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Physical modelling of active suction for offshore renewables

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ABSTRACT: Active suction is investigated as a strategy to temporarily increase the tensile capacity of bucket foundation for offshore floating renewables, which are subjected to high extreme loads. A centrifuge testing campaign was carried out in the new 10 m diameter beam centrifuge at UWA, using a purpose built suction application device. Preliminary results are presented, demonstrating the performance of the testing setup and the potential of the active suction concept to increase tensile capacity by up to 70%.

1 INTRODUCTION

Floating renewable energy devices, such as wave energy converters and floating wind turbines, experience very high extreme loads during storm events. Designing anchoring systems to resist these extreme loads appears to be extremely costly and inefficient, especially in sandy sea beds, and strategies to avoid or reduce extreme loads are sought to significantly reduce the size (and cost) of anchoring systems (Gaudin et al. 2017).

One such strategy is the application of active suction on bucket foundations (also called suction caissons). The concept of active suction consists of pumping water from the inside of the caisson to actively apply a differential pressure across the lid. The additional resistance due to this differential pressure increases the tensile capacity beyond that mobilised by friction at the soil-skirt interface (under drained loading).

From a design point of view, this potentially results in a foundation design that relies on friction at soil-skirt interface to withstand operational loads and on the temporary additional tensile capacity generated from active suction, when extreme loads are expected (Figure 1).

The increase in tensile capacity through active suction was first investigated in the 1970s through laboratory tests (e.g. Helfrich et al. 1976, Wang et al. 1975), as a means to provide a more efficient short term (2–3 days) anchoring solution for deep water buoys, coring platforms, or submersibles. More recently, a centrifuge testing campaign was conducted to investigate active suction applied to caisson foundations for the stabilisation of a vessel equipped with cranes (Allersma et al. 2003). In each case, a linear increase of the tensile capacity with differential pressure applied was observed. However, no insights on the generated physical mechanism, soil conditions and flow regime obtained with active suction are available in the literature and significant uncertainties still govern the quantification of the capacity increase.

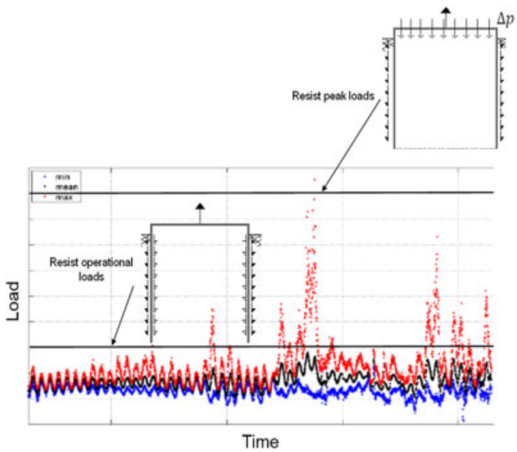

Figure 1. Load history of one mooring line of a WEC (after Herduin 2014). The active suction concept is represented as a means to resist the extreme peak loads, which can be almost three times larger than the operational loads.

The increase in tensile capacity generated by active suction is expected to be function of the differential pressure generated, the seepage regime within and around the caisson and its effect on the soil effective stresses (Fiumana et al. 2017).

To further investigate the key mechanisms governing active suction, an experimental campaign was carried out in the new 10 m diameter centrifuge at the University of Western Australia (UWA).

A new suction generation device was designed for this study, whereby suction was applied by lowering a water tank hydraulically connected to the inside of the caisson, hence creating a constant differential head pressure at a variable flow rate. This system differs from the syringe pump system used in UWA's 3.6 m diameter centrifuge for which a constant flow rate is generated at a varying suction pressure (House 2002). The constant differential head pressure is considered more appropriate for the investigation of active suction as the increase in uplift capacity can be directly associated to the constant differential pressure applied.

The testing programme presented in this paper was aimed at (i) quantifying the increase in foundation uplift capacity with respect to the differential pressure applied and the associated seepage regime in the soil, (ii) evaluating the time over which active suction can be sustained, and (iii) understanding the influence of the seepage regime on the soil behaviour, notably with respect to potential plug liquefaction and cavitation that may hamper the efficiency of active suction.

The paper presents the testing setup, the experimental procedure and some preliminary results that provide insights into the feasibility of active suction to anchor floating renewable energy devices.

2 EXPERIMENTAL SET UP

All the tests were carried out at a level of 40 g in water-saturated silica sand.

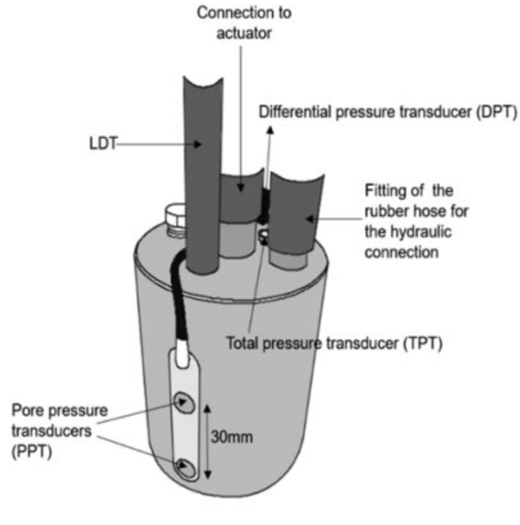

Figure 2. Scheme of the model caisson and instrumentation.

2.1 *Sample preparation*

The soil sample was contained in a strong box with a square base of 1000×1000 mm and a height of 500 mm.

The tests were conducted in UWA silica sand, which has been used extensively in centrifuge modelling at UWA. The properties of the sand are reported widely, e.g. Senders (2008) and Tran (2005). The sample was prepared by pluviating the silica sand over a 50 mm thick drainage layer of coarse sand covered by a layer of geotextile. The sample was subsequently levelled by vacuuming the excess sand from the surface in order to achieve a constant sample height of 200 mm. The sample was then saturated with water from the base of the strongbox, until the head of water reached 100 mm above the sand surface. The reconstitution process resulted in an effective unit weight for the sand of $\gamma' = 10.5\,\text{kN/m}^3$ and a relative density $D_r = 50\%$.

Soil characterisation was performed in-flight using a miniature cone penetrometer, 10 mm in diameter. Results indicated a linear increase of the penetration resistance, with a value of $q_c/\sigma'_{v0} = 150$, where q_c is the tip resistance and σ'_{v0} is the initial vertical effective stress in the soil at a depth of 70 mm (corresponding to the tip of the installed caisson). Tests performed in multiple locations in the sample showed very little variability, indicating good sample homogeneity.

2.2 *Foundation model and instrumentation*

The foundation model was manufactured from aluminium, with a diameter D equal to the skirt length L of 70 mm (aspect ratio $L/D = 1$), and a top plate 10 mm thick. A schematic of the model caisson and the instrumentation is presented in Figure 2.

The wall thickness, w_t, of the skirt is 3.5 mm ($t/D = 0.05$). This value is significantly larger than typical values for field scale caissons, but was necessary to accommodate pore pressure transducers on the inside and outside face of the skirt. As discussed later in the paper, the caisson was installed at 1g, modelling a wished-in place installation, so the thickness of the skirt does not interfere with the foundation uplift capacity as (i) soil disturbance due to penetration is limited and (ii) the inverse bearing capacity potentially mobilised at the skirt tip is a negligible component of the whole capacity, which is mainly developed from the friction mobilised along the skirt (e.g. Bye et al. 1995, Feld 2001, Houlsby & Byrne 2005a).

A differential pressure transducers (DPT) was fitted on the caisson lid to obtain a direct measure of the differential pressure generated by the active suction. The lid was also instrumented with an absolute total pressure transducer (TPT) that was used to measure the initial level of the water table, and to control it during the whole testing procedure. Both sensors have a capacity of 700 kPa.

Along the inside and the outside of the caisson skirt, two pairs of pore pressure transducers (PPTs) with a capacity of 500kPa, were installed, as shown in Figure 2. The top sensors (PPT_OT (outside) and PPT_IT (inside)) were placed 40 mm from the skirt tip and the bottom sensors (PPT_OB and PPT_IB) were located 10 mm from the tip. All the transducers were calibrated by placing the caisson in a pressure chamber and gradually increasing the ambient pressure to 250 kPa.

The caisson lid was fabricated with three fittings to allow connection to the actuator, the hydraulic connection for the suction application and a linear differential transducer (LDT). The LDT was used to obtain information on the plug heave during the 1g installation phase and during active suction uplift.

The actuator adopted for the caisson extraction was instrumented with a 2 kN axial load cell. The hydraulic connection for the suction application was a rubber tube 10 mm in diameter.

2.3 *Suction application device*

Suction installation of bucket foundations in centrifuge tests at UWA may be achieved using two modelling techniques as described below.

A syringe pump can be used, which applies suction by moving a cylindrical piston 50 mm in diameter at a maximum velocity of 3 mm/s. This system is able to generate a maximum flow rate of 5840 mm^3/s for a total volume of 384,945 mm^3 when completing a full stroke of 196 mm (Senders 2008). Although simple to implement and closer to actual prototype conditions, this system has three shortcomings:

1. The fixed volume of the syringe pump limits the duration of suction that can be generated,
2. A constant suction cannot be applied, unless the velocity of the syringe is linked to the suction value via a feedback loop and,
3. The maximum flow rate is not sufficient to generate suction in high permeability sand, resulting in the need to use a saturation fluid more viscous than water (such as silicon oil) to compensate (Senders, 2008).

To enable a better control of the suction applied as required by the present investigation, a gravity flow system was developed. Suction application by gravity flow was successfully implemented in 1g experiments by Tran (2005), by creating a head difference between the water level in the strongbox and the outlet of the hydraulic connection attached to the caisson. A measure of the flow rate was made by measuring the volume of water pumped, inferred from the change (over time) of measurements from pressure transducers placed on the bottom of a series of interconnected reservoirs collecting the water vacuumed from the inside of the caisson.

Taking advantage of the large dimensions of the strongbox, a gravity flow setup was developed for this project. The setup was designed to (i) enable a better control of the magnitude of the differential pressure applied across the lid of the caisson, (ii) sustain the differential pressure applied for a long period of time, and (iii) measure the flow rate generated.

The setup consists of a water tank with a volume of 5000 mm^3 connected to the inside of the caisson by a 10 mm diameter reinforced rubber tube and assembled on a linear actuator fitted on the side of the strongbox. By ensuring a saturated hydraulic connection with the caisson, equilibrium of the system is achieved when the water-filled tank is levelled with the water table in the sample. By lowering the tank to a targeted elevation, a constant head difference is created and a flow from the inside of the caisson to the water tank generated. By lowering the water tank continuously at a constant velocity, an increasing differential pressure can be generated, which can be useful to model suction installation. By bringing the tank above the water table in the centrifuge sample, the seepage can be reversed to generate reverse pumping and extraction of the caisson.

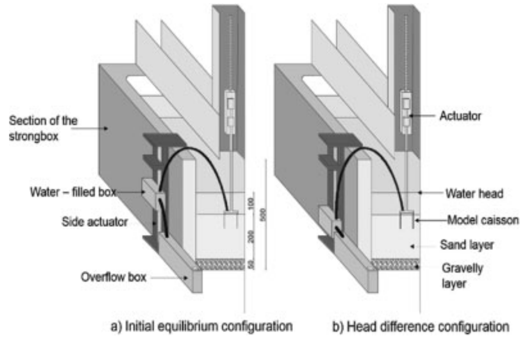

Figure 3. Schematic representation of the suction application device.

The maximum allowable differential pressure Δp is dependent on the acceleration level N:

$$\Delta p=\Delta h\cdot Ng\cdot\gamma_w \quad (1)$$

where Δh is the maximum head difference that can be generated by adjustment of the water tank height using the linear actuator (200 mm) and γ_w is the unit weight of water. At 40 g, this results in a maximum head pressure of 80 kPa.

In order for the differential pressure to be generated, the flow created by the head pressure difference must be higher than the seepage flow established in the soil under the differential pressure created across the lid (Fiumana et al. 2017). In sand, very high seepage is expected, and the setup must feature an appropriate hydraulic connection enabling a high flow rate between the caisson and the water tank. In the present case, a 10 mm rubber tube was used following some preliminary tests that showed that no suction was generated with lower diameter tubes.

The water flowing from the caisson to the water tank is allowed to overflow, through a hose of equal diameter, into a second tank placed at the base of the actuator and instrumented with a pressure transducer. The measure of pressure with time in the overflow tank provides an estimation of the flow rate generated by the active suction. The overflow tank has a length of 250 mm, a height of 100 mm and a width of 50 mm, such that the maximum volume capacity is 1250000 mm^3.

A schematic representation of the gravity flow system is presented in Figure 3.

2.4 *Experimental procedure and programme*

Considering the significant skirt thickness, installation was performed by simply penetrating the caisson using the electrical actuator at 1 g until the desired skirt penetration was reached. A gap of approximately 10 mm was left between the caisson lid and the soil surface, as informed by the LDT measurements. The purpose of this gap was to ensure a uniform differential pressure distribution when the active suction was applied.

Table 1. Testing programme and parameters.

Test name	Extraction type	Uplift velocity mm/s	Elevation below the water table mm	Active suction generated kPa
D	Drained	0.1	–	–
PU	Partially undrained	10	–	
AS1	Active suction	0.1	100	28
AS2	Active suction	0.1	75	18

The centrifuge was subsequently spun to 40 g prior to the caisson uplift tests. No movement of the LDT was detected during this phase, suggesting that no further settlement of the caisson occurred while increasing the g-level. For uplift tests without active suction, which were performed as baseline reference cases, the caisson was pulled out at constant velocity. For tests where active suction was applied, tests were performed in two stages. Firstly a targeted active suction was applied by lowering the water tank to the required elevation. Secondly, after a steady flow regime was established and constant differential pressure across the caisson lid achieved, the caisson was uplifted at a constant velocity. Approximately 4 s was needed for the pore pressures to stabilise.

Four tests from a comprehensive testing program are reported in this paper. The first two tests, D and PU, were undertaken without active suction at an uplift velocity of 0.1 and 10 mm/s respectively (covering three orders of magnitude of uplift velocity), aiming to replicate drained and partially undrained conditions. In the former, the caisson was fully vented, such that the uplift resistance is solely generated by the internal and external friction along the skirt. The 0.1 mm/s uplift rate resulted in drained extraction. In the latter (10 mm/s uplift rate), the caisson was sealed, such that some passive suction was generated at the lid invert, resulting in partially undrained conditions. It is acknowledged that fully undrained conditions could not be achieved with the current setup considering the high permeability of the sand and the limited maximum extraction velocity.

The remaining two tests featured active suction (AS1 and AS2), with varying magnitude of suction applied and two different uplift velocities, as presented in Table 1.

3 RESULTS AND DISCUSSION

3.1 *Tests without active suction*

Results obtained for tests performed without active suction are shown in Figure 4. The extraction resistance V is reported in terms of the pressure V/A as a function of the extraction depth z. Note that $p = 0$ mm indicates full extraction of the caisson (i.e. the tip of the skirt is at the soil surface).

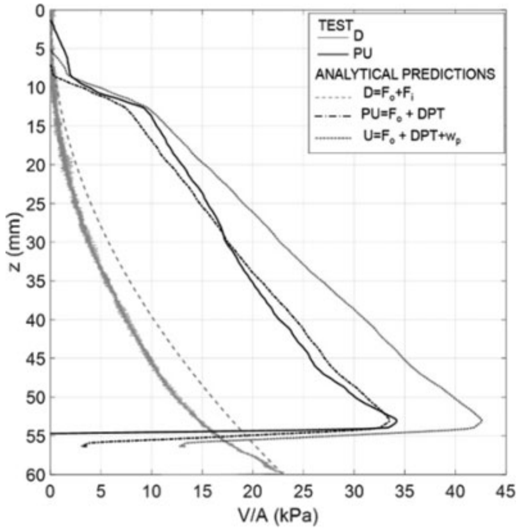

Figure 4. Extraction capacity for tests without active suction.

As evident from Figure 4, the drained uplift capacity of the caisson (Test D at $v = 0.1$ mm/s, Table 1) is correctly described by the sum of the friction mobilised along the inside and outside of the skirt. The frictional terms were computed as (Bye et al. 1995, Feld 2001, Houlsby & Byrne 2005a):

$$F_{i(o)} = \gamma'\cdot(z^2/2)\cdot(K\tan\delta)\pi D_{i(o)} \quad (2)$$

The term $K \tan\delta$ is the product of the earth pressure coefficient K and the interface friction angle, δ. A value of $K \tan\delta = 0.28$ was adopted, which is considered appropriate for the smooth stainless steel caisson skirt.

The response of the partially undrained tests undertaken at an uplift velocity $v = 10$ mm/s (Test PU, Table 1), is also reported in Figure 4. Results show a 70% increase in maximum uplift resistance, which is associated with the generation of negative excess pore pressure during extraction at the lid invert (Figure 5).

A reasonable approximation of the partially undraiend uplift resistance is obtained by adding the excessive negative pore pressure measured druing the test to the external frictional resistance, computed from (2) (Figure 4). This is in agreement with existing solutions for the tensile capacity of caisson foundations under rapid loads presented by Houlsby et al. (2005). No contributions to the capacity arises from the plug weight, indicating that fully undrained conditions couldn't be achieved at this uplift velocity.

The theoretical undrained response is presented for comparison in Figure 4, computing the plug weight w_p as:

$$w_p = \gamma'\pi(D_i/2)^2 z \quad (3)$$

The plug weight adds to the external friction F_o and excessive negative pore pressure generated during

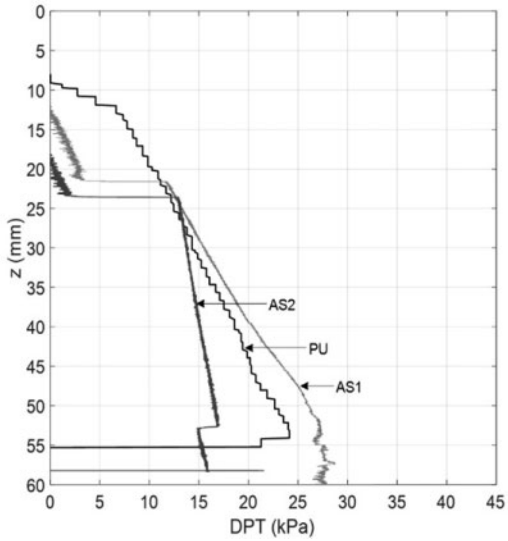

Figure 5. Differential pressures generated by active suction and compared with excess negative pore pressure generated from rapid uplift.

extraction. In case of a full reverse end bearing mechanism, with a gap forming at the base of the soil plug, only partial seepage might occur, with the excess negative pore pressure tranferred to the base (e.g. Senders 2008, Fiumana et al. 2017). This would result in lower magnitudes of differential pressure across the caisson lid with respect to partially undrained conditions. However, the differential pressure recorded during the test PU was considered for this prediction, giving an upper bound solution. In summary, Figure 4 indicates that the fully undrained capacity is about twice the fully drained capacity (42 kPa and 23 kPa, respectively), and the partially undrained capacity mobilised at $v = 10$ mm/s is about 70% higher than the fully drained capacity.

3.2 *Tests with active suction*

Tests performed with active suction, AS1 and AS2, also showed a capacity increase with respect to the drained capacity (Figure 6). The different target elevation assigned to the water tank prior to extraction, resulted in a different value of differential pressure generated (Figure 5), affecting the extraction response.

In test AS1 an initial differential pressure of 28 kPa developed, which remained constant for about 10 mm of extraction (Figure 5). This trend was reflected in the capacity mobilised during extraction, which was also held constant for the same amount of upward displacement (Figure 6) reaching a 60% increase after 5 mm extraction, with respect to the drained capacity.

For test AS2 the maximum differential pressure generated was around 18 kPa (Figure 5). However, it resulted in the initial highest capacity with a peak uplift resistance of 35 kPa, about 70% high er than the drained capacity (Figure 6). The uplift resistance

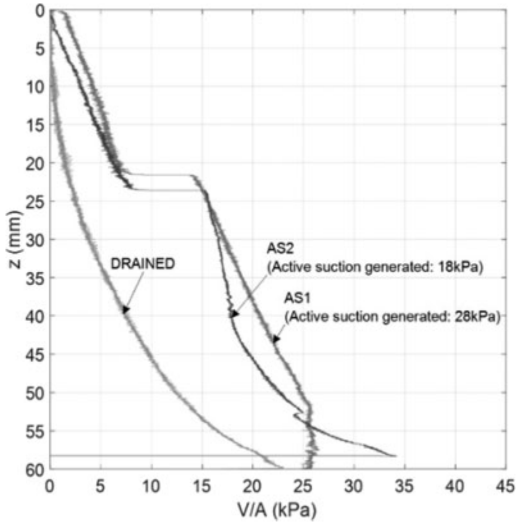

Figure 6. Extraction capacity for tests with active suction.

of AS2 decreased almost in parallel with the drained capacity for 20 mm, despite the differential pressure decreasing with a lower gradient with respect to AS1, as shown in Figure 5.

These results suggest that the magnitude of the differential pressure governs the seepage in and around the caisson and the uplift mechanism generated during uplift and hence the uplift capacity. Interestingly, the highest active suction may not result in the highest uplift resistance.

4 CONCLUSIONS

A centrifuge testing campaign was performed in the new 10 m diameter beam centrifuge at UWA to investigate the effect of active suction on the uplift capacity of caisson foundations. The instrumentation provided insights into the increase in uplift resistance due to active suction.

A new gravity based suction application device was developed, which enabled constant active suction to be applied with varying flow rate. A preliminary testing campaign was performed, mainly aiming to validate the concept of active suction.

Provided that an adequate head pressure is applied, active suction can be generated and maintained, resulting in an increase in uplift capacity.

An increase in capacity of up to 35 kPa was observed upon application of an active suction of about 18 kPa, corresponding to 70% of the drained capacity. Interestingly, the uplift capacity upon application of active suction is close to that measured under partially undrained conditions upon rapid uplift.

However, a different response was observed between partially undrained tests and active suction tests, as a consequence of the two different magnitudes of differential pressure generated. For active suction tests, the seepage process established in the soil around the caisson seems to have a significant influence on the mechanism governing the uplift resistance of the caisson.

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