SUCTION INSTALLATION OF MODULAR BUCKET FOUNDATION FOR LARGE OFFSHORE WIND TURBINES

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ABSTRACT

Suction bucket foundation is named by many experts in offshore geotechnics as an alternative to pile foundations for offshore wind turbines as it is often more cost-effective. The suction installation process is noise-free and requires less operational time. A simple design of suction bucket is a steel cylindrical thin structure. A significant increase in size of foundation requires a higher pressure for installation and, at the same time, increases the probability of buckling failure. The proposed modular bucket consists of trapezoidal wall sections that are convenient for industrialization. The structure is significantly thinner than a circular bucket, resulting in a weight saving of 28% for full scale model with diameter equal 8 m (EUDP, 2018). This design has been analyzed for buckling resistance and results in much better performance. The paper includes also the installation tests on a medium-scale bucket models, both the round and modular. Results prove that the initially large penetration resistance in sand is highly reduced by the seepage flow induced by applied suction. Moreover, the comparison of results shows that the extra increase in jacking required load for modular bucket due to larger area is minimized almost to no difference in the required suction between circular and modular bucket model. These findings can contribute to a significant decrease in energy production costs for offshore wind turbines allowing installation of bigger turbines with reduced cost of the foundations.

KEYWORDS

Modular bucket; Offshore wind turbines; Penetration resistance reduction

INTRODUCTION

The foundations for the offshore wind turbines rely mostly on the experience from the oil and gas offshore sector. However, the loading conditions between an offshore platform and a wind turbine differ significantly. The platform is a massive structure where the self-weight is a main component of the loading transferred to the soil, whereas the slender wind turbine tower with rotating blades is more susceptible to the cyclic loads that induce large moments at the seabed, the dominant load in this case.

The most widely used foundation for the offshore wind turbines is a monopile foundation (WindEurope 2019). The concept is well known and the design standards are detailed. As a deep foundation, it was very suitable for the soft clays deposited as the top layers in the seabed of the Gulf of Mexico, where the offshore structures have been installed in the 90's. Nowadays, the stratigraphy at locations for offshore wind farms consists of sands and stiff clays, like the North Sea locations, that is suitable for the shallow foundations. Moreover, the wind turbines tend to increase in their size. The solution of monopile becomes less economical when the diameter and the length must be increased. Therefore, the recent research focuses on other solutions that might contribute to the reduction in the foundation costs, hence the cost of the offshore wind energy. Byrne and Houlsby (2003) reported that the shallow foundations satisfy the bearing capacity requirements in some conditions, being at the same time more cost-effective than monopiles.

The shallow foundation that has been lately considered is the mono bucket foundation, proven already to be feasible for the offshore wind turbines (Houlsby et al. 2005; Ibsen 2008; Sturm 2017). The mono bucket foundation is only a small step from the full commercialization. The main contributions to such a development are the Energy Technology Development and Demonstration Program, EUDP, with different projects and the Offshore Wind Accelerator Program, OWA, created by the Carbon Trust Group (Carbon Trust 2019).

The design of the bucket foundation is a compromise between fulfilling the bearing capacity requirements and the feasibility of full installation. The research concerning the suction installation is available, but still some of the aspects are not fully-understood. The paper includes the research that means a step further, where the shape of the mono bucket foundation has been changed in order to obtain a better buckling resistance during the installation, which is one of the critical aspects of the design. The skirt is built from several trapezoidal modules, much thinner than the skirt of the regular bucket model. The model contains additional inside stiffeners, yet still uses less steel material and contributes to the cost reduction. The modules are easy for assembling and the market in Denmark is prepared for their industrialization. Such a bucket foundation is referred in this paper as a modular bucket, see Fig. 1. It is the main output of the project “Offshore wind suction bucket on an industrial scale” by EUDP. The paper includes the results of the laboratory tests on the suction installation in sand, where a medium scale model is tested. The main objective is to observe how the change in the shape of bucket foundation influence the installation process. Some recommendations for the design of the installation phase are given.

(a) (b)

Fig. 1. Modular model of bucket foundation: (a) outside and (b) inside with stiffeners

RECOMMENDATION FOR THE SUCTION INSTALLATION DESIGN

The design of the bucket foundation depends on the installation process, which differs a lot from other foundation concepts, and the in-place performance. The paper focuses only on the installation matter. The bucket foundation consists of a cylindrical skirt that is inserted into the soil. The skirt is closed at the top with a lid instrumented with a suction system that allows for the connection to a pump. The first part of the installation is a self-weight penetration, where the bucket drives into the soil due to its own weight. This phase ensures that the penetrated part of the skirt creates a hydraulic seal together with the surrounding soil, what enables a suction part of the installation. The activated suction pump lowers the pressure under the bucket lid which creates a downward force.

The suction installation puts away the requirements for the heavy drilling equipment and it additionally reduces the initial large soil penetration resistance in permeable soils (Hogervorst 1980; Bye et al. 1995; Koteras and Ibsen 2019). The applied pressure under the bucket lid induces a seepage flow around the skirt. Consequently, the hydraulic gradients occur around the skirt and change the effective soil stress. Therefore, the installation process is possible in dense sands where the penetration resistance is in principle very large. The installation, however, still requires a proper design and monitoring. The main failure criteria during the suction installation is the exceedance of the critical pressure that might lead to the generation of piping channels at the skirt wall, preventing further penetration. Another important aspect is the already mentioned buckling resistance of the structure. High pressures during the installation can cause significant deformations in the structure. Finally, the installation must reach the target depth; otherwise, the required bearing capacity is not obtained for the foundation performance.

The target penetration depth is designed based on the soil penetration resistance. The load applied on the bucket foundation must exceed the soil resistance at every depth, until it reaches the final depth. The CPT-based method is one of the methods that are recommended for the calculations of the soil penetration resistance, *R* (Houlsby et al. 2005; Senders and Randolph 2009). The inner and outer skirt friction and the skirt tip resistance are related to results of the cone resistance, q_c, from the cone penetration tests, CPT, through the empirical correlation coefficients k_f and k_p (DNV 1992). The procedure must also account for the reduction in soil penetration resistance due to the induced seepage flow. This is quantified through the β-factors that reduces the inner friction and the tip resistance. β_{out} is set to 1.0 based on reviewed research work (Lian et al. 2014; Koteras and Ibsen 2019), but I could in reality be slightly bigger that 1.0 due to downward seepage flow at the outside skirt. The following equations is recommended for the calculation of the soil penetration resistance reduced by the seepage flow.

$$R = \beta_{\mathrm{in}} A_{\mathrm{s,i}} \int_0^h q_{\mathrm{c}}(z)\, k_{\mathrm{f}}(z)\; dz \; + \beta_{\mathrm{out}} A_{\mathrm{s,o}} \int_0^h q_{\mathrm{c}}(z)\, k_{\mathrm{f}}(z)\, dz \; + \; \beta_{\mathrm{tip}} k_{\mathrm{p}}(h) A_{\mathrm{tip}} q_{\mathrm{c}}(h) \qquad (1)$$

where $A_{\mathrm{s,i}}$, $A_{\mathrm{s,o}}$ and A_{tip} are the area of the inside skirt, outside skirt and tip respectively, *z* is the soil depth and *h* is the penetration depth of the skirt tip. β-factors for inside friction and tip resistance are based on the ratio of applied pressure over critical pressure against the piping failure as shown in the following equation:

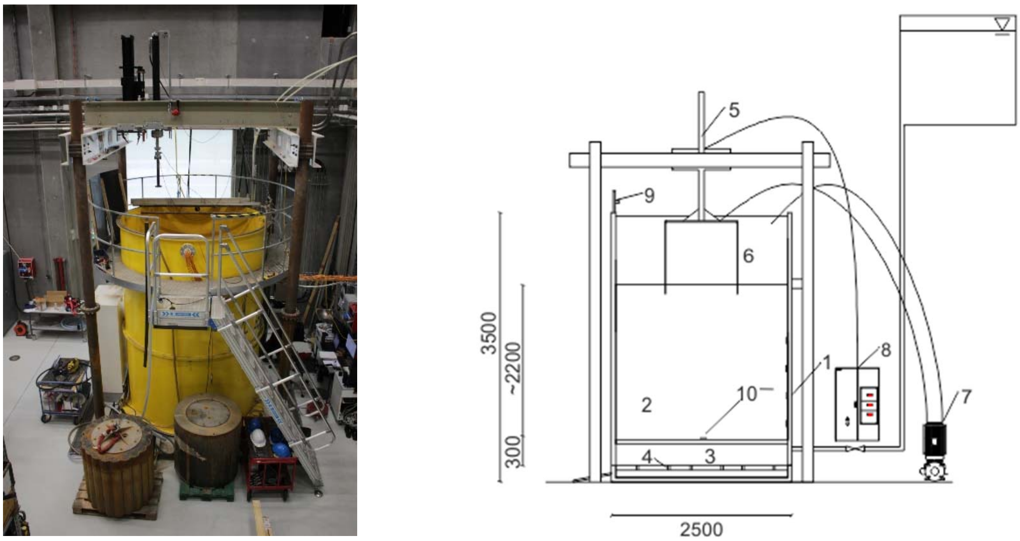
$$\beta_{\mathrm{in}} = \beta_{\mathrm{tip}} = 1 - r\left(\frac{p}{p_{\mathrm{crit}}}\right) \qquad (2)$$

The approach appears similarly in (Senders and Randolph, 2009) and assumes that both resistance components are completely lost when the applied suction follows the critical limit. However, the discussion whether the inside skirt friction and the tip resistance can be reduced to zero appears in Koteras and Ibsen (2018). Therefore, *r* coefficient is included in Eq. (2) to limit the quantity of the reduction.

The critical suction pressure is a theoretical value obtained based on the numerical simulations of seepage flow, and it is recommended to not be exceeded during the suction installation. The critical limit is considered when the exit hydraulic gradient at the inside skirt reaches its critical value, causing at the same time a piping channel on the entire inside skirt. The calculations are based on the seepage length analysis, by firstly determining the normalized seepage length and then presenting the results for the normalized critical pressure, as shown by Senders and Randolph (2009) or Koteras et al. (2016).

LABORATORY SET-UP

A series of tests were conducted at Aalborg University in the geotechnical laboratory. Figure 2 presents the testing set-up that consists of a steel tank (1) with a 2.5 m diameter and a 3.5 m height, filled up with the Aalborg University Sand no.1 (2) of known properties, see Table 1.



(a) (b)

Fig. 2. Laboratory set-up at Aalborg University geotechnical section

Table 1. Soil parameters of Aalborg sand no. 1 (Ibsen and Bødker 1994)

Soil parameter	Value	Unit
Specific grain density	2.64	[g/cm^3]
Maximum void ratio	0.854	[-]
Minimum void ratio	0.549	[-]
Grain size (50 % quantile)	0.14	[mm]
Uniformity coefficient	1.78	[-]

The sand layer of 2.2 m thickness is placed on top of a gravel layer (0.3 m), which is topped off by a geo-textile membrane (3) to prevent any sand deposition. The bottom of the tank is equipped with equally placed perforated pipes (4) that ensure an even pressure distribution during the saturation of sand or the gradient application. The sand is saturated and uniformly vibrated with a mechanical rod to get a desired soil relative density. An independent steel frame, holding a hydraulic piston (5) used for the installation tests, is surrounding the tank. The bucket model (6) is attached to the hydraulic piston prior each test. The tests carried out consist of two different types, the jacking installation where the hydraulic piston is used as a driving force and the suction installation where the suction pump (7) is attached to the bucket lid and creates a differential pressure inside the caisson. The differential pressure is the main driving force for suction installation. The analysis of both tests and their comparison leads to the isolation of the favorable seepage effects on the penetration resistance. The hydraulic piston is controlled through a control panel of the hydraulic system (8). The pore pressure transducers (9) are attached at the top of the soil tank. During the tests, a connection is made between them and the bucket foundation model to measure the excess pore pressure at the inside and outside skirt and the applied suction during the installation. The change in the pore pressure and also the change in soil stress is measured at the bottom of sand layer and at the side of the soil container (10). A mini CPT device with 15 mm diameter which measures the cone resistance of soil before and after each installation. The calculation of soil penetration resistance is based on cone resistance results.

The two tested models can be seen in Fig. 2 (a). The modular model consist of 21 trapezoidal modules and T-profile beams attached to each third connection between the sections as stiffeners. Table 2 shows all of geometrical specifications.

Table 2. Geometrical specifications for both bucket foundation models

Model	L [mm]	D [mm]	t [mm]	A_{side} [mm^2]	A_{tip} [mm^2]	A_{lid} [mm^2]	Mass [kg]
Round	1000	1000	3	6.26E6	9.40E3	776.0E3	214
Modular	988	~1000	1.7	8.23E6	8.58E3	748.3E3	244

Both models are equipped with valves at the lid that are connected to the pump during suction installation. The CPT after each test are preformed through those valves. The lid contains the connection channels for the measurements of the excess pore pressure. The channels have different length to measure the pressure at 1/3, 2/3 and 3/3 of the bucket skirt length and directly under the bucket lid. They are denoted as PP1-PP7, where PP1 is the outer location at the 1/3 of skirt length, then locations move down to the tip and again up at the inside skirt . PP7 is the location measuring excess pore pressure directly under the lid.

BUCKLING ANALYSIS

A comparison of a buckling resistance between the modular bucket and the regular round bucket indicates an increased resistance in favor for the modular bucket. A simulations were carried out in a commercial software Abaqus. Models used in the analysis are based on an eigenvalue buckling analysis using finite element method. Modelled geometries are similar to laboratory scaled prototypes but the same thickness is kept, 3 mm, so the buckling resistance can be compared. The modular bucket in this analysis does not include the inside stiffeners for simplicity. However, the full analysis performed for the need of the EUDP project shows that the stiffeners increase the buckling resistance by approximately 20% (EUDP, 2018).

The skirt of the foundation is modeled as a shell and the mesh consists of quadratic 8-noded elements. The simulations uses a linear elastic material model with $E = 210\ \mathrm{GPa}$ and $\nu = 0.3$ and account for the first five mode shapes for buckling. The boundary conditions applied in the models are pinned in top and bottom edges. An imposed edge pressure of 10^6 kPa is applied on the top edge and a constant side pressure of 10 kPa. Figure 3 shows deformed shapes caused by the first buckling mode on both models and the size of deformations. The eigenvalue for round model is equal to 38.8, which means that the structure exhibits the first buckling mode for the current load multiplied by that factor. For the modular model, the first eigenvalue is equal to 105.6. The comparison shows that the modular bucket has a buckling resistance that is around 2.7 times higher compared to the round model. This simple comparison confirms that the shape of the structure plays an important role with respect to buckling resistance. Another advantage in terms of the buckling resistance for modular shape is that it allows the inclusion of beam profiles in the inner edges of the modules, increasing even further the buckling limit. That increase on buckling resistance is beneficial in term of material usage optimization as smaller thickness would be required to provide similar resistance when comparing to a round shape.

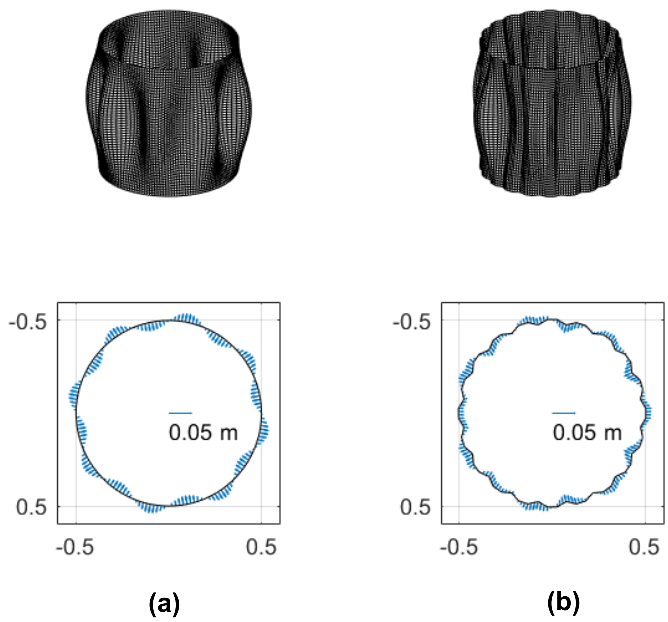


Fig. 3. Deformed shape of skirt for the first buckling mode

The flow induced by suction underneath the bucket lid is modeled using commercial software Plaxis 2D. The models performed in the analysis are only based on the flow analysis, which means that no deformations or loads are included in the calculation. The constitutive relation in the seepage analysis is the Darcy's law where the governing parameter is soil permeability.

Modelling of the seepage flow is necessary in order to quantify the theoretical limit of critical suction against piping during the installation. An axisymmetric model is used for simulations with diameter *D* and skirt length *L*. The installation is subdivided into a number of steps corresponding to a specific normalized penetration ratio *h/D* lying in the range from $0.1 < h/D < 1$, where the skirt inside the soil is modeled as an impermeable boundary condition for the flow. At each subdivision stage, the flow is assumed as steady state and therefore its results should only be used for permeable soils where the development of excess pore pressure occurs fast.

The axisymmetric boundary, the bottom boundary and the free side boundary are impermeable. An appropriate water head is applied on top surfaces, different for the surface inside the bucket and outside the bucket in order to simulate the applied suction. The model is first adjusted to replicate the laboratory conditions; the dimensions of the bucket are therefore $D = 1$ m and $L = 1$ m. The domain size is corresponding to the laboratory sand container, where the side and the bottom boundary are closed for the flow; the dimensions are the radius of the domain is 1.25 m and the height of the domain is 2.5 m Additionally, the model account for the changes in the soil plug permeability. The soil trapped inside the bucket becomes looser due to the seepage flow. Simulations assume the loosening of the inside soil plug to a different extend, what is controlled with a ratio of hydraulic conductivity between the inside soil plug and the outside soil, k_{fac}. The results are used as a theoretical limit for the critical suction and as a basis for the calculation of reduced soil penetration resistance due to the seepage flow. However, these are only valid for the specific laboratory conditions. The recommendation for the theoretical critical suction for the design in the real scale are derived from the numerical model with dimensions for the bucket to be $D = 8$ m and $L = 8$ m, and with the domain size of 40 m in the radial direction and 45 m in depth to avoid the effects of boundaries on the resulting flow. The mesh of the model is refined around the bucket skirt. The domain size analysis allows avoiding the boundary conditions influence on the results and the mesh analysis satisfies the convergences.

RESULTS

Suction installation performance

The laboratory set-up allows for both types of installation tests: the jacking installation tests and the suction installation tests. The former show the initial soil penetration resistance for the bucket foundation that is not affected by the seepage flow. The suction installation tests gives the total penetration resistance that the bucket foundation must overcome. Tests presented in this paper are performed in a dense sand, prepared for the relative soil density, I_D, of around 75 – 85 %. Figure 4 (a) depicts the total applied load during the jacking installation of chosen tests representing dense sand. Figure 4 (b) shows the applied pressure during the suction installations. Plain line represents the tests where the round bucket is installed, and the circles on the line represents the installation of modular bucket.

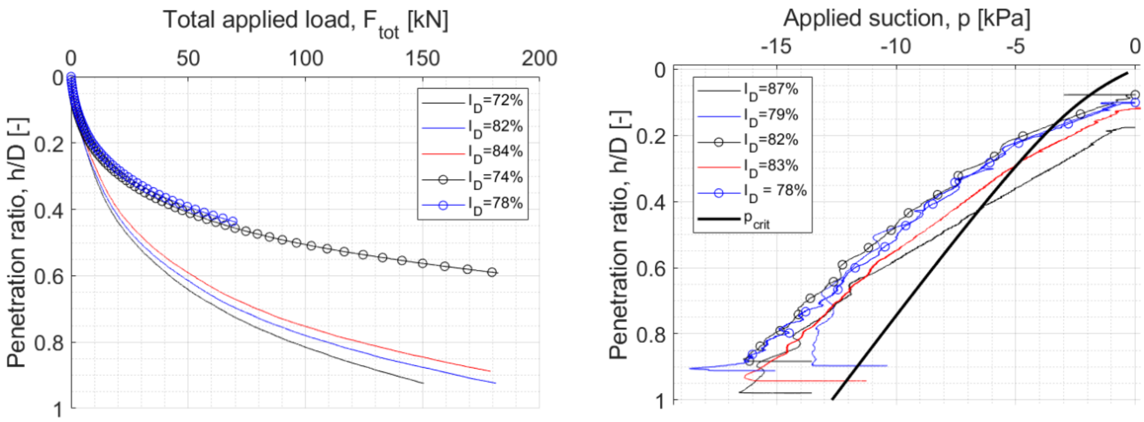


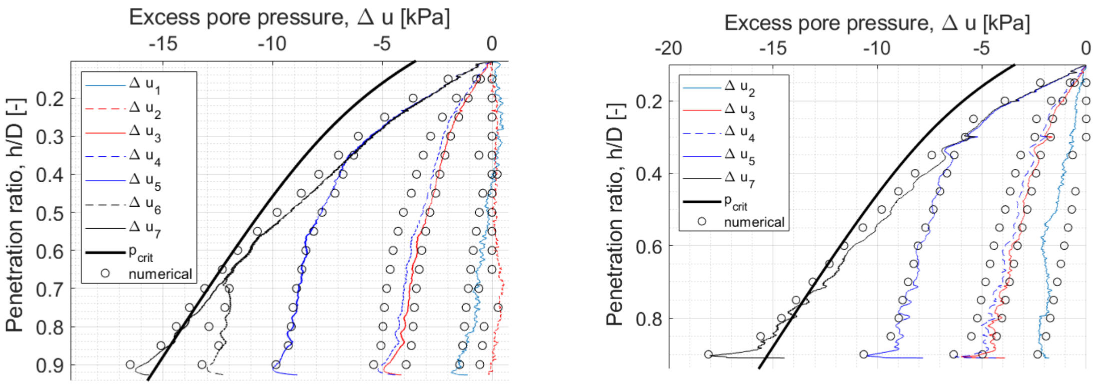
Fig. 4. (a) Total applied load during jacking installations and (b) applied pressure during suction installation

There is a significant difference in the total applied load during the jacking installation between the round and modular bucket model. The increased area of penetrated skirt and additional stiffeners inside has a great impact on the required load. However, the results of suction installation shows that the initial difference in the soil penetration resistance is almost negligible during the suction installation and there is almost no difference in the required suction. The critical suction plotted in fig. 4 (b) is recommended by Senders and Randolph (2009). The formula does not account for the increase permeability for the inside soil plug. The applied suction during all of the suction tests exceed this limit, without generating any piping channels.

Excess pore pressure development

The numerical simulations are performed for different models where k_{fac} is the changing factor. According to difference in the relative soil density, appropriate ratio is chosen. The expected model that should fit the laboratory results best was based on the results from the CPT performed before and after suction installation tests. According to the calculated relative soil density, the factor of permeability between inside and outside soil should be equal to around

1.7. However, the calculated critical suction against piping was still exceeded significantly. The best model fit was obtained for the ratio equal to 2.1, which assume the loosening of the soil plug from 80% of I_D to 20%. Figure 5 presents the results of the laboratory tests, where Δu_1 is the excess pore pressure measured by the pore pressure transducer PP1 and the rest of results follows the same numeration up to Δu_7 that corresponds to the applied suction under the bucket lid. The limit for the critical suction is acceptable, and the results of the excess pore pressure for different locations are with a reasonable fit. The results for the excess pore pressure at the tip are extracted not directly on the tip, as it is designed with no physical thickness, but in a close vicinity from the inside and the outside of the skirt. The small deviation was expected.



(a) (b)

Fig. 5. Comparison of the excess pore pressure developed around the bucket skirt with numerical results (a) for round model and (b) for modular model

CPT-based method application

The CPT-based method is applied on the results of the CPT tests performed before the suction installation and compared with the total load applied on the bucket during suction installation, see Fig. 6 (a). Two tests are chosen to compare the behavior of round bucket with modular bucket, $F_{tot,R}$ and $F_{tot,M}$ respectively, both in sand with I_D close to 80%. A significant reduction in the total applied load is observed when comparing to the results of the jacking installation presented in Fig. 4 (a).

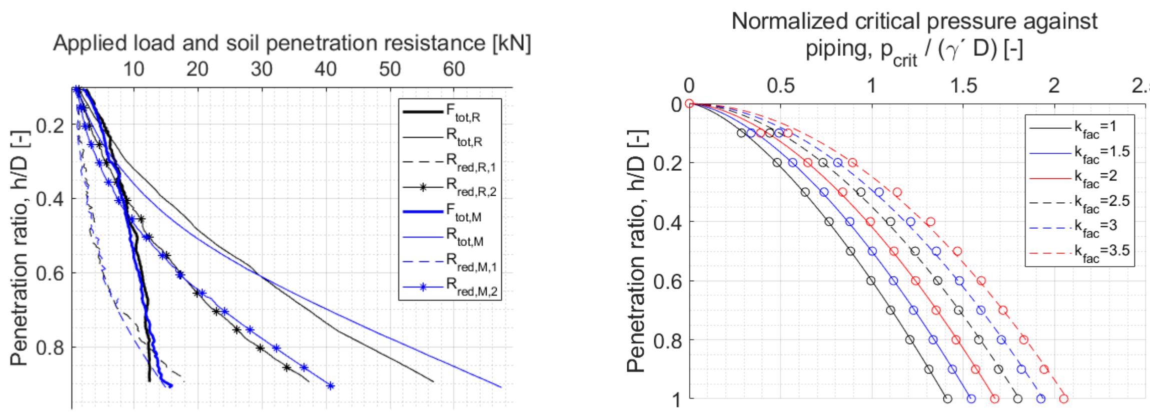


Fig. 6. (a) Applied load during suction installation, *F*, and calculated soil penetration resistance, *R*; (b) the limits for the critical suction for different k_{fac}

The total applied load is also significantly smaller from the total soil penetration resistance calculated from results of cone resistance, R_{tot}. When the reduction of the inside skirt friction and the tip resistance is applied according to eqs. (1-2), the calculated results, referred as $R_{red,1}$, are closer to the applied load, but underestimates the results. If the reduction is limited only to 50% (r=0.5 in eq.(2)), referred as $R_{red,2}$, the first part of the installation fits well, but when the penetration ratio increases above 0.5, the calculated resistance overestimates the real applied load. The empirical coefficients used in the method are 0.3 and 0.001 for k_p and k_f respectively.

Critical suction pressure

The critical suction limit recommended for the full scale design is based on the numerical model where the boundary conditions were adjusted to have no effect on the results of the seepage flow around the bucket skirt see Eq.(3).

$$\frac{p_{\text{crit}}}{\gamma' D} = (0.26\, k_{\text{fac}} + 1.15) \left(\frac{h}{D}\right)^{0.7 (k_{\text{fac}})^{-0.2}} \quad (3)$$

Figure 6 (b) shows the obtained results for the seepage analysis for six models where k_{fac} varies. However, in order to choose a correct ratio, a large database from the full-scale tests is required.

SUMMARY AND CONCLUSIONS

The paper presents the numerical and laboratory results concerning the installation of bucket foundation in dense sand. Two different models are presented in the paper. The buckling analysis compares the buckling resistance between the round and the modular model. The latter has higher resistance which means that higher suction pressure can be applied during its installation. When the performance of both models during the suction installation is compared, both are very similar and the difference in the required suction is negligible, even though the initial soil penetration resistance measured during jacking installation tests is significantly higher for the modular bucket. The seepage flow around the skirt induced by applied pressure diminishes those initial differences. At the same time, the modular bucket has more economical design. This demonstrates the potential of implementing the modular bucket on the large scale.

The flow is also responsible for the loosening effects in the soil plug. The reduction in the relative density, hence increased permeability has been confirmed by the CPT tests performed after suction installations. The numerical analysis of the seepage flow allows for a determination of the critical suction against piping. The recommendation for the full-scale model is given based on a different permeability ratio between the inside soil plug and the outside soil, but it should be confirmed with full-scale tests. Moreover, the CPT-based method does not fit perfectly to the results, so it is suggested that both, the inner friction and the tip resistance cannot be reduced to zero, but only to some extent. This should be proven by full-scale tests.

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