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

ISBN 978-2-85782-758-0

Sustained tensile loading analysis of suction buckets considering the load characteristics and drainage condition

M. Cramer*
Institute of Geotechnical Engineering and Construction Management, Hamburg University of Technology, Hamburg, Germany

P. Gütz
Ramboll Germany GmbH, Hannover, Germany

**mechthild.cramer@tuhh.de*

ABSTRACT: Suction bucket jackets are a foundation type for specific applications where driven piles are technically unfeasible or uneconomical. Certain load cases evoke sustained tensile loading of the suction bucket facilitating drainage. Consequently, the induced suction pressure dissipates and finally, the suction bucket can only mobilise its drained resistance. However, the suction pressure contributes to the resistance under undrained and partially drained conditions providing spare capacities to withstand temporarily higher loads. The aim is to optimise the design in terms of sustained tensile loading in order to achieve a robust and at the same time efficient result under consideration of the suction bucket's drainage condition and relevant load characteristics. This paper demonstrates a methodology adopting finite element modelling to calculate the drainage period, which is analysed against the load characteristics obtained from simulated load-time series. The key parameters influencing the drainage period are systematically analysed. Moreover, this paper outlines a method to extract loads and their associated durations from simulated load-time series and to transfer these to a design load curve. The results reveal that the hydraulic conductivity has a greater impact on the drainage period than the suction bucket's geometry, such as skirt length and diameter, while layered soil profile implicitly influence drainage. The conjunction between the drainage period and the design load curve highlights the importance of accounting the partial drained behaviour for an efficient design. Overall, this paper outlines refined analyses to avoid overly conservative designs in cases where sustained tensile loading is critical.

Keywords: suction buckets, tensile loading, drainage condition, consolidation

1 INTRODUCTION

Suction buckets are primarily vertically loaded in jacket structures as foundation for offshore wind turbines. The loading is irregular dynamic due to the impact from mainly currents, wind and waves. The suction bucket's response to tensile loading is categorised as drained, undrained or partially drained. Drained conditions occur in permeable soil under slow-rate, and sustained loading while undrained conditions arise in impermeable soil under rapid, short loading. The bearing capacity of suction buckets in dense sand can be up to 18-25 times higher than the drained capacity due to the suction effect (Nielsen, 2017). Typically for offshore wind turbines, partially drained conditions occur, where a negative pore pressure beneath the suction bucket's lid temporarily enhances the tensile resistance alongside skin friction until the negative differential pressure dissipates. Given the lack of specific design guidelines, conservative assumptions are necessary, such as designing the suction bucket's drained resistance, made up of the dead weight and skin friction, to withstand the highest expected prolonged loads.

This paper provides a methodology to design the sustained tensile load case which takes the dissipation time and generated cyclic load-time series into account. The dissipation process is driven by several parameters such as the drainage path, which is mainly dependent on the embedment depth (skirt length) L and the diameter D, and the soils hydraulic conductivity k_f (Kelly, 2006; Thieken, 2014, Gourvenec, 2009).

To date, there have only been a few studies that specifically address the consolidation process but focus on time dependent displacements. Gourvenec (2010, 2009) analysed the consolidation response of skirted foundations through numerical small strain finite-element analysis, while Mana (2013) investigated displacement rates of skirted foundations under tensile loading in clay soils. Rosati (2023) adopted centrifuge testing and numerical modelling to examine the load-time failure of suction buckets under sustained tensile loading. The results show load levels in varying holding times and failure mechanism in which the suction buckets bearing capacity is exceeded. Although the displacement rate is the limiting factor in the design of suction buckets, the focus of this study is on the drainage period, i.e. the time during which a certain amount of differential pressure is still present.

2 DRAINAGE PERIOD

2.1 Model set-up

An axisymmetric numerical model was developed using PLAXIS 2D 2024.1 to determine the drainage period. The model set-up is shown in Figure 1. The soil is assumed homogenous, isotropic and following a linear elastic behaviour. The simple constitutive model was adopted in this study since the effective stresses introduced are negligible and to focus on the hydraulic processes, which are dominating the drainage period. The calculation domain is set to 4 times the skirt length in width and height. Within the sensitivity study, the soil's hydraulic conductivity is varied between k_f = 7.5E-4 m/s and 2.5E-6 m/s to represent a range from clean sand to silty sand. Water is modelled as nearly incompressible with a bulk modulus of K = 2.2E6 kN/m² and fully saturated soil conditions are assumed. The suction bucket's length and diameter are defined by the length and position of a vertical impermeable interface.

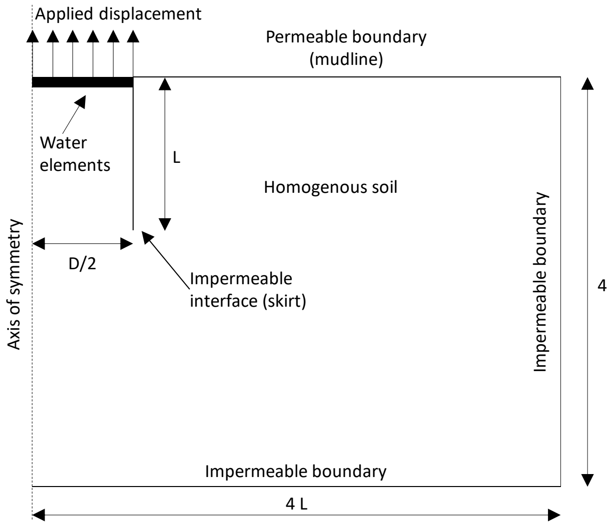

Figure 1. Numerical model set-up

A 5 cm layer of "water elements" is introduced under the lid to preserve pore water volume and maintain a constant negative differential pore pressure under the lid (Cao, 2002). The calculation process is divided into three stages: The initial stress conditions are calculated in the first phase. In a second phase, the uppermost nodes of the water elements are subjected to a displacement of 1 cm to generate a negative differential pressure. A time step length of 1,000,000 s is chosen to ensure that the flow field develops fully as shown in Figure 2. During the linear applied displacement of the water elements, the negative differential pressure increases until it reaches a steady state. The negative differential pressure is normalised by its maximum value, so the stagnating negative differential pressure under the lid reaches p/p_{max} = 1 (see Figure 3).

In the third phase, no additional displacements or loads are applied on the water elements. Hence, the negative differential pressure is allowed to dissipate, and the phase is calculated until 99.9% of the initial negative differential pressure have dissipated (see Figure 3, right). It is verified that soil elements are subjected to negligible strains.

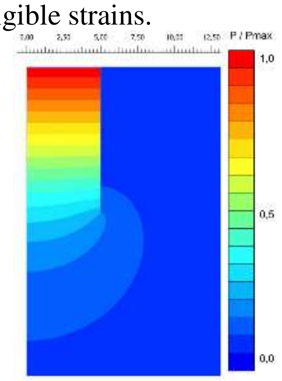

Figure 2. Steady state pore pressure field after 1,000,000 s

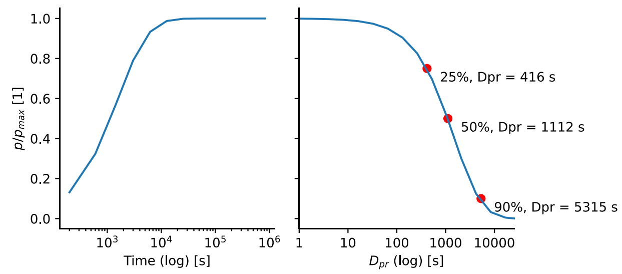

Figure 3. Exemplary build-up during the applied displacement (left; Phase 2) and dissipation (right; Phase 3) of negative differential pressure

2.2 Sensitivity study

The negative differential pressure beneath the suction bucket lid at the axis of symmetry is evaluated over the process of time. The drainage period D_{pr} is defined as the time from the start of the dissipation phase to the point where a specified percentage of dissipation is reached (shown in Figure 3, right). The degree of dissipation may be defined specifically to accommodate for particular purposes, project specifications and requirements. Exemplarily, Figure 3 presents three dissipation levels and associated drainage periods for a reference system of k_f = 1E-5 m/s and $L = D$ = 10 m.

The sensitivity study varies the parameters of length, diameter and hydraulic conductivity and compares the drainage periods after 25%, 50% and 75% of the initial negative differential pressure dissipated. In Figure 4 the results of a 25% dissipation level are fitted by an empirical expression accounting for the relation between the drainage period and the hydraulic conductivity by $D_{pr} = n/k_f$, where n varies with different geometries. The results show that the hydraulic conductivity has the greatest influence on the drainage period. The impact of the skirt length on the drainage period was found to be greater than that of the suction buckets diameter when varied by the same absolute value.

Table 1 shows the fitted values of *n* for various dissipation levels and geometries based on which the drainage period may be an initial estimate. The parameter n_{50} is in average 27.3 times higher than n_{25} (standard deviation of 0.4) and n_{75} is in average 2.3 times higher than n_{50} (standard deviation of 0.02). Consequently, an increment of 25% dissipation takes longer at the beginning of the dissipation phase compared with later stages. Further, the almost constant ratios for different geometries (low standard deviation) demonstrates that the dissipation level is barely affected by the suction bucket's diameter and length, indicating minimal dependence on geometry.

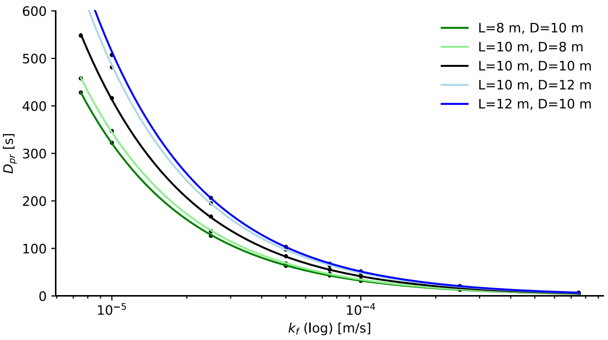

Figure 4. Calculated drainage period (25% dissipation) dependent from the hydraulic conductivity and suction bucket geometries

Table 1. Parameter n (Equation $D_{pr} = n/k_f$) for different suction bucket geometries and dissipation levels

L [m]	D [m]	n_{25} [m]	n_{50} [m]	n_{75} [m]
8	10	3.21E-4	8.60E-3	2.02E-2
10	8	3.44E-4	9.58E-3	2.25E-2
10	10	4.13E-4	1.14E-2	2.67E-2
10	12	4.85E-4	1.31E-2	3.02E-2
12	10	5.14E-4	1.41E-2	3.25E-2

The influence of a layered soil profile was analysed using a model with a suction bucket geometry of 10 m in diameter and length embedded in soil with a hydraulic conductivity of k_{f1} = 1E-5 m/s as a reference. Layers with thicknesses of 1 m and 2 m and hydraulic conductivities of k_{f2} = 1E-4 m/s and k_{f2} = 1E-6 m/s at varying depths *z* between 0 m and 11 m (top of layer) were implemented in the soil profile. Their drainage periods (25% dissipation) were examined (see Figure 5 and Figure 6). The results indicate that a 2 m thick and 10 times less permeable layer increases the drainage period by up to approximately 850 s, while a 10 times more permeable layer reduces it only by up to approximately 130 s, both in relation to the drainage period of homogenous soil of k_f = 1E-5 m/s. In lower-permeable layers, the impact of layer thickness is more pronounced and increases with the layers' depth. However, the influence reduces again if not the full thickness of the layer is within the embedment of the skirt ($z > L-d$).

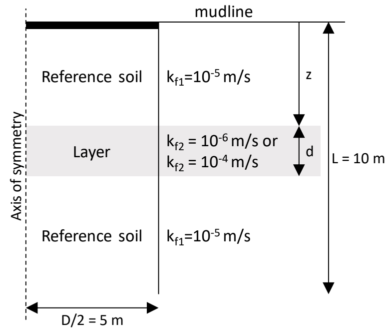

Figure 5. Model set-up to study the impact of soil layering

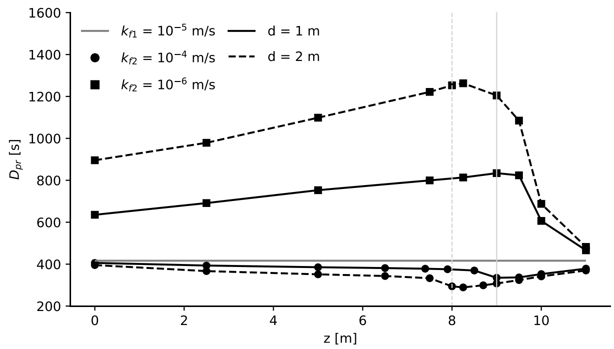

Figure 6. Influence of soil layers with different hydraulic conductivities on the drainage period

These findings highlight the importance of determining the drainage period for every soil profile, as it is sensitive to soil layering and assuming homogenous soil can oversimplify the site conditions. Despite the simplifications made in the investigation, the present results provide valuable insight into key factors that influence the drainage period.

3 LOAD CHARACTERISTICS

The loading on a suction bucket is irregular dynamic. Load-time series are generated in the iterative design process, incorporating key parameters such as wind speed, wave height, and current, along with site-specific probability data. The loads are computed through hydrodynamic load analysis adopting a generic jacket model in combination with loads from aero-elastic simulations using a generic wind turbine model at the interface of the transition piece to yield dynamic load-time responses for 600 s, which are extracted at the suction buckets lid. The load-time series database used in this study is based on an exemplary load case of sustained tensile loading, with only the vertical loads on the bucket considered. The load-time series are normalised to the highest occurring force. The raw load signal is filtered using a low-pass filter, based on the occurring high frequencies, to remove higher frequencies of the generated load signal (see Figure 7). From these filtered signals, the exceedance periods are determined, which reflect how long a specific force level is surpassed. Figure 7 illustrates this with horizontal lines representing exceedance periods evaluated in increments of 0.025 F/F_{max}, with three examples highlighted in red, green and yellow. The size of the load increments can be selected based on project requirements, with smaller increments resulting in more precise results but increasing computational effort. All load-time series where tensile loads occur, were analysed and all exceedance periods and corresponding load magnitudes were extracted. These points are plotted in Figure 8. The exemplary highlighted exceedance periods and load magnitudes in Figure 7 are analogously highlighted in Figure 8. Finally, an envelope over the data points gives the maximum forces that might occur for the range of exceedance periods identified in the load-time series. This envelope is forming the conservative design load curve.

4 DESIGN CONCEPT

The mobilisation of negative differential pressure along with the time-dependent dissipation of differential pressure allows suction buckets to temporarily withstand higher tensile loads than their drained resistance. This contribution addresses the load case of prolonged tension, investigating the period over which the negative differential pressure contributes to the tensile resistance until drainage is reached, in here defined as drainage period. The occurring loads during prolonged tension are analysed with respect to their duration, resulting in a so-called design load curve. Linking these two results proposes a new design concept that carefully considers the dissipation process to optimise the design.

Typically, the drained resistance of the suction bucket is designed for a load magnitude that persists for relatively short duration. By combining the drainage period with the derived design load curve, a new

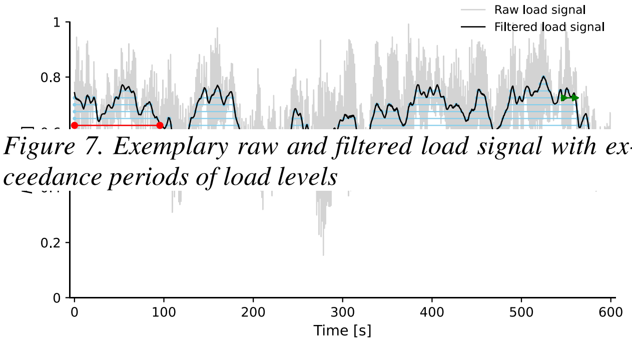

Figure 7. Exemplary raw and filtered load signal with exceedance periods of load levels

design load can be identified, provided that the drainage period is equal to or higher than the duration of the

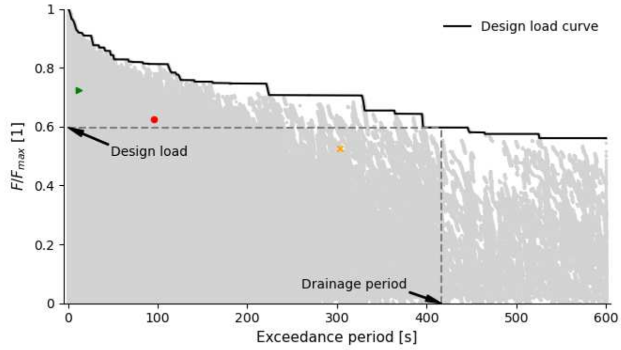

Figure 8. Design load curve obtained from exceedance period of load levels obtained from all generated tensile load-time series

new design load. Based on that load, the suction bucket may be designed to provide sufficient drained resistance (equal to or higher than this new design load). Hence, the design process is iterative, as changes in the suction bucket's geometry alter the drainage period and the drained resistance simultaneously.

An example is shown in Figure 8. After the drainage period of 416 s, in the reference system (k_f = 1E-5 m/s and $L = D$ = 10 m), is determined, the new design load of 0.59 F/F_{max} is obtained from the design load curve and is the greatest load persisting for at least 416 s. The new design load is then adopted to design the suction buckets geometries to withstand by the drained resistance.

The maximum optimisation of the design concept is limited by the force which is surpassed for 600 s, in this exemplary dataset 0.56 F/F_{max}. The load-time series are simulated for 600 s, defining this threshold. For a drainage period of 600 s, the drained resistance will be designed to withstand 0.56 F/F_{max}, resulting in a substantial improvement in the design for sustained tensile loading, compared to previous assumptions of a much shorter drainage period. The highest reductions in the drained resistance occur at lower exceedance periods, as the highest loads are only sustained for a short time. After approximately 60 s, the design load curve flattens with smaller step reductions.

5 DISCUSSION

The presented methodology allows accounting for the drainage period, during which negative differential pressure under the suction buckets lid contributes to its tensile bearing capacity. Several aspects of this methodology are critical for its application in a design procedure.

The degree of dissipation controls the conservatism of the method. Since numerical results lack experimental validation, uncertainties remain but can be operated by selecting a conservative dissipation level such as the value of 25% suggested in this study. This approach provides additional capacity, as the differential pressure still contributes to tensile resistance, but can be further adjusted after on-site dissipation measurements.

The sensitivity analysis revealed that the skirt length has a greater influence on the drainage period than the suction bucket diameter, consistent with findings from other studies (Barari, 2011; Whang, 2018). However, the impact should not be overestimated and in the design process, a reasonable balance between the suction bucket geometries, site-specific soil profiles and loading conditions is to be established.

The study on the impact of soil layering shows that a tenfold decrease in hydraulic conductivity extends the drainage period more than a tenfold increase shortens it. Therefore, the authors suggest that if cautiously realistic values of hydraulic conductivity are adopted in the design, the presence of an undetected, more permeable layer is not too concerning. Equally, a less permeable layer would increase the drainage period substantially and could compensate underestimated hydraulic conductivities to a certain extent.

The results show that a layer with a reduced hydraulic conductivity has a greater impact on the drainage period as its depth increases. During the dissipation phase, the water flows upwards through the suction bucket to equalise the pressure difference. The deeper a less permeable layer is located, the more water needs to pass through, prolonging the dissipation. Vice versa, a more permeable layer in greater depths shortens the drainage period. The depth influence diminishes once the bottom of the layer is below the skirt’s tip, since the layer does not fully cover the drainage path anymore. The effect occurs not immediately, because the water is not only flowing from beneath the bucket but also from the radial vicinity of the suction buckets skirts end.

The low-pass filter with a cut-off frequency of up to 0.2 Hz excludes high-frequency loads lasting up to five seconds. However, previous findings suggest that the high frequent loading of suction buckets result in an undrained or partially drained behaviour, which is higher than the drained resistance and thus not relevant for prolonged tension loading (Gütz, 2021; Nielsen, 2017).

The design load curve does not decrease continuously with exceeding time but exhibits steps (Figure 8). When the drainage period approaches one of these steps, a higher design load should be adopted to maintain conservatism, as small deviations in the drainage period could lead to large increase in loads that exceed the drained resistance. For example, in Figure 8, if the drainage period is 20 s lower than anticipated, the highest force the drained resistance must sustain would rise from 0.59 F/F_{max} to 0.63 F/F_{max}. Designing with a higher new design load implies larger suction bucket geometry to provide sufficient drained resistance, which would then again increase the drainage period and by that increase the conservatism of the design.

The considered load-time series are based on distinct load cases, which represent certain probabilities for the design of the entire structure. This additional dimension of analysis is neglected so far in this study. A holistic design approach shall incorporate the probabilities of the load cases. This consideration would enable statistically based design method, which balances all parameters appropriately, i.e. dissipation levels, probabilities of individual load cases and ranges in the definition of soil parameters.

6 CONCLUSION

This paper presents a numerical model to determine the drainage period of a suction bucket, which depends on the soil’s hydraulic conductivity and the suction bucket’s geometry. It outlines a methodology to link the drainage period with generated load time series to optimise the design of sustained tensile loading. The following key findings are identified:

- The numerical model calculates the drainage period, indicating how long negative differential pressure remains under the suction bucket's lid for a certain percentage of dissipation.
- The length of the suction bucket skirt has a greater influence on the drainage period than the diameter. The hydraulic conductivity impacts the drainage period the most.
- Less permeable soil layers affect the drainage period more than more permeable layers, which may be, however, critical for design.
- A design load curve derived from load-time series can be used to optimise the design by determining the tensile load magnitude appropriate for a certain drainage period.

- The suggested design concept allows for optimisation by reducing the design load from previous design approaches but still implies conservatism on both sides, the determination of drainage period and prolonged tension load.

The methodology is an iterative process that is developed for implementation in projects. The high efficiency of the numerical model allows for the analyses of a large number of soil profiles and suction bucket geometries. Thus, position specific and iterative investigation of the prolonged tension load case are enabled. Justification of assumptions by measurements of pore water pressure under the suction bucket lid, combined with load measurements, or centrifuge testing are crucial for further optimisation of the design and for adjusting the conservative recommendations suggested in this contribution.

AUTHOR CONTRIBUTION STATEMENT

Mechthild Cramer: Writing – original draft, Investigation, Methodology, Visualization, **Patrick Gütz**: Conceptualization, Writing – review & editing, Investigation, Methodology, Supervision

REFERENCES

Barari, A., and Ibsen, L. B. (2011). Effect of embedment on the vertical bearing capacity of bucket foundations in clay. In Proceedings of the 2011 Pan-Am CGS Geotechnical Conference Pan-Am, Toronto, Canada.

Cao, J., Qi, C., Yang, X. S., and Li, M. Y. (2002). Numerical analysis of the behavior of suction caissons in clay. In: Proceedings of the International Society of Offshore and Polar Engineers, Kitakyushu, Japan, pp. 795–799.

Gourvenec, S., and Randolph, M. F. (2009). Effect of foundation embedment on consolidation response. In: Foundations in Offshore Engineering, vol. 17, pp. 638-646. http://doi.org/10.3233/978-1-60750-031-5-638

Gourvenec, S., and Randolph, M. F. (2010). Consolidation beneath circular skirted foundations. *International Journal of Geomechanics*, 10(1), pp. 22–29. http://doi.org/10.1061/(ASCE)1532-3641(2010)10:1(22)

Gütz, P., and Achmus, M. (2021). Suction bucket foundations under cyclic tensile loading—physical and numerical modeling. *Geotechnical Testing Journal*, 44(3), pp. 756–781. http://doi.org/10.1520/GTJ20190225

Kelly, R. B., Houlsby, G. T., and Byrne, B. W. (2006). Transient vertical loading of model suction caissons in a pressure chamber. *Géotechnique*, 56(10), pp. 665–675. http://doi.org/10.1680/geot.2006.56.10.665

Mana, D. S. K., Gourvenec, S., and Randolph, M. F. (2014). Numerical modelling of seepage beneath skirted foundations subjected to vertical uplift. *Computers and Geotechnics*, 55, pp. 150–157. http://doi.org/10.1016/j.compgeo.2013.08.007

Nielsen, S. D., Ibsen, L. B., and Nielsen, B. N. (2017) Transiently loaded bucket foundations in saturated dense sand – demonstration of the boot effect. *Geotechnical Testing Journal*, 40(6), pp. 1101-1114, https://doi.org/10.1520/GTJ20160339

Bentley Systems (2024). PLAXIS 2D 2024.1, PLAXIS 2D Geotechnical Engineering software. Available at: bentley.com/software/plaxis-2d/, accessed: 28/10/2024.

Rosati, A., Desideri, A., Rampello, S., Randolph, M. F. and Gaudin, C. (2023). Load-time failure envelopes for suction caissons under sustained vertical loading. In: Proceedings of the 9th International Conference, Innovative Geotechnologies for Energy Transition, London, UK, pp. 1813–1820.

Thieken, K., Achmus, M., and Schröder, C. (2014). On the behavior of suction buckets in sand under tensile loads. *Computers and Geotechnics*, Volume 60, pp. 88–100. http://doi.org/10.1016/j.compgeo.2014.04.004

Wang, X., Zeng, X., and Li, J. (2019). Vertical performance of suction bucket foundation for offshore wind turbines in sand. *Ocean Engineering*, Volume 180, pp. 40–48. http://doi.org/10.1016/j.oceaneng.2019.04.024