## Medium-scale Laboratory Model of Mono-bucket Foundation for Installation Tests in Sand

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Medium-scale Laboratory Model of Mono-bucket Foundation for Installation Tests in Sand

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Abstract

Design implications of suction installation of bucket foundations are still not well understood. During suction installation, applied suction under the bucket lid results in seepage flow through the surrounding sand. Seepage flow plays a pivotal role in reducing the penetration resistance, allowing for full penetration despite the initial large soil resistance. However, loosening of the inside soil plug might be problematic when the soil approaches its failure stage, due to soil piping or extensive soil heave inside the bucket foundation. To understand better the interaction between the soil and bucket skirt during suction installation, this paper describes the results of medium-scale tests of bucket foundation installation in sand, comparing jacking and suction installation. Experimental measurements of the pore pressure around the bucket skirt are compared to the numerical simulation results, to validate the finite-element model and to enable analysis of the soil behavior around the skirt.

Keywords: Bucket foundation, Dense sand, Suction, Seepage, Soil resistance
Introduction

Development of offshore wind energy has led to an increase in research aimed at reducing the total cost of wind turbines, particularly by developing cost-effective design solutions for the foundation. Suction bucket foundation technology, where the bucket lid is equipped with special valves for suction installation, offers advantages over jacking installation. Compared to jacking installation, the suction process is more environmentally friendly, cost-effective, and feasible, as it requires no heavy drilling equipment. Suction anchors have been extensively installed in various engineering devices and systems across different offshore sites. There are well-documented examples of skirted structures installed as foundations (Tjelta 1995; Andersen et al. 2008). For instance, a suction bucket foundation was used in the Frederikshavn, Denmark, for a wind turbine, which was the subject of a 5-year research project by Ibsen (2008) documenting its installation and operation.

The dense-sand seabed of the North Sea is the site of numerous offshore projects. Cohesionless soils have a higher penetration resistance than clay, and installation in these soils might be more problematic. Past research has shown that the application of suction not only creates the downward force required for installation, but also provides a large decrease in resistance for all permeable soils (Bye et al. 1995; Hogervorst 1980). Generation of seepage flow around the bucket skirt induces an upward hydraulic gradient within the inner soil and a downward gradient on the outside of the skirt, which changes the effective soil stress and reduces the total soil penetration resistance (SPR). Studies have proposed different methods for calculating the soil resistance during the suction installation process for bucket foundations in sand (Erbrich and Tjelta 1999; Houlsby and Byrne 2005; Andersen et
al. 2008; Senders and Randolph 2009). While consistently showing that the soil resistance varies
dependent on the value of the applied suction, these studies have not analyzed the interaction between
the bucket skirt and the surrounding soil during seepage flow.

The suction installation process for a bucket foundation in sand consists of two parts: self-weight
penetration and suction penetration. Self-weight penetration is necessary to create a sufficient seal
between the bucket skirt and surrounding soil, without which suction application will not be effective.
During the suction penetration stage, the required suction for a given penetration depth must be
determined. Although the general principle for the relationship between suction and penetration depth
is known, detailed design improvements for the installation can and should be made.

This paper presents a series of medium-scale tests for the bucket foundation installation using jacking
and suction installation. Pore pressure (PP) around the bucket skirt and applied suction under the
bucket lid are monitored during installation. Fig. 1 shows the model used for installation tests.
Measurements were used to confirm previous findings about the reduction in soil resistance and to
investigate seepage flow around the bucket foundation. In addition, numerical simulations of suction
installation tests were performed under the same conditions as the lab set-up. Comparing numerical
and lab results allows analysis of the critical allowable suction for bucket foundation installation and
better understanding of experimental results.
Fig. 1. Bucket foundation model in test sand container with internal diameters $D_{in}$.

Soil Penetration Resistance of Skirt Structures

**Calculation methods**

Penetration resistance can be calculated based on either the ultimate bearing capacity theory or an empirical model that relates the results of the Cone Penetration Test (CPT) to SPR. In general, the total penetration resistance, $R_{tot}$, consists of the skirt tip resistance, $Q_{tip}$, and the inner and outer friction along the skirt, $F_{inner}$ and $F_{outer}$ respectively.

Eq. (1) presents the classical approach based on the bearing capacity theory for the pile design (API 2014).

$$R_{tot} = A_{tip} \cdot min \left[ \sigma'_v(h) \cdot N_q, Q_{lim} \right] + (A_{s,o} + A_{s,i}) \cdot min \left[ K \cdot \tan \delta \cdot \int_0^h \sigma'_v(z)dz, f_{lim} \right],$$

where $A_{tip}$, $A_{s,o}$, and $A_{s,i}$ are the tip area, outside skirt area, and inside skirt area, respectively; $\sigma'_v$ is the effective vertical soil stress; $z$ is the depth below the soil surface; and $h$ is the penetration depth. $D_o$
and $D_i$ are the outside and inside diameters of the bucket; and $Q_{lim}$ and $f_{lim}$ are the suggested limiting values for tip resistance and skirt friction, respectively.

Calculating total resistance with the classical approach presents difficulties for estimating the soil parameters, including the bearing capacity factor $N_q$, coefficient of lateral earth pressure $K$, and interface angle $\delta$. In this respect, the CPT-based approach is more straightforward (DNV 1992) because the measured cone resistance $q_c$ can be linked to the skirt and the tip resistance of the foundation (eq. (2)). The CPT-based method is also more reliable than the classical approach because the CPT gives a record of the soil resistance with depth. Senders et al. (2009) and Chen et al. (2016) found that resistance calculated by the CPT-based approach fit the experimental data better than resistance calculated by the classical approach in eq. (1).

$$R_{tot} = A_{tip} \cdot q_c(h) \cdot k_p + (A_{s,o} + A_{s,i}) \cdot \int_0^h q_c(z)dz \cdot k_f$$

Empirical coefficients $k_p$ and $k_f$ relate the cone resistance to the skirt tip resistance and the friction along the skirt, respectively. A wide range of those parameters for sand are given by DNV (1992); however, many past studies on the penetration of skirted foundations have attempted to reduce this range (Lian et al. 2004; Lehance et al. 2005; Andersen et al. 2008).

To enable detailed design of the suction installation process, effects of seepage must be included. The applied suction $p$ and developed excess PP $u$ around the bucket skirt change the resistance of sand. However, the complexity of the stress state during suction installation makes it difficult to provide a
good estimate of those changes. According to Houlsby and Byrne (2005), the stress state used to calculate SPR should be changed due to the hydraulic gradient $i$ that develops in the surrounding soil. They assumed that a linear distribution of excess PP on the inside and outside of the skirt with depth. Therefore, the applied pressure and the development of excess PP at the tip provide sufficient information to estimate the stress level for each penetration depth. The PP factor $\alpha$ is the ratio of excess PP at the skirt tip to the applied suction. Based on numerical analyses, Houlsby and Byrne (2005) proposed a solution for the PP factor when the hydraulic conductivity $k$ is uniform (eq. (3)) and the hydraulic conductivity of the inside plug is increased (eq. (4)). The ratio between the inside and outside hydraulic conductivity values, $k_{in}$ and $k_{out}$, respectively, is termed $k_{ratio}$.

\[
\begin{align*}
\text{(3)} \quad \alpha &= 0.45 - 0.36 \cdot \left(1 - \exp\left(-\frac{h}{0.48 \cdot D}\right)\right) \quad \text{for uniform } k; \\
\text{(4)} \quad \alpha &= \frac{\alpha_1 \cdot k_{ratio}}{(1 - \alpha) + \alpha \cdot k_{ratio}} \quad \text{for increased } k_{in}. 
\end{align*}
\]

The reduced soil resistance is calculated by replacing the effective soil unit weight $\gamma'$ with its reduced or increased value for the upward gradient on the inside skirt and for the downward gradient on the outside skirt, respectively $\left(\gamma' - \frac{(1 - \alpha) \cdot P}{h}, \gamma' + \frac{\alpha \cdot P}{h}\right)$. Comparison of the calculated resistance with the installation cases showed a good fit. However, certain variations of the key soil parameters were required to obtain a good fit.
Koteras et al. (2016) proposed another formulation that gives the best fit to the results of numerical analysis performed in PLAXIS 2D. Eq. (5) was found for the installation in sand of uniform hydraulic conductivity.

\[ \alpha = \frac{0.21}{b + 0.44} \]

**Critical pressure for suction installation**

The design method for suction installation should consider limiting conditions, including the critical pressure \( p_{\text{crit}} \) that can be applied under the bucket lid during installation. As the hydraulic gradient develops inside the surrounding soil, the sand on the upward flow side loosens. The decrease in soil density can cause complete loosening of soil around the skirt, breaking the seal between the bucket skirt and soil. In this case, known as “piping,” the installation process cannot proceed due to loss of the seal. The hydraulic gradient when the effective soil stress drops to zero is called the critical gradient, \( i_{\text{crit}} \).

\[ i_{\text{crit}} = \frac{\gamma}{\gamma_w} \]

The critical gradient is initially achieved around the skirt tip. As the localized pipes are constrained with surrounding soil, the critical gradient proceeds upward along the skirt, until it reaches the inner soil surface. The hydraulic gradient that controls piping is the exit gradient at the inner soil surface adjacent to the skirt (Senders and Randolph 2009). Critical pressure studies are normally performed with numerical simulations.

Erbrich and Tjelta (1999) proposed a solution for the critical suction number \( S_N \), reflecting the applied suction that causes the critical hydraulic gradient as a function of penetration ratio \( \left( \frac{h}{D} \right) \), where \( h \) is penetration depth, and \( D \) is the foundation diameter. The solution is based on numerically performed
steady-state flow calculations. More recent studies relate the critical suction to a value of normalized
seepage length at the exit, \( \frac{s}{h} \)\(_{\text{exit}} \). The seepage length at the exit is calculated based on the definition
of hydraulic gradient that is equal to the change in hydraulic head \( \Delta H \) divided by the exit seepage length
\( s \). The value of exit hydraulic gradient, \( i_{\text{exit}} \), can be determined from numerical simulation. The change
in hydraulic head is equal to the applied suction divided by the water unit weight, and the exit seepage
length is calculated from eq. (6).

\[
(6) \quad s = \frac{\Delta H}{i_{\text{exit}}} = \frac{p}{i_{\text{exit}} \cdot \gamma_w}
\]

Senders and Randolph (2009) performed numerical simulations of suction bucket installation in PLAXIS.
To obtain normalized seepage length as a function of penetration ratio, PLAXIS results were analyzed
with results by Erbrich and Tjelta (1999) and theoretical values for a sheet-pile wall (eq. (7)). Critical
pressure for piping was calculated by combining equations for the critical gradient and seepage length
(eq. (8)).

\[
(7) \quad \left(\frac{s}{h}\right)_{\text{exit}} = \pi - \tan \left(5 \cdot \left(\frac{h}{D}\right)^{0.85}\right) \cdot \left(2 - \frac{s}{\pi}\right)
\]

\[
(8) \quad \frac{p_{\text{crit}}}{\gamma \cdot D} = \left(\frac{h}{D}\right) \cdot \left(\frac{s}{h}\right)
\]

Two assumptions were made: i) the inner friction along the skirt and the resistance at the skirt tip
decrease linearly from their maximum values (no applied suction) to zero (critical suction); and ii) the
outside friction along the skirt is unaffected (Senders and Randolph 2009). Reduced soil resistance is calculated with eq. (9), which is valid for $p \leq p_{crit}$.

$$R_{\text{reduced}} = (Q_{\text{tip}} + F_{\text{inner}}) \cdot \left(1 - \frac{p}{p_{\text{crit}}}\right) + F_{\text{outer}}$$

The proposed method gives a good fit with results of suction installation tests performed in a centrifuge. However, compared to field tests of installation, the critical suction is exceeded with no failure occurrence.

Ibsen and Thilsted (2010) presented a similar solution for normalized seepage length based on simulations performed in FLAC (eq. (10)).

$$\left(\frac{s}{h}\right)_{\text{exit}} = 2.86 - \arctan\left[4.1 \cdot \left(\frac{h}{D}\right)^{0.74}\right] \cdot \left(2 - \frac{1.8}{\pi}\right)$$

Koteras et al. (2016) conducted a similar study in PLAXIS 2D and obtained eq. (11) for the normalized seepage length of the exit hydraulic gradient. The CPT-based method was used to calculate soil resistance during the installation. However, changes in outside and inside friction on the skirt and the change in skirt tip resistance were based on normalized seepage lengths obtained for hydraulic gradients calculated on the inside skirt, outside skirt, and around the skirt tip, respectively. A comparison with laboratory or field tests has not yet been made.

$$\left(\frac{s}{h}\right)_{\text{exit}} = \pi - \arctan\left[3.6 \cdot \left(\frac{h}{D}\right)^{0.74}\right] \cdot \left(2 - \frac{1.8}{\pi}\right)$$
Lian et al. (2014) and Chen et al. (2016) conducted laboratory tests of suction installation of bucket foundations in sand, using medium-scale (diameter: 0.5 m, skirt length: 0.5 m) and large-scale (diameter: 1.5 m, skirt length: 0.5 m) bucket models, respectively. Models were equipped with soil pressure gauges to record soil resistance inside and outside of the skirt. In both cases, suction measured during installation exceeded the critical value reported by Senders and Randolph (2009). Lian et al. (2014) proposed reduction coefficients for the inside friction on the skirt and for tip resistance (outside skirt friction was unaffected). When suction fell below the critical value, the reduction was linear between the maximum soil resistance and zero. When critical suction was exceeded without failure, the range for applied pressure increased by a factor of 1.5. For suction between $p_{crit}$ and $1.5p_{crit}$, there was no resistance from the outside skirt or from the tip. Chen et al. (2016) concluded that the change in resistance was not linear and was different between the inner skirt friction and the tip resistance (outside skirt friction was not affected). They reported reduction ratios $\beta_I$ (eq. (12)) and $\beta_{tip}$ (eq. (13)), and proposed calculating the SPR as shown in eq. (14).

\begin{equation}
\beta_I = 0.865 \cdot \left(\frac{p}{p_{crit}}\right)^{1.03}
\end{equation}

\begin{equation}
\beta_{tip} = 0.707 \cdot \left(\frac{p}{p_{crit}}\right)^{1.86}
\end{equation}

\begin{equation}
R_{\text{reduced}} = Q_{\text{tip}}(1 - \beta_{\text{tip}}) + F_{\text{inner}}(1 - \beta_I) + F_{\text{outer}}
\end{equation}
In summary, either the bearing capacity- or CPT-based approach can be used to calculate SPR during bucket foundation installation, but the calculation must account for effects of suction-induced seepage. The above-mentioned methods lack accuracy, as they assume linear changes of soil resistance with penetration depth. Only Chen et al. (2016) proposed that those changes are nonlinear. To analyze changes in soil stress during suction installation, medium- or large-scale tests are required to investigate the interaction between the soil and bucket skirt. As the development of excess PP around the bucket skirt plays a key role in the suction installation process, it is important to record excess PP during tests. The present study focuses on these aspects.

**Loosening of soil plug**

In suction installation, seepage induced within the soil reduces the inside soil resistance. This reduction in soil resistance might alter the soil hydraulic conductivity inside the bucket. Houlsby and Byrne (2005) obtained reasonable fits of calculated SPR with field tests when applying $\alpha$ for increased $k_{in}$. Comparing the reduction in soil resistance with centrifuge results presented by Tran and Randolph (2008), a much better fit was obtained with $k_{ratio} = 1.5$. Harireche et al. (2014) showed results of the numerical analysis for pressure gradient development inside the soil related to the change in soil resistance. Comparison with centrifuge test results presented by Tran and Randolph (2008) showed that $k_{ratio}$ should be $> 1$ and should increase with increasing penetration depth. Further investigation is needed to understand how the change in soil hydraulic conductivity inside the bucket should be included in the design calculation.
The test procedure presented in this paper includes CPTs performed before and after installation of the bucket foundation. Tested positions are both inside and outside the bucket, to capture changes in relative soil density due to suction installation and gradients in soil hydraulics as they appear. Then, possible changes in soil hydraulic conductivity can be assessed from the results of relative soil density.

**Lab Model and Test Procedure**

**Set-up and bucket foundation model**

The main aim of the lab tests reported herein is to analyze the soil-skirt interaction during installation of the bucket foundation model. The set-up is shown in Fig. 2. Vaitkunaite et al. (2014) first introduced this facility for testing the capacity of the bucket foundation in sand. After adjustments, the same set-up is used for testing installation of the bucket foundation by jacking and suction installation approaches.
The soil container (internal diameter: 2.5 m, height: 1.52 m) is equipped with a drainage system, consisting of pipes that are equally distributed over the bottom, a 300-mm layer of highly permeable gravel, a geotextile sheet for preventing downward movement of sand particles, and a 1.20-m layer of sand (Aalborg University Sand No. 1).

A medium-scale model of the bucket foundation is used (Fig. 3), corresponding to a prototype size in 1:10 scale. The internal diameter $D$ is 1 m, skirt length $d$ is 0.5 m, and skirt thickness $t$ is 3 mm. The self-weight of the model, including the connection flange to the loading system, is 201 kg. The bucket model is equipped with 4 valves on the lid, which are connected to the vacuum system during the suction procedure. Six PP transducers are attached to the inside and outside of the bucket skirt and under the
bucket lid, for continuous analysis of seepage flow around the skirt during installation. PP is measured through open-ended pipes attached to the skirt. Open ends are positioned at locations PP1-PP3 on the outside skirt, PP4-PP6 on the inside skirt, and under the bucket lid. A displacement transducer is attached to the top of the bucket model, to measure bucket displacement during tests. A beam with PP transducers is installed close to the edge of the soil container to measure PP at the boundary.

Fig. 3. Model of bucket foundation (dimensions in mm).

**Soil material**

The chosen soil material is Aalborg University Sand No. 1, which mainly contains quartz. The sand is graded; the largest grains are round, and the small grains are sharp-edged. Sand properties were measured directly by Ibsen and Brødker (1994) and are as follows: maximum void ratio $e_{\text{max}} = 0.854$, minimum void ratio $e_{\text{min}} = 0.549$, 50%-quantile $d_{50} = 0.14$ mm, uniformity coefficient $C_u = 1.78$, and specific grain density $d_s = 2.64$ g/cm$^3$. CPT results can be used to derive important soil parameters.
(Ibsen et al. 2009), including relative soil density $I_D$, triaxial friction angle $\varphi_{tr}$, triaxial dilation angle $\psi_{tr}$, in situ void ratio $e_{\text{insitu}}$ and effective soil unit weight $\gamma'$. Ranges of values from all performed tests are included in Table 1.

Falling head tests were used to assess soil hydraulic conductivity ($k$) for different relative densities of material (Sjelmo 2012). For dense sand of $\sim 90\%$ of relative soil density (average density for all tests in this paper), test results indicated $k \sim 7 \cdot 10^{-5}$ m/s.

**Test procedure**

Sand was saturated during the preparation procedure and the installation test through the drainage system. Before each test, sand was prepared to a dense, uniform condition. Relative density across tests ranged 88% to 91%. An upward hydraulic gradient of 0.9 was applied by controlling the gradient through valves and an ascension pipe connected to the bottom of the sand container. Next, sand was vibrated to the desired density as follows. A wooden template with evenly located holes was set on the sand container. Then, a rod vibrator was slowly pushed into the sand through every second hole of the template, followed by the remaining holes on the way back, with the vibrator being slowly pulled each time.

To capture changes in soil resistance, sand conditions were analyzed through the CPT before and immediately after each installation test. A laboratory CPT device developed at Aalborg University was used. The device has a 15-mm-diameter cone with a cone angle of 30° and was calibrated at the laboratory before use. CPTs were performed at 4 positions before bucket installation (2 inside, 2
outside) and 8 positions after bucket installation (4 inside, 4 outside); see Fig. 4. CPTs inside the bucket were performed through holes in valves on the bucket model. CPTs after bucket installation were performed within 5 min after the installation process was completed. Differences in relative soil density before and after installation indicated whether density changed due to the installation process.

Fig. 4. Positions used for CPTs performed before (a) and after (b) installation (dimensions in mm).

During jacking installation, a hydraulic piston was used to apply the required jacking force. A hydraulic motor worked as a displacement control with a displacement rate of ~ 0.13 mm/s. Valves on the bucket lid were open during installation; thus, no excess PP inside the bucket was expected.

The suction installation process was divided into two steps: self-weight installation and suction application. Self-weight installation was performed by switching the hydraulic motor to work as a force control and applying a force corresponding to the self-weight of the bucket model. The achieved penetration depth provided an appropriate hydraulic seal between the soil and the bucket skirt for further suction application (minimum 50 mm). Suction was applied through the vacuum system by
connecting the valves on the bucket lid with the vacuum pump. Pressure on the vacuum tank was manually increasing slightly until penetration occurred. Because the vacuum pump extracted water during installation, the water level had to be maintained by continuously refilling the water. Tilting of the bucket model was negligible. During installation, readings were recorded from the displacement, PP, and force transducers. All sensors were connected to signal transducer boxes, and recordings were transmitted through signal amplifiers (Spider8 and GC Plus) to the Catman program on the computer. Koteras (2017) described the model and test procedure in more detail.

An overview of all tests can be found in Table 2. In the suction installation tests (Tests 1-3), a constant force of 2 kN was applied along with the bucket self-weight of 2 kN, for a total self-weight of 4 kN. This force was added to the force from applied suction throughout the entire penetration depth. In the pure suction installation tests (Tests 4, 5, and 9), the self-weight was 2 kN. The hydraulic motor worked as a force-controlled motor. Different self-weight penetration depths were obtained and its effect on the results is assessed later on in this paper. In the jacking installation tests (Tests 7, 9, and 10), there were 2 values of maximum penetration (Table 2). The first value corresponded to the maximum force recorded when the bucket lid contacted the soil. As the sand continued to be pushed and the particles re-arranged to be more equally distributed under the bucket lid, the force increased significantly and penetration proceeded, resulting in the second maximum penetration value.
Development of Hydraulic Gradients

Numerical formulation of seepage flow

Seepage in sand was formulated with a numerical model. Seepage flow around the bucket skirt during installation was simulated in the commercial program PLAXIS 2D. An axisymmetric model was generated, in which the bucket skirt was simulated as a rigid line segment with an impermeable interface. The line segment had a length equal to the designed penetration depth \( h \) and was situated 0.5 m from the center axis (same distance as the radius \( r \) of the bucket model). The center axis, bottom and side boundaries were modelled as closed flow boundaries. Total dimensions of the model were the same as those of the sand container used in the lab set-up. A sketch of the mesh numerical model is shown in Fig. 5. Simulations were performed for a penetration ratio \( \left( \frac{h}{D} \right) \) between 0.1 and 0.5, with an interval of 0.02.

![Mesh numerical model with boundary conditions (dimensions in mm).](https://mc06.manuscriptcentral.com/cgi-pubs)
Although the installation process is continuous, it is presented here as a series of discrete steps, with equilibrium between the soil resistance and the driving force being assumed in each step. Seepage flow was calculated as steady-state groundwater flow because the seepage is approximately stationary.

Using the same approach, Tran and Randolph (2008) obtained good agreement of their numerical simulations with pressure results from centrifuge tests when installing the bucket foundation. Flow around the skirt was simulated by applying the flow boundary condition on the inner soil surface with an appropriate hydraulic head, \( H \). A hydraulic head on the outer soil surface of 2 m was used. This number can be arbitrary, but must be sufficient to initiate the suction installation process. The head difference was directly related to the value of the applied suction. Here, the same model assumptions were applied as were used in Koteras et al. (2016), except that the distances to the boundaries were different. Suction values for each step of the numerical simulations were based on mean values from lab tests 5 and 9. In these tests, the self-weight penetrations of the bucket were the shortest (and, hence, the skirt penetration distances due to suction were the longest) among all tests.

The soil hydraulic conductivity \( k \) is relevant for flow calculations. Sjelmo (2012) performed falling head tests for Aalborg University Sand No. 1 of different relative soil densities \( I_D \), reporting \( k = 0.7 \cdot 10^{-4} \) m/s for \( I_D = 90.8\% \) and \( k = 1 \cdot 10^{-4} \) m/s for \( I_D = 60.5\% \). These values are similar to the average \( I_D \) before suction installation (\(~90\%) and the inside \( I_D \) after suction installation (\(~60\%), respectively, in the present study and, therefore, were chosen to represent the lab test conditions for numerical analysis. A value of \( k = 1 \) m/s was used for gravel below the sand.
Test Results

Reduction in SPR

Results of CPTs were investigated and relative soil density was derived based on past CPT calibration (Ibsen et al. 2009). Fig. 6 compares relative soil density results for suction and jacking installations from CPTs performed before and immediately after installation, for soil inside and outside the bucket.

Fig. 6. Relative soil densities before and after installation for (a, b) Test 5 and (c) Test 6. See Fig. 4 for locations of CPTs.

Relative density of the soil plug significantly decreased with use of suction installation due to increased seepage, whereas changes in relative soil density on the outside of the bucket were insignificant. Jacking installation did not significantly change the relative soil density in the soil plug or in the soil outside the bucket. For all suction installation tests, the relative soil density showed a similar trend to Test 5. For all jacking installation tests, the CPT results were comparable to results of Test 6 (no change in relative soil density).
Table 3 presents the mean relative soil density values for each test before and after installation, for soil inside the soil plug and outside the bucket, and the percentage change between results before and after installation ($\Delta/\bar{D}_{\text{mean}}$). Calculations of mean values excluded the top 100 mm of sand because of fluctuations resulting from the presence of the sand surface. Relative soil density results obtained before installation were compared with the results of the two closest CPT locations (see Fig. 4). Mean values of the two comparisons inside and the two comparisons outside the bucket are also given in Table 3. There was a significant, nearly 30% decrease in relative soil density inside the soil plug after suction installation, but minimal changes in the soil inner plug after jacking installation ($<6\%$). For the outside soil, the changes were much less significant after suction or jacking installation. Only values from Tests 1 and 2 showed significant changes ($\sim15\%$); however, in both tests, only two locations (CPT1_o and CPT2_o) were analyzed (signals for locations CPT3_o and CPT4_o were not recorded). As only changes on one side of the bucket were investigated, these results are not very reliable.

A reduction in relative soil density is directly related to a reduction in SPR. As sand loosens, it shows less resistance to skirt penetration into the soil. This feature is beneficial for installation but might lead to failure or heave development. Reduced soil resistance was visible from the CPT tests and also from comparisons of the force required for jacking or suction installation. In the 4 jacking installation tests, results of applied force vs. penetration depth were similar. This finding was expected because the same soil conditions were achieved before each of those tests (Fig. 7a). The mean maximum force from all
jacking installation tests was 57 kN. The maximum value was the point where the displacement curve flattened, corresponding to the position where the bucket lid came in contact with the sand.

Next, the average force reduction for suction installation, $\Delta F_{avg}$, was calculated. Average force values from all 4 jacking installation tests were found for all recorded penetration depths, $F_{jacking, mean}$. These values were compared to the force used during each suction installation for each recorded penetration depth, $F_{suction}$.

$\Delta F_{avg}$ was determined as the mean change in force for all recorded penetration depths between 100 mm and the maximum penetration depth. For each suction installation test, force included components resulting from the suction and from the self-weight of the bucket. The difference in bucket self-weights between Tests 1-3 (4 kN) and all other tests (2 kN) allowed investigation of the influence of different lengths of self-weight penetration on the final results. For Tests 1, 2, and 3, the $\Delta F_{avg}$ values were 43%, 45%, and 46%, respectively. For Tests 4, 5, and 9 (pure suction tests), reduction levels were slightly higher ($\Delta F_{avg} = 57\%, 54\%, \text{ and } 50\%$, respectively). For these tests, suction was applied later, when self-weight penetration was longer, meaning that the reduction in force (and, thus, SPR) was induced on a shorter penetration length. As an example, the average reduction in force for Test 5 is shown in Fig. 7b.
**Fig. 7.** Results of jacking installation (a) and of suction (Test 5) vs. jacking installation (b).

Application of suction reduced the force on the entire penetration depth in each test by 40-60%.

Compared to the mean maximum force from all 4 jacking installation tests (57 kN), the maximum force required by suction installation (Table 2) was reduced 80-84%. The reduction in force can only be explained by the reduction of SPR. These results can be compared with past studies that identified the reduction factor for SPR by analyzing results of applied force. Allersma et al. (2003) found a reduction factor of 8 using centrifuge installation tests. Lian et al. (2004) found a reduction of 78-94% when comparing suction with jacking installation on a 1G set-up with a small-scale model. These results are comparable with the findings described above.

**Soil heave development**

Sand loosening is beneficial for installation because it reduces SPR, but it also causes the appearance of sand heave inside the bucket. Previous experimental studies in dense sand showed that soil heave...
development is highly probable during the suction installation process (Allersma et al. 2003; Tran et al. 2005). Heave development might be problematic for bucket performance as it can reduce the total stiffness of the foundation, therefore, should be considered during design. Table 4 shows the heave height during all tests. Suction installation resulted slightly larger heaves than did jacking installation.

Soil movement towards the bucket cavity during sand installation is dictated by volume expansion, which results from the change in void ratio (Table 4). An increase in void ratio inside the plug results in a larger void volume. With a constant volume of solid material, the increase in total volume results in increased heave development. Additionally, soil displaced by the bucket skirt is pushed inside or outside of the bucket. However, flow generated during suction installation pushes the soil inside according to the direction of flow. The heave height, \( r_{heave} \), as a percentage of the total skirt length ranged 8-11\% for suction installation and 7-8\% for jacking installation. Tran et al. (2005) found 6-8\% of the embedded length as the heave development for suction installation tests. Observing similar results, Allersma et al. (2003) found that the amount of soil heave depended on the wall thickness, giving an increase of 5-10\% of the embedded skirt length. The present paper did not test the influence of wall thickness on heave, although the results of heave development are comparable to those found in cited literature. The average amount of heave development for suction installation tests was \(~10\%\). The difference between jacking and suction installation is expected to be even more significant for full-scale tests.

**Skirt-soil interaction due to seepage**

Application of suction results in seepage flow around the bucket skirt. The total PP of water was recorded directly from lab tests. To determine the excess PP, hydrostatic pressure was subtracted from
the total water pressure value. To observe the variation of PP during jacking installation both PP recorded \( p_{measured} \) and calculated excess PP \( u \) are shown in Fig. 8 (results of Test 6).

![Figure 8](https://example.com/figure8.png)

**Fig. 8.** Measured PP (a) and calculated excess PP (b) during jacking installation for Test 6.

As excess PP did not develop during jacking installation, seepage flow was not induced and, thus, there were no significant changes in SPR. For all jacking installation tests, a 1-kPa change was observed during the last stage of installation, which was related to the height of the open valves on the bucket lid. As the bucket lid came in the contact with water, the water column inside the valves raised to the valve height, resulting in observed excess PP change.

To observe the variation of PP during suction installation both PP recorded \( p_{measured} \) and calculated excess PP \( u \) are shown in Fig. 9 (results of Test 5).
Fig. 9. Measured PP (a) and calculated excess PP (b) during suction installation for Test 5.

PP6 corresponds to the suction pressure under the bucket lid (so $u_6$ is an exact value of applied pressure $p$). All other transducers showed a total pressure that included both hydrostatic pressure and excess PP. There was a significant amount of excess PP on the inside of the skirt (PP4 and PP5). The measured pressure was already negative, even though the hydrostatic pressure had not yet been deducted (Fig. 9a). On the outside skirt, the excess PP was much smaller (PP1-PP2) and approached zero after the hydrostatic value was subtracted from the measured pressure. Hydrostatic pressure depends directly on the depth under the water table; thus, the highest value was reached in location PP3, followed by PP2, and the lowest value was at PP1. Excess PP was highest at location PP3, followed by PP2, and was nearly absent at PP1. As the excess PP was negative pressure, the highest total water pressure was obtained at PP2, followed by PP1; the total water pressure was nearly zero at PP3. Approaching the skirt tip from the outside soil surface and the inside plug of the bucket, there was an increase in
generated excess PP. The excess PP results showed that there was an upward flow on the inside bucket wall, and that SPR was reduced due to the reduction in effective stress. Downward flow on the outside skirt was limited to locations close to the skirt tip, as there was almost no excess PP at PP1. Seepage flow was limited; thus, the changes in excess PP at the outside skirt were less significant than changes at the inside skirt. These findings suggest that it is reasonable to assume a constant SPR on the outside skirt and a reduction in the inside soil plug. Interestingly, during all installation processes, the applied suction exceeded the theoretical value of critical suction given by Koteras et al. (2016) (see eqs. (8) and (11)), but no piping failure occurred. Exceedance of critical suction pressure is shown in Fig. 9b. It is assumed that piping forms around the skirt tip and proceeds above the inside soil surface. When piping reaches the soil surface, the hydraulic seal between the soil and skirt breaks, failure occurs, and no further installation is possible. In this study, no lab test failed. A discussion of the exceedance of critical pressure is presented later in the paper.

Next, the force required for suction installation was normalized to the average jacking force, $F_{\text{jacking, mean}}$. This normalized force was compared to the applied suction (normalized to the critical theoretical value of suction; eqs. (8) and (11)) and the penetration ratio for Tests 1 and 2. As shown in Fig. 10, the reduction in the force required for suction installation (and, thus, in SPR) depended on the amount of applied suction. Soil resistance was reduced due to the seepage flow induced by the applied suction under the bucket lid. The reduction in soil resistance increased in proportion to the amount of applied pressure.
Fig. 10. Required installation force ratio between suction and jacking installations. Solid line refers right y-axis; dotted line refers to left y-axis.

When the normalized pressure was 1 or more, the normalized suction installation force dropped more significantly. This drop occurred at a penetration ratio of around 0.25-0.3. Suction was kept more constant for the rest of the penetration, while the normalized suction installation force continued to decrease. This finding suggests that suction was kept close to the critical level; however, the critical value was not exceeded, as none of the suction installation tests failed. A reduction factor $> 1$ at the beginning of the installation should be ignored because the suction force included both the force arising from applied suction and the self-weight of the bucket.

Finally, the exit hydraulic gradient during suction installation was calculated from the excess PP results, based on results of suction applied at PP6 and excess PP at PP5 (closest location on the inside skirt).
The change in excess PP between PP5 and PP6 was divided by the distance between those points (165 mm), which was divided by $\gamma_w$. Fig. 11 presents results of the calculated exit gradient for all suction installation tests (a) and the normalized critical pressure calculated from these exit gradient results (b). Critical pressure was calculated, as explained before, by multiplying exit seepage length (eq. (6)) by the effective soil unit weight.

**Fig. 11.** Exit hydraulic gradients for suction installation tests (a) and normalized critical suction pressure based on those gradients numerical solution (eq. (11))(b).

The results in Fig. 11 explain why there was no piping during suction installation, even though the theoretical critical suction was exceeded. The values of the exit hydraulic gradient (less than or equal to ~0.5) were much less than the critical gradient (~1.0). The critical pressure allowance based on exit critical gradients from experimental data was clearly larger than the limit suggested by numerical
calculations. The normalized critical suction pressure calculated from experimental data was at least twice as large as the normalized numerical critical pressure.

**Boundary effects**

The accuracy of scaled lab tests often depends on the boundary conditions of the set up. The seabed is unlimited, whereas the set-up boundaries were situated near the testing area. During each installation test, a beam with PP transducers was inserted into soil at the closest possible distance to the wall of soil container (see Fig. 2). Positions of PP transducers on the beam are indicated in Fig. 12a. Transducers were zeroed before the start of each test, such that direct measurements indicated the excess PP values. Fig. 12b shows the development of excess PP on the beam during Test 5 (suction installation). The excess PP is plotted versus the penetration depth of the bucket. Significant development of negative PP was observed, which increased as the installation progressed. The same trend was observed with all suction installation tests, whereas PP changes at the boundary were negligible for jacking installation tests.
Fig. 12. Beam with PP transducer (a) and results of excess PP at beam during suction installation (b).

Seepage flow at the boundaries might influence seepage flow around the bucket skirt. The numerical model should have the same boundary conditions as the lab model, so that the comparison can be reasonable. The change in the model might therefore influence the normalized exit seepage from simulations and thus, theoretical critical suction

**Comparison of Excess PP and Applied Suction Results**

Next, the numerical model was adjusted to simulate the lab conditions. The numerical model included appropriate boundary conditions and increased hydraulic conductivity for the inner plug. Results of numerical simulations were compared to mean values of excess PP from Tests 5 and 9. Numerical simulations of suction installation tests provided results of total PP experienced by the soil. Excess PP values were calculated by subtracting the hydrostatic pressure from total PP. Fig. 13 presents the
development of excess PP due to the applied suction from both lab tests and numerical simulations, with excess PP results normalized by \((\gamma' \cdot D)\).

![Graph showing normalized excess PP](image)

**Fig. 13.** Comparison between numerical and lab results of PP change at skirt; Test 5 (a) and Test 9(b).

Results of excess PP from medium-scale tests and numerical simulations were comparable, which confirmed that the numerical models can reasonably simulate installation data. The trend for the development of excess PP (and, thus, seepage flow) around the skirt was the same for both numerical and lab results (accuracy of pressure transducers used in lab tests was ±0.2 kPa). Results were the most diverse at the skirt tip, where the difference in excess PP between the numerical model and lab tests was \(~ 1\) kPa. Excess PP values measured during the lab tests were higher than values calculated numerically. Numerical simulations assumed a steady flow condition. Suction installation of a bucket
foundation is generally assumed to be stationary, but seepage flow around the bucket tip does not have
time to develop fully because the tip is constantly penetrating into the soil. Therefore, the flow behavior
around the tip might be unsteady, which can explain why the numerical results of excess PP differed
from measured results at the tip.

A new formulation for PP factor (ratio of excess PP at the skirt tip to the applied suction) was derived
based on data extracted from numerical simulations by curve fitting (eq. (15)).

\[ \alpha = 0.47 - 0.25 \left( 1 - e^{-\left( -\frac{h}{D \cdot 0.32} \right)} \right) \]

As the boundary conditions and hydraulic conductivity for the inner plug \( \frac{k_{\text{out}}}{k_{\text{in}}} \approx 1.4 \) were different,
this new formulation differed slightly from the one given in Koteras et al. (2016), resulting in greater
excess PP at the skirt tip, a difference that increased with increasing penetration depth. Fig. 14 presents
the new formulation of the PP factor as a function of penetration ratio \( \frac{h}{D} \), compared to the previous
expression from Koteras et al. (2016), together with experimentally measured values from all suction
installation tests.
Fig. 14. Comparison between numerical and lab tests of pressure factor at the tip.

The numerical expression underestimated excess PP measured around the tip. Interestingly, the trend for the PP factor is different from the trends in the literature. All studies presented in the Background section assumed a constant increase in excess PP with penetration; in contrast, the lab results here clearly stabilized to a constant value at around $\frac{h}{D} = 0.3$. However, as the data here were limited to $\frac{h}{D} < 0.5$, this trend should be investigated for higher penetration ratios. The change in bucket self-weight did not affect the PP factor, with results of tests using a self-weight of 4 kN or 2 kN being comparable.

Although the critical suction limits given in the previous literature were exceeded in the lab tests, piping failure was not observed. The critical condition for stationary flow arises when the critical gradient is developed ($i = i_{crit} = \gamma'/\gamma_w$). It is important to consider $\gamma'$, as a higher value will allow for more suction before the critical gradient is reached. Nevertheless, CPT results indicated that the sand loosened...
during installation, leading to a small drop in effective soil unit weight. However, plug loosening changes
the void ratio and, thus, the hydraulic conductivity of soil. Seepage flow becomes less limited, and the
hydraulic gradient drops due to the loss in hydraulic head $\Delta H$.

A new formulation for critical suction pressure was derived based on the numerical results, using
appropriate boundary conditions and increased plug hydraulic conductivity. The value of the exit flow
velocity $v_{exit}$ was determined from the model results. Using Darcy’s law, the gradient was calculated as
the ratio between the flow velocity and hydraulic conductivity. The critical pressure for the exit
hydraulic gradient was calculated. The expression for normalized critical pressure was derived by curve
fitting (eq. (16)). Fig. 15 presents results of the numerical simulations with eq. (16) and eq. (17) (using
$k_{ratio} = 1.4$). Houlsby and Byrne (2005) developed eq. (17) as a solution for critical suction pressure,
accounting for the increase in inner plug hydraulic conductivity ($\alpha$ in eq. (4)).

$$\frac{p_{crit}}{\gamma' D} = 1.32 \left( \frac{h}{D} \right)^{0.44}$$

$$\frac{p_{crit}}{\gamma' D} = \left( \frac{h}{D} \right) \left( 1 + \frac{\alpha \cdot k_{ratio}}{1 - \alpha} \right)$$
As shown in Fig. 15, the new formulation fit the lab data better, as the critical pressure was not exceeded for any suction installation test. Hydraulic conductivity increased inside the soil plug and, therefore, more suction could be applied without piping. The same trend could very likely be applied in full-scale tests, although this possibility requires confirmation. Eq. (17) by Houlsby and Byrne (2005) did not give a good approximation for critical suction, even with $k_{ratio} = 1.4$, as the theoretical critical pressure was significantly exceeded by lab data. The ratio of 1.4 is similar to the average $k_{in}/k_{out}$ ratio of 1.5 (range: 1–2) reported by Tran et al. (2005), who used centrifuge tests during bucket foundation installation and showed that relative soil density drops and sand loosens with increasing penetration.
Finally, calculation of the exit hydraulic gradient from the lab tests (Fig. 11) indicated that the normalized critical pressure can be approximately 2 times larger than the limit given by numerical simulations and can be larger than the limit given by the new numerical expression (eq. (16)). These results must be confirmed by additional tests with longer penetration depths and by full-scale models. Nevertheless, such an increase in the critical suction limit would allow for the installation of large-diameter bucket foundations, which would markedly reduce costs for offshore foundations.

Conclusions

Soil-skirt interactions during suction and jacking installations of a bucket foundation were analyzed by performing 10 medium-scale tests in dense sand. Soil resistance was significantly lower during suction than during jacking installation; this reduced soil resistance was confirmed by measurements of soil conditions before and after each installation through CPTs. Calculated relative soil density was decreased for soil inside the plug, but soil changes outside the bucket were negligible. These results confirmed the proposed assumptions for the calculation of SPR during suction installation. Whereas the inside friction and tip resistance were reduced by the applied suction, the possible increase on the outside friction can be neglected.

Excess PP values measured around the bucket skirt during suction installation confirmed the appearance of seepage flow that generally reduced SPR. Analysis of gradient development during installation was helpful in the assessment of the redistribution of effective stresses and, thus, changes in SPR. Experimental and numerical results were comparable, thus validating the finite-element model and its assumptions. These findings allow for better understanding of the critical suction limits and
piping. Sand loosening within the inside plug results in an increase of hydraulic conductivity. Increased hydraulic conductivity increases this limit for pressure, which is beneficial for suction installation, allowing deeper penetration and the installation of larger buckets. Finally, soil heave developed in dense sand in all suction installation tests, with a heave height of ~ 10% of the total skirt length. The inside soil heave must be included in the design, as it can decrease the total stiffness of the foundation.

Acknowledgements

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References:


Harireche, O., Mehravar, M., and Alani, A. 2014. Soil condition and bounds to suction during the


19-33.

University, Aalborg.

Symposium on Frontiers in Offshore Geotechnics (ISFOG), Perth, Australia, pp. 421-426.

Ibsen, L. B., Hanson, M., Hjort, T., and Thaarup, M. 2009. MC-Parameter Calibration of Baskarp Sand
No. 15. DCE Technical Report, No. 62, Aalborg University, Denmark.


Table 1. Range of values for soil parameters from CPTs for all installation tests.

<table>
<thead>
<tr>
<th>Soil parameters</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative soil density [%]</td>
<td>88 - 91</td>
</tr>
<tr>
<td>Triaxial friction angle [°]</td>
<td>54 - 55</td>
</tr>
<tr>
<td>Triaxial dilation angle [°]</td>
<td>20 - 21</td>
</tr>
<tr>
<td>In situ void ratio [-]</td>
<td>0.63 - 0.65</td>
</tr>
<tr>
<td>Effective soil unit weight [kN/m³]</td>
<td>9.7 - 9.9</td>
</tr>
</tbody>
</table>
Table 2. Overview of test campaign

<table>
<thead>
<tr>
<th>Test</th>
<th>Driving force for the installation</th>
<th>Maximum installation force, $F_{\text{max}}$ [kN]</th>
<th>Required suction for $h = 450\text{mm}$, $p_{\text{req}}$ [kPa]</th>
<th>Self-weight penetration, $h_{\text{self-weight}}$ [mm]</th>
<th>Maximum penetration, $h_{\text{max}}$ [mm]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Suction + Force</td>
<td>11.6</td>
<td>9.18</td>
<td>125</td>
<td>462 / 470</td>
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<tr>
<td>2</td>
<td>Suction + Force</td>
<td>11.6</td>
<td>9.21</td>
<td>127</td>
<td>468 / 468</td>
</tr>
<tr>
<td>3</td>
<td>Suction + Force</td>
<td>11.1</td>
<td>8.23</td>
<td>130</td>
<td>468 / 471</td>
</tr>
<tr>
<td>4</td>
<td>Suction</td>
<td>8.9</td>
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<td>78</td>
<td>460 / 474</td>
</tr>
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<td>5</td>
<td>Suction</td>
<td>9.0</td>
<td>8.67</td>
<td>73</td>
<td>462 / 466</td>
</tr>
<tr>
<td>6</td>
<td>Force</td>
<td>57.7</td>
<td>-</td>
<td>-</td>
<td>483 / 487</td>
</tr>
<tr>
<td>7</td>
<td>Force</td>
<td>59.1</td>
<td>-</td>
<td>-</td>
<td>483 / 488</td>
</tr>
<tr>
<td>8</td>
<td>Force</td>
<td>58.0</td>
<td>-</td>
<td>-</td>
<td>477 / 482</td>
</tr>
<tr>
<td>9</td>
<td>Suction</td>
<td>9.7</td>
<td>9.52</td>
<td>66</td>
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</tr>
<tr>
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<td>Force</td>
<td>53.1</td>
<td>-</td>
<td>-</td>
<td>472 / 479</td>
</tr>
</tbody>
</table>
## Table 3. Results of relative soil density, $I_D$, and effective soil unit weight, $\gamma'$

<table>
<thead>
<tr>
<th>Test</th>
<th>$I_{D,\text{mean}}$ [%]</th>
<th>$\gamma'_{\text{mean}}$ [kN/m$^3$]</th>
<th>Inside the bucket</th>
<th>Outside the bucket</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{D,\text{mean}}$ [%]</td>
<td>$\Delta I_{D,\text{mean}}$ [%]</td>
<td>$I_{D,\text{mean}}$ [%]</td>
<td>$\Delta I_{D,\text{mean}}$ [%]</td>
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<td>28.3</td>
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<td>91</td>
<td>9.9</td>
<td>66</td>
<td>27.7</td>
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<td>89</td>
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<td>64</td>
<td>27.8</td>
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<td>90</td>
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<td>86</td>
<td>4.4</td>
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</table>
Table 4. Change in void ratio and corresponding height of inside heave

<table>
<thead>
<tr>
<th>Test</th>
<th>Height of heave plug, $h_{\text{heave}}$ [mm] $(\pm 5)$</th>
<th>Void ratio before, $e_{\text{before}} [-]$</th>
<th>Void ratio after, $e_{\text{after}} [-]$</th>
<th>Ratio of heave height to the skirt length, $r_{\text{heave}}$ [%]</th>
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</thead>
<tbody>
<tr>
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<td>45</td>
<td>0.65</td>
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<td>9.0</td>
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<tr>
<td>2</td>
<td>47</td>
<td>0.63</td>
<td>0.84</td>
<td>9.4</td>
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<tr>
<td>3</td>
<td>44</td>
<td>0.65</td>
<td>0.86</td>
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<tr>
<td>4</td>
<td>42</td>
<td>0.63</td>
<td>0.84</td>
<td>8.4</td>
</tr>
<tr>
<td>5</td>
<td>49</td>
<td>0.63</td>
<td>0.84</td>
<td>9.8</td>
</tr>
<tr>
<td>6</td>
<td>38</td>
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<td>8</td>
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<td>0.630</td>
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<td>10</td>
<td>36</td>
<td>0.637</td>
<td>0.671</td>
<td>7.2</td>
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</tbody>
</table>
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