Suction caisson foundations for offshore wind energy: cyclic response in sand and sand over clay

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ABSTRACT

This technical note considers experimental data on the long-term response of a suction caisson in sand and sand over clay to lateral cyclic loading. Installation of the caisson under suction in a geotechnical centrifuge provides insight into the contribution of this installation process, as well as the effects that soil drainage and consolidation in the clay layer have on the accumulated caisson rotation and change in stiffness. The tests focused on sand over clay, and considered variations in the cyclic load magnitude and symmetry. One-way cyclic loading in sand over clay is seen to result in higher rotation than two-way loading, which contrasts with findings from previous studies in sand. Excess pore pressure dissipation in the clay layer leads to strength increases that stabilise caisson rotation and increase stiffness. The rate of accumulation in caisson rotation is observed to be the same from centrifuge and single gravity tests, while the initial rotation differs with stress level, drainage regime, loading magnitude, soil profile and installation method. The centrifuge tests are considered collectively with equivalent single gravity tests to form a basis for predicting the long-term response of a monopod suction caisson.

KEY WORDS: centrifuge modelling; offshore engineering; soil/structure interaction; deformation; stiffness
**NOTATION**

- \(c_v\): vertical coefficient of consolidation
- \(D\): caisson diameter
- \(D_r\): relative density
- \(e\): eccentricity of lateral load
- \(H\): lateral load
- \(H_{sand}\): sand layer thickness
- \(k\): unloading stiffness
- \(k_1\): unloading stiffness in the first cycle
- \(k_N\): unloading stiffness in cycle number \(N\)
- \(L\): skirt length
- \(M\): overturning moment
- \(M_{min}\): minimum moment in a load cycle
- \(M_{max}\): maximum moment in a load cycle
- \(M_{ult}\): ultimate moment capacity
- \(N\): number of cycles
- \(s_u\): undrained shear strength
- \(t\): skirt thickness
- \(T\): dimensionless time
- \(\alpha\): dimensionless variable
- \(\beta\): dimensionless variable
- \(\nu_w\): viscosity of water
- \(\nu_c\): viscosity of cellulose ether fluid
- \(\zeta_b\): parameter describing cyclic loading magnitude
- \(\zeta_c\): parameter describing cyclic loading symmetry
- \(\theta\): caisson rotation
- \(\theta_0\): maximum rotation during preloading to \(M_{max}\)
- \(\theta_N\): maximum rotation in cycle number \(N\)
- \(\Delta \theta(N)\): accumulated rotation during cyclic loading
- \(\Delta u\): change in excess pore pressure
- \(\Delta u_{i}\): maximum excess pore pressure
- \(\sigma'\): soil self-weight vertical effective stresses at the skirt tip
INTRODUCTION

Monopod suction caisson foundations for offshore wind turbines are subjected to long-term metocean cyclic loading acting laterally on the superstructure. Owing to the sensitivity of turbines to non-verticality and dynamics (Bhattacharya, 2014), the evolution of foundation rotation and foundation-soil stiffness over the design life needs to be understood. Investigations of long-term cyclic loading of suction caissons predominantly focused on sand (e.g. Zhu et al., 2013; Foglia et al., 2014; Cox et al., 2014). Limited data are available for sand overlying clay (Zhu et al., 2018). However, dense sand over over-consolidated clay seabeds are prevalent in areas of wind farm development in the North Sea (De Ruiter and Fox, 1975; Bond et al., 1997; BGS, 2002). Zhu et al. (2018) provide the only publicly available database to date of caisson response under lateral cyclic loading in sand over clay. These tests were performed over approximately \( N = 10^6 \) load cycles and were complemented with single layer sand and single layer clay experiments. The capacity and rotation response was shown to approach that measured in the sand when the sand-clay interface is located at or beneath the caisson skirt tip, while they differ when the sand layer thickness is approximately half the skirt length \( (H_{\text{sand}} = 0.5L) \). These experiments were performed as scaled model tests at single gravity, were the caisson was installed by jacking as in most experiments, showing trends of rotation accumulation that were consistent across the database and with published research on this topic. Therefore, this note considers centrifuge tests that deal with the remaining knowledge gaps associated with the effects of soil self-weight stresses, suction installation and drainage conditions. Considered collectively with the findings from single gravity tests over one million cycles (Zhu et al., 2018) and confirming the trend of rotation accumulation, a simple calculation method is proposed for predicting suction caisson response to long-term lateral cyclic loading in this database.

CENTRIFUGE MODELLING

The experimental details are described in Zhu (2018) and Bienen et al. (2017), with only brief descriptions provided here.

The centrifuge testing campaign was designed to specifically explore the effects soil self-weight stresses, suction installation and drainage conditions to complement the long-term cyclic loading tests performed at single gravity (Zhu et al., 2018). These had identified the soil profile of dense sand with a thickness of approximately half a caisson skirt length \( (H_{\text{sand}} = 0.5L) \)
over over-consolidated clay to differ from stratigraphies with larger sand layer depth. As in Zhu et al. (2018), the caisson aspect ratio of skirt length over diameter in the centrifuge tests was \( L/D = 0.5 \), which is realistic and has been adopted in other suction caisson research (e.g. Zhu et al., 2013). The model caisson (Figure 1) diameter was \( D = 80 \text{ mm} \), noting that the intention was to examine fundamental behaviour, rather than to model a particular caisson dimension. The load eccentricity \( M/HD = 3.5 \) is also within the range realistic for field conditions (e.g. Cox et al. 2014) and has been chosen to correspond to the value in the single gravity tests of Zhu et al. (2018).

The centrifuge tests were conducted in a beam centrifuge at an acceleration of 100g. This resulted in soil self-weight vertical effective stresses at the skirt tip of \( \sigma'_v = \gamma' L = 40 \text{ kPa} \) in the centrifuge tests (in sand), compared to \( \sigma'_v = 0.8 \text{ kPa} \) in the corresponding single gravity model scale tests (Zhu et al., 2018). The caisson was installed at the testing acceleration, initially under vertical load control to an applied load of 200 N \( (V = 2 \text{ MN in prototype scale}) \) and then by suction using a syringe pump (with recorded installation data in Zhu, 2018). The caisson self-weight was then increased to 350 N \( (V = 3.5 \text{ MN}, \text{ modelling the increase in weight due to the wind turbine installation}) \) before applying either a monotonic or cyclic lateral load, \( H \), at a height \( 3.5D \) above the caisson lid invert (Figure 1). The magnitude of the corresponding dimensionless group is \( V/\gamma'D^3 = 0.68 \) (in sand; \( \gamma' = 10 \text{ kN/m}^3 \)), which is within the range employed in existing studies: \( V/\gamma'D^3 = 0.62 \) (Zhu et al., 2018), \( V/\gamma'D^3 = 0.57 \) (Zhu et al., 2013), \( V/\gamma'D^3 = 0.69 \) (Cox et al., 2014) and \( V/\gamma'D^3 = 0.86 \) (Foglia et al., 2014), and is within the \( V/\gamma'D^3 = 0.09 - 0.91 \) range suggested by Foglia and Ibsen (2016) for field scale suction caissons supporting offshore wind turbines.

The sand and clay properties are listed in Table 1. The clay layer was prepared by preconsolidating kaolin slurry to achieve an undrained shear strength, \( s_u \approx 80 \text{ kPa} \). Sand was then pluviated over the clay to a relative density, \( D_r = 83\% \), before saturating from the base of the sand layer. Both drained and partially drained behaviour in the sand was modelled by using water as the pore fluid in one sample and a high viscosity pore fluid (viscosity, \( \nu_c = 700 \text{ cSt} \)) in the remaining two samples. Figure 2 shows the CPT profiles.

RESULTS AND DISCUSSION
The experimental database comprised eight cyclic loading tests to investigate the following effects (Table 2):

- soil stress level in sand (Test 1-2 compared with testing at single gravity);
- drainage regime in sand (Tests 1-2 and 2-1);
- installation method in sand (Tests 2-1 and 2-3);
- sand over clay (Tests 2-3 and 3-3);
- cyclic load magnitude and symmetry in sand over clay (Tests 3-2 to 3-6).

The cyclic load magnitude and symmetry were described using the parameters $\zeta_b$ and $\zeta_c$ respectively (LeBlanc et al., 2010)

$$
\zeta_b = \frac{M_{\text{max}}}{M_{\text{ult}}}, \quad \zeta_c = \frac{M_{\text{min}}}{M_{\text{max}}}
$$

where $M_{\text{min}}$ and $M_{\text{max}}$ are the minimum and maximum moments in a load cycle, and $M_{\text{ult}}$ is the ultimate moment capacity obtained from the monotonic tests.

### Accumulated rotation

**Effects of installation method, stress level and drainage in sand**

The accumulation of rotation with cycle number is examined in Figure 3 for tests in sand with $\zeta_b = 0.4$ and $\zeta_c = 0.1$. Rotation data are expressed in normalised form, $\Delta \theta(N)/\theta_0 = (\theta_N - \theta_0)/\theta_0$ (LeBlanc et al. 2010), where $\theta_0$ and $\theta_N$ are the maximum rotation during first loading to $M_{\text{max}}$ and in cycle number $N$, respectively. The rotation response can be captured by a power law:

$$
\frac{\Delta \theta(N)}{\theta_0} = \beta \times N^\alpha
$$

where $\beta$ quantifies the initial rotation from $\theta_0$ to $\theta_1$ and $\alpha$ quantifies the rate of rotation accumulation with cycle number. The best fit (based on least-squares regression) with the tests on Figure 3 and other tests in this research was obtained using $\alpha = 0.29$, which is comparable with $\alpha = 0.31$ for monopiles (Abadie et al., 2015; LeBlanc et al., 2010), $\alpha = 0.30$ (Cox et al., 2014) and $\alpha = 0.28$ (Zhu et al., 2018) for suction caissons. Zhu et al. (2013) report a higher $\alpha = 0.39$ for suction caissons in loose dry silty sand, and suction caisson data in dense sand reported by Foglia et al. (2014) gave $\alpha = 0.18$. Values of $\theta_0$, $\beta$ and $\alpha$ from this study and previous work are summarised in Table 3. Although the rate of caisson rotation (captured by $\alpha$) is identical for all tests in this research, the initial rotation when loaded to $M_{\text{max}}(\theta_0)$ (which reflects the cyclic load magnitude and soil type), and the accumulated rotation after one cycle $\Delta \theta(1) = \theta_1 - \theta_0$ (captured by $\beta$) differs for each test. This directly affects the absolute
magnitude of accumulated rotation (Equation (2)), which is held to strict limits over the design life (e.g. 0.5°, DNV 2016). The different initial rotation that arises in sand and sand over clay is quantified in Table 3 for different soil self-weight stress levels (i.e. at 1g and Ng), different drainage responses and as a result of the more realistic suction assisted installation over jacked installation.

The effect of sand permeability and loading rate is emphasised in the centrifuge test data investigating drainage\(^1\), which indicate the accumulated rotation at \(N = 1\) (i.e. \(\Delta \theta (1) = \theta_0 \times \beta\)) to be higher (by a factor of approximately four for these tests) when the loading response is drained (in water) than partially drained (in high viscosity pore fluid), following jacked installation. Jacked installation appears to lead to lower rotation at \(N = 1\), which highlights the importance of understanding the effects of the installation process on the soil state. The additional information of initial rotation following jacked installation (Tests 1-1 and 2-1) allows accumulated rotation of suction caissons in sand to be predicted using previously published rates of accumulation (e.g. Cox et al., 2014) as the difference to suction assisted installation is now known.

Assessment of the long-term response to cyclic loading requires data over large numbers of cycles. The centrifuge tests are therefore considered collectively with the equivalent single gravity test data reported in Zhu et al. (2018) that involved up to one million loading cycles. A comparison in Figure 4a for jacked installation in sand (\(\zeta_b = 0.4, \zeta_c = 0.1\)) shows that the long-term rate of accumulation is almost identical: \(\alpha = 0.28\) in the single gravity tests and \(\alpha = 0.29\) in the centrifuge tests, although as expected from the preceding discussion, the magnitude of \(\Delta \theta (N)/\theta_0\) at \(N = 1\) is lower in the single gravity tests (\(\beta = 0.06\)) than in the centrifuge tests (\(\beta = 0.15\)). The same rate of accumulated rotation between single gravity and centrifuge tests is also shown to hold for sand over clay (\(\zeta_b = 0.4, \zeta_c = 0.1\), Figure 4b). These comparisons provide support to an approach of using single gravity tests to assess long-term behaviour, whilst employing centrifuge tests, involving fewer number of loading cycles, to quantify the response at relevant stress levels, including suction installation and pore pressure response.

\(^{1}\) Full dissipation of excess pore pressures was achieved in less than 30 s in the sand with high viscosity pore fluid (Sample 2) following the step change of lateral load at the end of the test. In the sand saturated with water (Sample 1), the dissipation period was too short to be measured, but should be approximately 700 times less than that in Sample 2 due to the difference in pore fluid viscosity.
Effect of underlying clay layer

Figure 5 compares $\Delta \theta(N)/\theta_0$ during cyclic loading with $\zeta_b = 0.4$ and $\zeta_c = 0.1$ in sand (Test 2-3) to that in sand over clay (Test 3-3) following suction installation. Also included on Figure 5 are fits to the data using Equation (2), with $\alpha = 0.29$. The response in the two tests appears broadly similar, although rotation accumulation is initially more rapid in the sand and the rotation eventually stabilises in the sand over clay at $N \approx 10^4$. This stabilisation is not observed in the sand, and although it may be argued that this is due to the lower number of cycles ($N = 16,377$), equivalent tests in Zhu et al. (2018) each with $N \sim 10^6$ show stabilisation in the sand over clay and continuing rotation in the sand. The rotation stabilisation is due to consolidation-induced strength increases in the clay layer, as considered in more detail later. Although the magnitude of $\Delta \theta(N)/\theta_0$ is similar in the sand and the sand over clay, the absolute rotation is slightly higher in the sand over clay profile considered here, as shown by the inset figure.

Effect of cyclic load magnitude and symmetry

Figure 6 allows for an examination of the effect of cyclic load symmetry ($\zeta_c = 0.5, 0.1$ and -0.7 at constant cyclic load magnitude, $\zeta_b = 0.4$, Figure 6a) and magnitude ($\zeta_b = 0.4, 0.55$ and 0.7 at a fixed one-way load symmetry, $\zeta_c = 0.1$, Figure 6b) on rotation accumulation in sand over clay. Figure 6a shows that the normalised accumulated rotation, $\Delta \theta(N)/\theta_0$, is similar for both one-way cyclic loading cases considered ($\zeta_c = 0.5$ and 0.1) and larger than that under two-way cyclic loading ($\zeta_c = -0.7$). The normalised rotation, $\Delta \theta(N)/\theta_0$, is similar and accumulates with cycle number at the same rate ($\alpha = 0.29$; the stabilised rotation observed in some of the tests was not included in the regression analysis to obtain $\alpha$ and $\beta$), but as shown by the inset figure, the absolute rotation, $\theta_N$, increases with $\zeta_b$. The increase is apparent by the first cycle indicating that the rotation simply increases with load magnitude during the initial loading to $M_{\text{max}}$. The above trends are consistent with the observations of Zhu et al. (2018) from single gravity tests in the same soil profile ($H_{\text{sand}}/L = 0.5$) where the caisson was installed by jacking and water was used as pore fluid.

The rotation in Test 3-3 (in sand over clay) stabilised at about $N = 10^4$. Similar behaviour is also apparent in Test 3-5, although the effect is not as prominent due to the lower number of cycles involved in this test ($N = 16,999$). As similar behaviour was not observed in the sand samples, this stabilising response must be due to strength changes in the clay layer. Supporting evidence is provided in Figure 7 which plots the pore-pressure response for Test 3-3 and Test...
3-5. Approximately 90% of the excess pore pressure (measured at the caisson lid invert) is dissipated by $N = 10^4$, which is approximately the same point at which the rotation stabilised. This consolidation will cause a strength increase in the clay, which will limit the rotation. Also shown on Figure 7 is the corresponding pore pressure response for Test 2-3 in sand (saturated with the high viscosity pore fluid), where the pore pressure, $\Delta u$, is normalised by the average maximum pore pressure, $\Delta u_{i}$, measured in the sand over clay tests. Accumulation of pore pressures during cyclic loading in sand is negligible compared with that in sand over clay.

Figure 6 and Figure 7 also include the dimensionless time $T = c_v t / D^2$ as secondary horizontal axes (where $t$ is the time since then the onset of cyclic loading and $c_v$ is the coefficient of consolidation of the clay, which will dominate the drainage response). The use of $T$ (applicable to the sand over clay results) permits assessment of consolidation for other caisson dimensions and soil properties. For example, caisson rotation stabilises in the sand over clay tests at $T \approx 0.7$, which for the prototype equivalent of the caisson and soils used in these centrifuge experiments, corresponds to a duration of approximately 6 years.

Application to field conditions

Applying Equation (2) to the prototype caisson geometry and soil properties considered in these tests would result in 0.3° of rotation for two-way loading ($\zeta_c = -0.7$) and 1.1° of rotation for one-way loading ($\zeta_c = 0.1$) for a load magnitude, $\zeta_b = 0.4$ and one million loading cycles. On the basis of this simple calculation, the one-way loading would exceed the DNV (2016) rotation limit of 0.5°, although this conservative estimate neglects the stabilising effect from consolidation in the clay. In contrast the same calculations for one-way loading scenario in sand would lead to a more moderate rotation of 0.3° (i.e. using $\beta = 0.45$ and $\theta_0 = 0.013°$).

Unloading stiffness

This section examines the effect of cyclic loading on unloading stiffness, $k$, determined from the maximum and minimum loads and rotations in cycle $N$ relative to that in the first cycle and expressed as $k_N/k_1$, as illustrated in Figure 8.

Stiffness in sand

The evolution of $k_N/k_1$ (Figure 9) in sand is similar over the initial ten cycles, and the test results most relevant to field conditions (with high viscosity pore fluid) exhibit a steady but
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285 moderate 20 - 50% increase in stiffness throughout. The stiffness ratio in the jacked test in
286 water saturated sand increases to \( k_N/k_1 = 1.6 \) before showing a drop, consistent with
287 observations from single gravity tests (Zhu et al., 2018). This drop is not evident following
288 suction installation.

289

Stiffness in sand over clay

290 In sand over clay (Figure 10a), tests involving one-way loading (\( \zeta_c \geq 0 \)) at relatively low load
291 magnitudes (\( \zeta_b = 0.4 \)) show a reduction in unloading stiffness that (partially) recovers over the
292 duration of the test. In contrast, the low load magnitude two-way cyclic loading test (\( \zeta_c = -0.7, \zeta_b = 0.4 \))
293 and the one-way cyclic loading test at a higher load magnitude (\( \zeta_c = 0.5, \zeta_b = 0.7 \))
294 show little change in stiffness but then start to increase, moderately at first, but more rapidly at
295 \( N \approx 5,000 \) in Test 3-5, which reaches \( k_N/k_1 \approx 2.75 \) after \( N \approx 10,000 \). The point at which the
296 stiffness starts to increase (\( N \approx 200 \)) appears to be consistent with when the pore pressure
297 measured at the lid invert starts to reduce (see Figure 7). The more rapid increase in stiffness
298 observed at \( N \approx 5,000 \) in Test 3-5 is coincident with when pore pressure dissipation is near
299 complete (Figure 7), which leads to stabilisation of the rotation and hence a rapid increase in
300 stiffness. Comparisons with equivalent single gravity tests (Figure 10b) show that the stiffness
301 increase is more moderate and steady in the long-term. The disparity may be due to soil self-
302 weight stress level effects and warrants further attention given the potential for stiffness
303 changes to affect system dynamics.

304

CONCLUSIONS

305 This note discusses the response of a suction caisson subjected to lateral cyclic loads on the
306 basis of collective consideration of single gravity and centrifuge test results. The centrifuge
307 tests model the correct soil self-weight stress levels, installation process and drainage response
308 but could only test in the order of \( 10^4 \) cycles. This note has shown that for the conditions within
309 this study these accurate post-installation centrifuge measurements can be combined with the
310 results from single gravity model tests on significantly more cycles to predict the long-term
311 serviceability response of a suction caisson under lateral cyclic loading, with the accumulation
312 of caisson rotation captured by a simple calculation approach. Application of this calculation
313 approach to field conditions showed that the long term rotation for one-way loading would be
314 higher for a sand over clay seabed than for a sand seabed. Evidently the validity of this finding
315 needs to be established beyond the parameter base considered in these model tests. Beneficial
effects from densification of sand and consolidation in the clay lead to stiffness increases – the
effect of these increases on the natural frequency of the offshore wind turbine needs to be
considered in design.

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REFERENCES

cyclic lateral loading in cohesionless soils. In Proceedings of the 3rd International
Symposium on Frontiers in Offshore Geotechnics (ISFOG) (Meyer, V. (ed)). Leiden,
assessment - SEA2 & SEA3 (TR_008), Nottingham, UK: BGS. See
/TRA_SEA3_Geology.pdf.
Engineering & Technology Reference. Stevenage, UK: Institution of Engineering and
Technology (IET).
installation and response under long-term cyclic loading. Proceedings of 8th Offshore
Site Investigation & Geotechnics International Conference (OSIG 2017), Kensington,
London, pp. 524-531.
the North Sea. Liverpool, UK: Health & Safety Executive, HSE Books.
Centrifuge study on the cyclic performance of caissons in sand. International Journal
of the 7th Annual Offshore Technology Conference (OTC). Houston, Texas, OCT 2246,
pp. 25-30.
Norway: DNV.


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Table 1: Engineering properties of silica sand (after Chow et al., 2015) and kaolin clay (after Stewart, 1992; Richardson et al., 2009).

<table>
<thead>
<tr>
<th></th>
<th>Silica sand</th>
<th>Kaolin clay</th>
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<tbody>
<tr>
<td>Specific gravity, $G_s$</td>
<td>2.65</td>
<td>2.6</td>
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<td>Mean particle size, $d_{50}$ (mm)</td>
<td>0.19</td>
<td>Liquid limit, LL (%)</td>
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<td>Minimum dry density, $\rho_{\text{min}}$ (kg/m$^3$)</td>
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<td>Plastic limit, PL (%)</td>
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<td>1774</td>
<td>Plastic index, $I_p$ (%)</td>
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<tr>
<td>Critical state friction angle, $\phi'_{cv}$ (º)</td>
<td>30</td>
<td>Critical state friction angle $\phi'_{cv}$ (º)</td>
</tr>
<tr>
<td>Coefficient of consolidation, $c_v$ (m$^2$/year) at $D_r = 83%$</td>
<td>16,000$^*$</td>
<td>Coefficient of consolidation, $c_v$ (m$^2$/year), estimated for stress level at skirt tip and $OCR = 20$</td>
</tr>
<tr>
<td></td>
<td>1.1×10$^7$†</td>
<td></td>
</tr>
</tbody>
</table>

* when saturated with 700 cSt cellulose ether pore fluid
† when saturated with 1 cSt water pore fluid
Table 2: Centrifuge test programme.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Soil sample</th>
<th>Soil type</th>
<th>Pore fluid</th>
<th>Installation</th>
<th>Loading type</th>
<th>$\zeta_b$</th>
<th>$\zeta_c$</th>
<th>Cycles $N$</th>
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<td>Monotonic</td>
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<td>-</td>
<td>-</td>
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<td>High viscosity pore fluid (700 cSt)</td>
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<td>High viscosity pore fluid (700 cSt)</td>
<td>Suction</td>
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<td>-</td>
<td>-</td>
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<td>Sand</td>
<td>High viscosity pore fluid (700 cSt)</td>
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<td>0.1</td>
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<td>Sand over clay ($H_{\text{sand}}/L = 0.5$)</td>
<td>High viscosity pore fluid in sand (700 cSt)</td>
<td>Suction</td>
<td>Monotonic</td>
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<td>High viscosity pore fluid in sand (700 cSt)</td>
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<td>Water in clay (1 cSt)</td>
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<td>Sand over clay ($H_{\text{sand}}/L = 0.5$)</td>
<td>Water in clay (1 cSt)</td>
<td>Suction</td>
<td>Cyclic</td>
<td>0.55</td>
<td>0.1</td>
<td>2,677</td>
</tr>
</tbody>
</table>
Table 3: Fitted $\alpha$ and $\beta$ from tests in sand and sand over clay ($H_{\text{sand}}/L = 0.5$).

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$N$</th>
<th>$\theta_0$</th>
<th>Soil type</th>
<th>Install.</th>
<th>Pore fluid in sand</th>
<th>$\zeta_b$</th>
<th>$\zeta_c$</th>
<th>Approach</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.53</td>
<td>$\sim 10^4$</td>
<td>*</td>
<td>Sand</td>
<td></td>
<td>Water</td>
<td>0.4</td>
<td>-0.05</td>
<td>1g</td>
<td>Foglia et al. (2014) †</td>
</tr>
<tr>
<td>0.39</td>
<td>0.10</td>
<td>10,325</td>
<td>*</td>
<td>Sand</td>
<td></td>
<td>Dry sand</td>
<td>0.37</td>
<td>0</td>
<td>1g</td>
<td>Zhu et al. (2013) †</td>
</tr>
<tr>
<td>0.30</td>
<td>0.10</td>
<td>71</td>
<td>*</td>
<td>Sand</td>
<td></td>
<td>Dry sand</td>
<td>0.4</td>
<td>0.02</td>
<td>Ng</td>
<td>Cox et al. (2014) †</td>
</tr>
<tr>
<td>0.28</td>
<td>0.15 ± 0.03</td>
<td>1,204,998</td>
<td>0.017°</td>
<td>Sand</td>
<td>Jacked</td>
<td>Water</td>
<td>0.4</td>
<td>0.1</td>
<td>1g</td>
<td>Zhu et al. (2018) †</td>
</tr>
<tr>
<td>0.29</td>
<td>0.06</td>
<td>5,222</td>
<td>0.013°</td>
<td>Sand</td>
<td></td>
<td>Water</td>
<td>0.4</td>
<td>0.1</td>
<td></td>
<td>This study, test 1-2</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>547</td>
<td>0.006°</td>
<td>Sand</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.4</td>
<td>0.1</td>
<td>This study, test 2-1</td>
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</tr>
<tr>
<td></td>
<td>0.45</td>
<td>16,377</td>
<td>0.013°</td>
<td>Sand</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.4</td>
<td>0.1</td>
<td>This study, test 2-3</td>
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<tr>
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<td>0.67</td>
<td>91,793</td>
<td>0.029°</td>
<td>Sand over clay</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.4</td>
<td>0.1</td>
<td>Ng</td>
<td>This study, test 3-3</td>
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<tr>
<td></td>
<td>0.62</td>
<td>4,543</td>
<td>0.035°</td>
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<td>Suction</td>
<td>High viscosity pore fluid</td>
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<td>0.5</td>
<td>This study, test 3-4</td>
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</tr>
<tr>
<td></td>
<td>0.17</td>
<td>16,999</td>
<td>0.032°</td>
<td>Sand over clay</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.4</td>
<td>-0.7</td>
<td>This study, test 3-5</td>
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</tr>
<tr>
<td></td>
<td>0.52</td>
<td>2,677</td>
<td>0.042°</td>
<td>Sand over clay</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.55</td>
<td>0.1</td>
<td>This study, test 3-6</td>
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</tr>
<tr>
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<td>0.29</td>
<td>2,369</td>
<td>0.286°</td>
<td>Sand over clay</td>
<td>Suction</td>
<td>High viscosity pore fluid</td>
<td>0.7</td>
<td>0.1</td>
<td>This study, test 3-1</td>
<td></td>
</tr>
</tbody>
</table>

* Not known.
† Only data for $\zeta_b \approx 0.4$ and $\zeta_c \approx 0.1$ are provided here. Parameters relevant to other values of $\zeta_b$ and $\zeta_c$ can be found in the original studies.
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391  Figure 1 Experimental arrangement: (a) schematics, and (b) photos.

392  Figure 2 CPT profiles.

393  Figure 3: Effect of installation method on caisson rotation in sand ($\zeta_b = 0.4$, $\zeta_c = 0.1$).

394  Figure 4: Accumulated caisson rotation for (a) jacked installation in fully drained sand and (b) sand over clay following jacked installation in single gravity test (Zhu et al., 2018) and suction installation in Test 3-3 of this centrifuge study ($\zeta_b = 0.4$, $\zeta_c = 0.1$).

395  Figure 5: Effect of an underlying clay layer on accumulation of caisson rotation during cyclic loading with $\zeta_b = 0.4$ and $\zeta_c = 0.1$.

396  Figure 6: Accumulated rotation with number of loading cycles for tests in sand over clay: (a) $\zeta_b = 0.4$ with $\zeta_c = 0.5$, 0.1 and -0.7, and (b) $\zeta_c = 0.1$ with $\zeta_b = 0.4$, 0.55 and 0.7.

397  Figure 7: Pore-pressure response during cyclic loading in sand over clay.

398  Figure 8: Definition of accumulated rotation and stiffness (after LeBlanc et al., 2010).

399  Figure 9: Evolution of unloading stiffness with number of loading cycles in sand ($\zeta_b = 0.4$, $\zeta_c = 0.1$) with different pore fluids and installation methods.

400  Figure 10: Evolution of unloading stiffness with number of loading cycles in sand over clay: (a) with different cyclic load magnitude and symmetry ($\zeta_b$ and $\zeta_c$), and (b) compared with long-term data reported in Zhu et al. (2018).