Monotonic response of a partially and fully Installed suction caisson.

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ABSTRACT: Over the past decade, suction caissons have gained popularity as a foundation for offshore wind turbines due to the speed of installation and because they avoid the potential for harmful acoustic emissions associated with driving of monopiles. After suction assisted penetration, underlid grouting is usually carried out to ensure contact between the caisson lid and the seabed. This underlid grout operation results in additional offshore time and costs. This paper explores the effect of underlid grouting on suction caisson response to drained compressive loading by comparing results from centrifuge model tests on partially (without grout) and fully installed caissons (with grout). The load-displacement of partially and fully installed buckets is shown to be similar at the early stages of loading, indicating that skirt resistance is identical for a partially installed and a fully installed caisson. The results in this paper are the catalyst for a more comprehensive investigation into the behaviour of partially installed caissons to monotonic loading under different drainage conditions.

1 INTRODUCTION

While monopiles continue to dominate as the preferred foundation option for offshore wind energy developments, a number of challenges prompt the need for alternative solutions. This is where suction caissons come into play as they are a potentially more economical and sustainable offshore foundation for offshore wind turbines (Lawson, 2013). Suction caisson foundations are suited to various soil types and avoid the acoustic emissions associated with pile driving, thereby causing no disturbance to marine life. Additionally, these offshore foundations are recyclable, allowing for retrieval at the end of their design life.

Suction caissons are cylindrical-like foundations that are open at one end and closed at the other. Installation of these foundations involves an initial self-weight installation stage followed by suction-assisted installation (Bienen *et al.*, 2018). In the first stage, the caisson is lowered into the seabed and allowed to settle under its own weight. It continues to settle until the soil resistance equals the caisson weight. Suction-assisted installation then begins by pumping water out of the caisson. This causes a differential pressure across the lid of the caisson leading to further penetration.

Suction caissons were first utilised for offshore oil and gas developments (Eide & Andersen, 1984; Andersen *et al.*, 2005), but are now used increasingly for offshore wind energy developments (OWA, 2019).

This take-up is partly because their installation avoids acoustic emissions and they can be retrieved from the seabed, but also because design methods for installation and capacity are mature and reliable.

Suction caisson capacity is derived from a combination of bearing resistance at the underside of the caisson lid, skirt friction, and bearing resistance at the skirt tips (Strum, 2017). Current design approaches (e.g. OWA, 2019) assume that to activate bearing resistance at the underside of the lid requires contact between the lid of the suction caisson and the seabed. However, it has been observed that achieving this contact during installation is often challenging due to various factors. These include undulation of the seabed, plug heave during installation, and subsequent settlements over time (Randolph & Gourvenec, 2011). Additionally, there are pumping limitations, as continuing to pump as the lid approaches the seabed may result in suction of soil into the pump, with the potential for pump malfunction (Rolstad, 2018; Sturm, 2017). Therefore, a deliberate gap is typically maintained between the seabed and the suction caisson lid during installation. To ensure the activation of the end bearing response, this gap is often filled and grouted using a low-strength cement-sand slurry. However, there is a lack of consensus on the effectiveness of grouting. Kay *et al*. (2021) suggest that it may not be feasible to verify that the gap is filled with grout. Additionally, the soil plug may settle after installation, which would potentially form a gap sometime after grouting, potentially causing the grout to separate from the soil (Offshore Wind Accelerator, 2023; Strum, 2017). Other more recent studies have questioned if grouting is even necessary (da Silva Pereira *et al*. 2023; Tapper *et al*. 2023).

In many cases, it is generally assumed that the resistance offered by the caisson skirts (in friction and bearing) is sufficient to resist the design load. Additionally, caisson capacity is influenced by the rate of loading as at faster rates the water-filled cavity may be able to support the load if drainage in the soil cannot occur quickly enough. Hence the requirement of grout becomes questionable (Cotter 2010; da Silva Pereira et al. 2023).

This paper addresses the question of whether partial installation affects the load-sharing response of suction buckets under slow loading rates.

2 METHODOLOGY

The experiments described in this paper were conducted at the National Geotechnical Centrifuge Facility located at the University of Western Australia using their 3.6 m diameter fixed beam centrifuge. This facility has been utilised in numerous previous physical modelling studies on suction caissons (e.g. Bienen et al. 2018a; Stapelfeldt et al. 2020, 2021; da Silva Pereira et al. 2023) and as such, existing equipment developed for suction caisson installation in a centrifuge environment was availed of for the tests reported here.

2.1 Sample preparation and soil properties

Sand samples were prepared by air pluviation in a sample container measuring 650 mm long, 390 mm wide and 325 mm deep. The silica sand has a mean grain size of 0.18 mm, specific gravity of 2.67, permeability of 1×10^{-4} m/s, and minimum and maximum dry densities of 1497 and 1774 kg/m^3, respectively (Chow *et al.,* 2019). After pluviation the sample surface was vacuum levelled to achieve a final sample thickness of 130 mm. Measurements of the sample mass and volume indicated that the relative density was ~75%. This corresponds with a peak friction angle of $\phi'_{peak} \approx 40°$ at an initial vertical effective stress similar to that at the suction caisson skirt tip level after installation (Chow *et al.*, 2019).

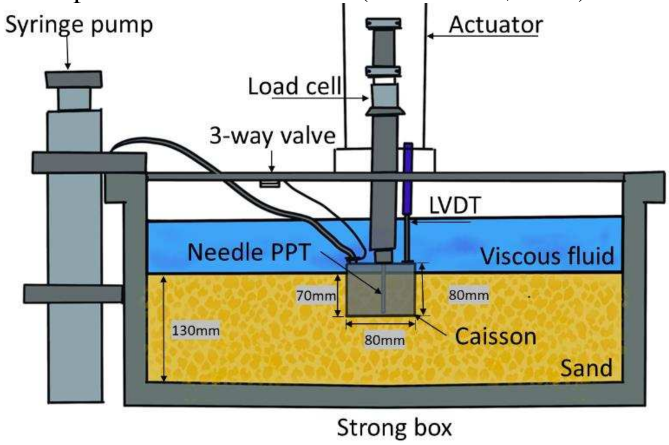

Figure 1 Schematic of the experimental setup (adapted from Bienen et al., 2018).

The dry sand sample was saturated from the base using a methylcellulose solution with concentration of 2.27%, resulting in a pore fluid dynamic viscosity of 500 mPas (i.e. 500 times that of water). For this pore fluid dynamic viscosity, the coefficient of vertical consolidation is $c_v = 2.7\times10^{-6}$ m^{2}s^{-1}, which allowed drainage conditions relevant to the field to be simulated (Bienen et al. 2018; da Silva Pereira et al. 2023). Viscous fluid was used in these experiments to investigate partially drained and undrained behaviour, although this aspect of the testing is not addressed in this paper. The sand layer was saturated in-flight at a centrifuge acceleration of $100g$, which allowed for faster pumping rates whilst minimising the risk of piping. A fluid level of 120 mm above the sand surface was maintained over the course of the tests, ensuring that the caisson remains submerged such that there were minimal changes in buoyancy detected by the load cell during installation (see Fig. 1).

The sand was characterised in-flight by cone penetrometer tests (CPTs), using a model-scale piezocone penetrometer, 10 mm in diameter that was penetrated into the sand at a rate of 1 mm/s. The piezocone measures tip and sleeve resistance and pore pressure at the u_2 position (i.e. at the cone shoulder). Fig. 2 shows depth profiles of net cone resistance obtained at different locations across the sample, before and after the caisson tests. There is little variation between the different profiles, indicating that the soil density (and hence strength) was relatively consistent across the sample and over the course of the tests.

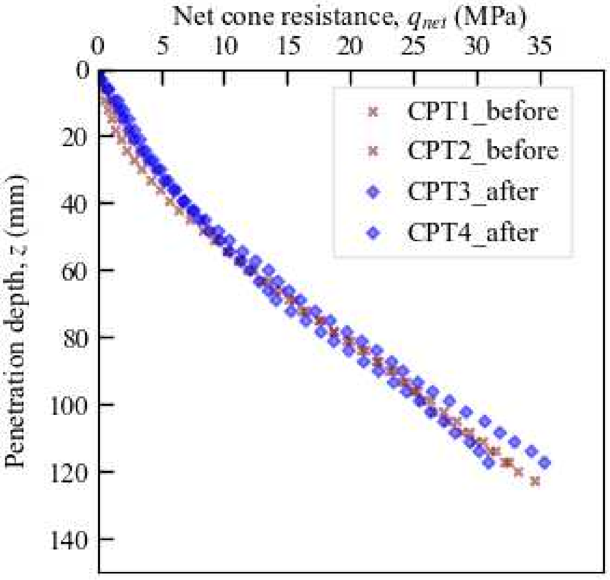

Figure 2 Depth profiles of net cone resistance in the sand sample.

2.2 Model suction caisson

The model caisson (Fig. 3) was fabricated from aluminium and has a diameter of D = 80 mm, a total skirt length of 80 mm and a wall thickness of t = 0.5 mm. At the testing acceleration of $100g$, these dimensions correspond to an 8 m diameter caisson with 8 m long skirts that are 50 mm thick. A 10 mm thick aluminium plate was attached at the caisson lid invert for the fully installed tests, such that the installation skirt penetration depth of fully and partially installed caisson tests was equivalent. The use of the thick aluminium plate resulted in an available skirt length of 70 mm for the fully installed caisson. Profilometer measurements of the skirt gave a centreline average roughness of 0.435 μm.

The model caisson lid is instrumented with three pore pressure transducers (PPT) and two total pressure transducers (TPT), with a measurement range of 3,000 kPa and 700 kPa, respectively (see Fig. 3). Fluid pressure above the bucket lid was measured with a TPT. Pressure at the lid invert was measured with two PPTs and one TPT. Pore pressure was also measured at caisson tip level using an aluminum needle, 80 mm in length and with an internal diameter of 1 mm, that was connected to a digital pressure sensor in the caisson lid. A porous stone filter was placed at the bottom of the needle (i.e. at caisson skirt tip level) so to prevent sand particles from entering the needle. Caisson displacement was monitored with a Linear Variable Differential Transformer (LVDT), mounted on an independent beam and in contact with the caisson lid.

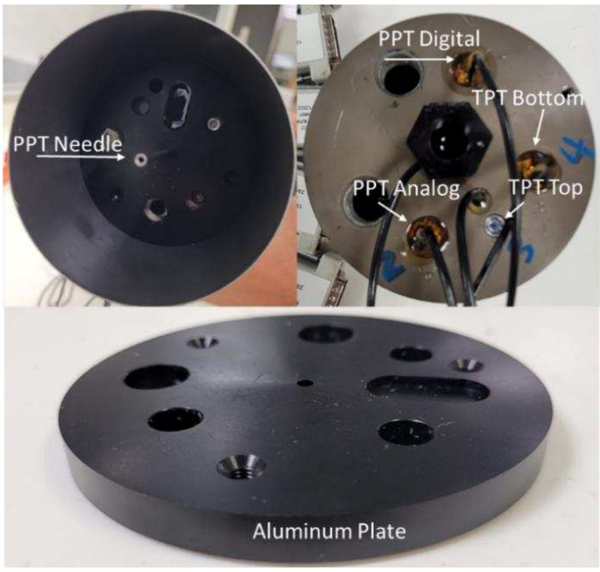

Figure 3 Suction caisson model and instrumentation.

A three-way valve was located on a port in the caisson lid (see Fig. 1). This valve can be controlled in-flight such that the caisson interior is either connected to the free fluid or to a syringe pump (described later) or closed such that the caisson is sealed.

2.3 Experimental procedure

The suction caisson was installed using an electro-mechanical actuator and a syringe pump. A vertical shaft connected to the top of the caisson (see Fig. 3) was located on the vertical axis of the actuator, allowing the caisson to be loaded in either displacement- or load-control. The syringe pump was used to extract fluid from the caisson, creating a pressure differential across the caisson lid for the suction assisted phase of the installation. Caisson resistance was monitored using a load cell (with a measurement range of 10 kN) that was located between the vertical shaft and the connection to the vertical axis of the actuator (the actuator has a capacity of 7 kN in compression and 5 kN in tension). Two installation scenarios were considered, one with a gap between the caisson lid invert and the sand surface and the other where there was contact between the lid invert and the sand surface. There two installation scenarios are hereafter referred to as partially and fully installed caissons.

All tests were conducted at a centrifugal acceleration equivalent to 100g. Caisson installation followed a similar procedure as outlined in Bienen et al. (2018) and da Silva Pereira et al. (2023). This involved an initial self-weight installation phase that was modelled by penetrating the caisson vertically into the sand in vented mode at a rate of 1 N/s (Fig. 4) until the installation resistance reached the targeted vertical self-weight of V = 350 N (V/A = 69.6 kPa).

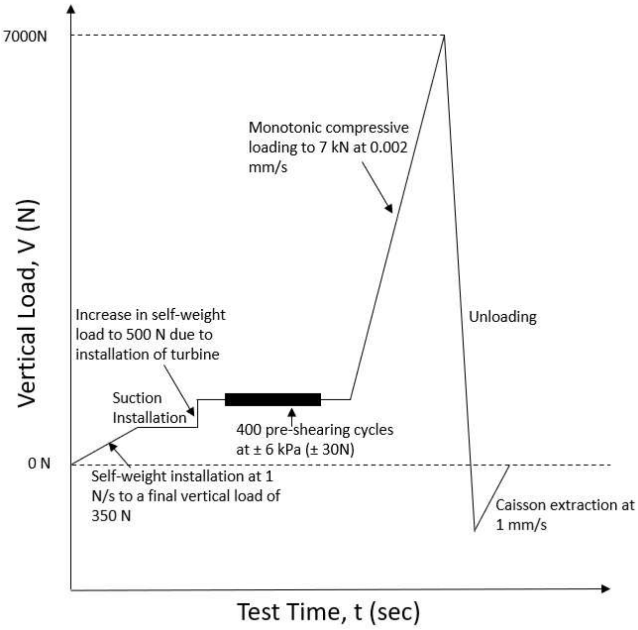

Figure 4 Various loading stages employed in the centrifuge tests (not to scale).

The self-weight load was maintained until dissipation of excess pore pressures at the lid invert was almost complete. The suction-assisted installation phase was then started by adjusting the three-way valve to form a hydraulic connection between the caisson and the syringe pump. The syringe pump was then operated to pump fluid from the caisson interior at a flow rate of 982 mm^3/s until the targeted installation depth was achieved for the partially installed caisson tests and until there was contact between the lid invert and the soil plug for the fully installed caisson tests.

Once installation was complete, the three-way valve was adjusted to seal the caisson and an additional vertical load of 150 N applied (representing the additional weight from the wind turbine), such that the total vertical load was V = 500 N (V/A = 99.5 kPa). A pre-shearing sequence composed of 400 cycles with an amplitude of 6 kPa was then applied to the caisson (see Fig. 4), emulating the bedding-in process observed in the field (Andersen, 2015). The three-way valve was then adjusted to the vented position, and the caisson monotonically jacked at a displacement rate of 0.002 mm/s until the capacity of the actuator was reached (7 kN, V/A ≈ 1390 kPa). The caisson was then extracted in-flight at 1 mm/s. A centre-to-centre distance of at least 2D between test locations was adopted.

3 RESULTS AND DISCUSSION

This section considers the installation response and behaviour during drained monotonic loading of partially and fully installed caissons.

3.1 Installation and plug heave.

The vertical stress and differential pressure across the lid during installation for a partially installed (test 1) and fully installed (test 2) caisson are presented in Figures 5 and 6, respectively.

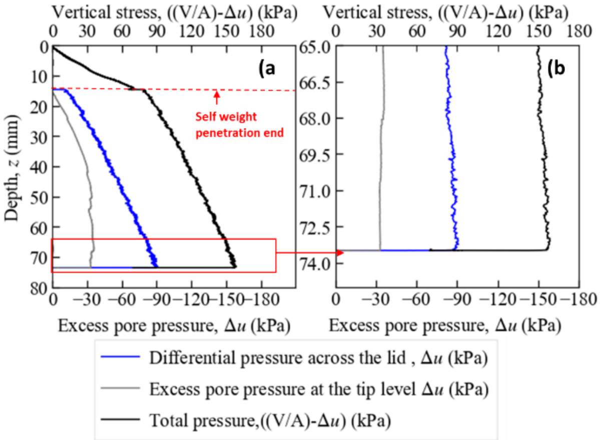

Figure 5 Installation of a partially installed caisson (without grout) (test 1): (a) complete installation, (b) towards the end of installation.

The self-weight penetration depth is relatively similar for both tests – 14.5 mm for test 1 and 16 mm for test 2 (indicated by the horizontal dashed line). Both tests also produced similar differential pressure across the lid and excess pore pressure at the caisson tip level during suction installation. At the start of the suction installation, the pressure at the lid invert is similar to that at the caisson tip level. However, as penetration proceeds, the magnitude of excess pore pressure magnitude at the caisson tip level increases only very slightly with depth, from Δu = -1.0 kPa at the start of pumping to about Δu = -36 kPa at the end of installation. In contrast the magnitude of the differential pressure increases from Δu = -0.5 kPa (i.e. approximately the same as at the caisson skirt level) to about Δu = -90 kPa at the end of installation. This observation indicates that during suction installation in sand, the hydraulic gradient between the soil surface and the skirt tip increases as installation proceeds.

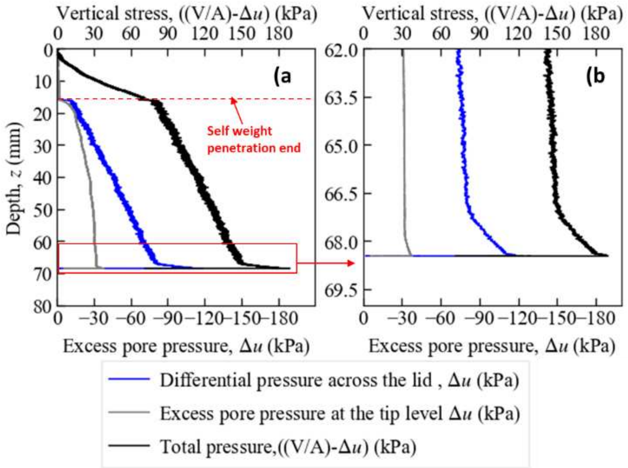

Figure 6 Installation of a fully installed caisson (with grout) (test 2): (a) complete installation, (b) towards the end of installation.

Plot (b) in Figs. 5 and 6 shows the response towards the end of suction installation. For the fully installed bucket (Fig. 6 (a)) there is a noticeable sharp increase in vertical stresses and pore pressure approximately 1.5 mm before reaching full skirt penetration (70 mm). This increase is consistent with mobilisation of bearing resistance at the caisson lid invert level, and hence plug heave of 1.5 mm may have occurred. If all the soil displaced by the advancing skirts were to be displaced inwards, this would result in almost 2 mm of heave. Hence, the 1.5 mm inferred from the experiments is likely to be due to soil displaced by skirts (noting that it is unlikely that all the soil will move inwards) rather than loosening of the soil caused by suction installation. For the partially installed caisson (Fig. 5(b)) there is no sharp increase in penetration resistance as suction installation was halted at ~70 mm, and hence prior to achieving full skirt penetration (80 mm).

3.2 Drained response – comparison between fully and partially installed caissons

Figure 7 compares the drained loading response of partially installed (test 1) and fully installed (test 2) caissons. Since the valve is open for the drained response, excess pore pressures (Δu) are zero (as depicted in Fig 7).

The partially installed caisson requires a higher displacement (approximately 4 mm, which is represented by relative depth, where z is the current depth of the skirt tip and z_0 is the installation depth of the skirt tip) to generate the same resistance as the fully installed caisson. This is expected as the lid is not in contact with the soil plug at the early stages of the monotonic loading phase, and hence the large resistance component of lid bearing is not mobilised.

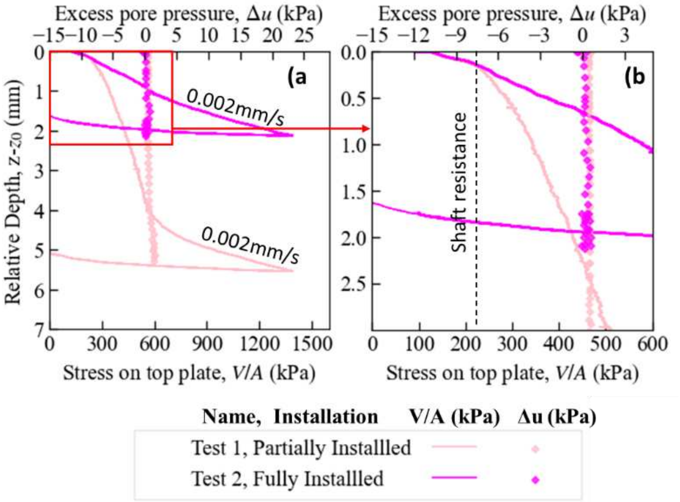

Figure 7 Mobilised skirt resistance under drained conditions for a partially installed caisson (test 1) and a fully installed (test 2) caisson: (a) complete response, (b) initial mobilisation.

Figure 7(b) shows that capacity mobilisation of the fully and partially installed caisson resistance is identical up to approximately 230 kPa. This initial agreement for both tests indicates that skirt friction is mobilised initially (potentially with some skirt tip resistance). Therefore, it can be concluded that the skirt friction resistance is unaffected by whether the caisson is fully or partially installed.

Loading rates are faster in the field, and partially drained conditions have been observed for suction caisson for offshore wind turbines (Shonberg et al., 2017). Hence, it is evidently necessary to compare the response of partially and fully installed caissons under such drainage conditions. The response of partially installed caissons at higher loading rates was also investigated in these experiments and this aspect will be addressed in a future publication.

4 CONCLUSIONS AND FUTURE SCOPE

Based on above observations, the following conclusions can be drawn from this work:

- The hydraulic gradient within the caisson was shown to increase as the caisson penetrates further into the soil during suction installation.

- Mobilisation of skirt friction under drained compressive loading is considered to be identical for partially installed and fully installed caissons.

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REFERENCES

Andersen, K.H., Murff, J.D., Randolph, M.F., Clukey, E., Erbrich, C.,Jostad, H.P., Hansen, B., Aubeny, C., Sharma, P., Supachawarote, C., 2005. Suction anchors for deepwater applications, in: Gourvenec, S., Cassidy, M. (Eds.), Proceedings of International Symposium on Frontiers in Offshore Geotechnics (ISFOG), CRC Press (Taylor & Francis), Boca Raton, FL, USA. pp. 3–30

Bienen, B., Klinkvort, R. T., O'Loughlin, C. D., Zhu, F. & Byrne, B. (2018a). Suction caissons in dense sand, part I: installation, limiting capacity and drainage. Géotechnique 68, No. 11, 937–952, https://doi.org/10.1680/jgeot.16.P.281.

Bienen, B., Klinkvort, R. T., O'Loughlin, C. D., Zhu, F. & Byrne, B. (2018b). Suction caissons in dense sand, part II: vertical cyclic loading into tension. Géotechnique 68, No. 11, 953–967, https://doi.org/10.1680/jgeot.16.P.282.

Cao (2003) conducted centrifuge modeling and numerical analysis of the behavior of suction caissons in clay as part of their doctoral (PhD) thesis at Memorial University of Newfoundland.

Chow, S. H., Roy, A., Herduin, M., Heins, E., King, L., Bienen, B., O'Loughlin, C., Gaudin, C., & Cassidy, M. (2019). Characterisation of UWA Superfine Silica Sand (Report No. GEO 18844). The University of Western Australia,Perth,Australia.

da Silva Pereira, F., Bienen, B., & O'Loughlin, C. D. (2023). Mind the Gap – An Experimental Study on the Need for Grouting Suction Buckets in Sand under Vertical Cyclic Loading. *Géotechnique*.

Dendani, H., and J-L. Colliat. "Girassol: Design Analysis and Installation of the Suction Anchors." Paper presented at the Offshore Technology Conference, Houston, Texas, May 2002. doi: https://doi.org/10.4043/14209-MS

Kay, S., Gourvenec, S., Palix, E., & Alderlieste, E. (2021). *Intermediate Offshore Foundations*. CRC Press

Lawson, J. (2013, December 13). Good foundations: the pros and cons of monopiles. World Wind Technology.

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

Shonberg, A., Harte, M., Aghakouchak, A., Cameron, S. D., Brown, M. P. A. & Liingaard, M. A. (2017). Suction bucket jackets for offshore wind turbines: application from in situ observation. In Proceedings of the 19th international conference on soil mechanics and geotechnical engineering (ICSMGE) (eds W. Lee, J.-S. Lee, H.-K. Kim and D.-S. Kim) pp. 65–77. Seoul, South Korea: Korean Geotechnical Society.

Skempton, A. W. (1970). First-time slides in over-consolidated clays. *Géotechnique*, 20(3): 320-324.

Stapelfeldt, M., Bienen, B. & Grabe, J. (2020). The influence of the drainage regime on the installation and the response to vertical cyclic loading of suction caissons in dense sand. Ocean Engng 215, 107105,

Stapelfeldt, M., Bienen, B. & Grabe, J. (2021). Influence of low-permeability layers on the installation and the response to vertical cyclic loading of suction caissons. J. Geotech. Geoenviron. Engng 147, No. 8, 04021076,

Sturm, H. (2017). *Design Aspects of Suction Caissons for Offshore Wind Turbine Foundations*. Computational Geomechanics, Norwegian Geotechnical Institute (NGI), Oslo, Norway.

Tapper, A. B., Author, C., & Surname, D. (2023). *SUT template and guidelines for contributors to OSIG 2023*. Presented at the 9th International Conference on Innovative Geotechnologies for Energy Transition (OSIG 2023), London, UK.

Zhao, L., Bransby, M.F. & Gaudin, C. Centrifuge observations on multidirectional loading of a suction caisson in dense sand. *Acta Geotech.* **15**, 1439–1451 (2020). https://doi.org/10.1007/s11440-020-00970-4

Zhang, Y., Sudhakaran, K., & Askarinejad, A. (September 2020). Centrifuge Modelling of Suction Caissons Subjected to Cyclic Loading in Tension. In *4th European Conference on Physical Modelling in Geotechnics*.

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