same parameters were adopted as the one used in the back-calculations described in section 4.2 (see Table 4). The only difference lies in the permeability ratios chosen. As a result, the calculated suction curves replicate the experimental curves accurately at greater embedment depths but significantly overestimate the required suction at shallower depths for the SB-D1600-II.

## 5 CONCLUSIONS

This study evaluated established methods for predicting suction pressures during the installation of caissons in nearly dense sand. Based on the large-scale experimental results, a number of key findings emerged that fundamentally address the research questions posed at the outset in the introduction.

A largely consistent set of input parameters for the CPT-based methods according to Senders & Randolph (2009) and Andersen et al. (2008) was identified for the two investigated continuous installation scenarios. By back-calculating the experimental installation curves, a significant influence of the permebility ratios on the required suction pressure was found. By varying the permeability ratio in the CPT-based methods, both installation tests could be approximated. In this study, higher penetration rates are associated with a reduction in the required suction pressures when assuming lower permeability ratios. This observation implies a correlation that should be verified in future studies to establish causality. The results of the cyclic and interrupted installations demonstrate the effectiveness of these reactive mitigation measures to improve installation efficiency, reduce suction pressure and control penetration. However, standard prediction models do not take these effects into account as well as neither the effect of the penetration rate, indicating that further research ist needed for clarificaying and adapting existing calculation methods to more realistic offshore installation scenarios.

## AUTHOR CONTRIBUTION STATEMENT

**Dariya Heinrich:** Conceptualization, Methodology, Investigation, Visualization, Data curation, Writing – original draft, review & editing. **Tulio Quiroz:** Conceptualization, Methodology, Investigation, project administration, Writing – review & editing. **Waldemar Elsesser:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Bert Schädlich:** Conceptualization, Writing – review & editing. **Immo Sanders:** Conceptualization, Writing – review & editing

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