Physical Modelling in Geotechnics

Response of suction buckets in layered soils under storm loading

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ABSTRACT: Layered soils are frequently encountered in intermediate water depths, where suction bucket jackets are considered an economically competitive foundation for offshore wind turbines. Permanent tilting can make the turbine inoperable, such that excessive differential movement between buckets must be avoided. This paper presents results from centrifuge tests designed to investigate the suction bucket response to sequences of storm loading in a clay over sand soil profile. Results indicate the suction buckets in clay over sand can sustain a 0 kPa mean stress with transient tensile loads reaching up to 1.9 times the tensile resistance with negligible uplift. For a mean compressive stress, the bucket experiences net settlement, even with excursions into tension reaching up to 2.8 times the tensile resistance.

Keywords: suction bucket jackets, centrifuge modelling, layered soils.

1 INTRODUCTION

Suction Bucket Jackets (SBJs) are increasingly considered as a foundation solution for offshore wind turbines. In a SBJ system, the overturning moment caused by horizontal loads is typically resisted by a 'push-pull' effect between the windward (reducing vertical load) and leeward (increasing vertical load) buckets. Of particular concern is the movements experienced by the windward bucket, as settlement for the leeward bucket is expected to be limited due to the large bearing resistance in compression.

Suction bucket response to vertical cyclic loading has been studied in uniform soils (Kelly et al., 2006; Bienen et al., 2018b, Low et al., 2020; Stapelfeldt et al., 2020). However, experimental data in layered soils, which are frequently encountered in intermediate water depths where SBJ are economically competitive, are scarcer (Stapelfeldt et al., 2021). Furthermore, most of the available data are from experiments that explored packets of uniform cyclic loading, which is argued to lead to more onerous design than realistic storm loading (Low et al., 2020). This paper considers data from centrifuge tests on suction buckets subjected to realistic storm loading in clay over sand, addressing the dearth of experimental data for this particular design scenario.

2 EXPERIMENTAL DETAILS

This paper considers test data from two suction bucket model tests that form part of a much broader testing programme, aimed at providing insights on the response of suction buckets in layered soils when subjected to a range of cyclic loading conditions. The experiments were carried out at an acceleration of 100g using the 3.6 m diameter beam centrifuge (Randolph et al., 1991) at the National Geotechnical Centrifuge Facility (NGCF) located at The University of Western Australia. The tests were conducted in a sample comprising a ~50 mm (5 m at prototype scale) overconsolidated kaolin clay layer overlying dense silica sand and involved suction assisted installation of the bucket before applying packets of storm loading.

2.1 Experimental arrangement

The experimental arrangement is similar to that used in Bienen et al., (2018a), and only a brief description is provided here. The setup comprises an actuator to control the bucket load/movement, a motor to operate the three-way valve at the top of the bucket, allowing the bucket to be vented, sealed or connected to a syringe pump, used to evacuate fluid from inside the bucket, leading to a pressure differential across the bucket lid that enables suction installation. A camera was used to monitor the three-way valve position and a linear displacement transducer was used to measure vertical displacement of the bucket.

The model suction bucket has a skirt length, L, and a diameter, D = 80 mm, hence an aspect ratio, L/D = 1. The bucket was fabricated from aluminium and then anodised to give an average roughness of R_a = 0.435 μm, such that for the silica sand used in these experiments (d_{50} = 0.18 mm; Chow et al. 2019) leads to a relative roughness of R_a/d_{50} = 0.0024 allowing the surface to be considered smooth (Dietz, 2000). The model is instrumented with two total pressure transducers (TPTs) and two pore pressure transducers (PPTs). One TPT is located at the top of the lid (to measure hydrostatic pressure of the free fluid above the bucket) while the other TPT and the PPTs are positioned at the lid invert (Figure 1).

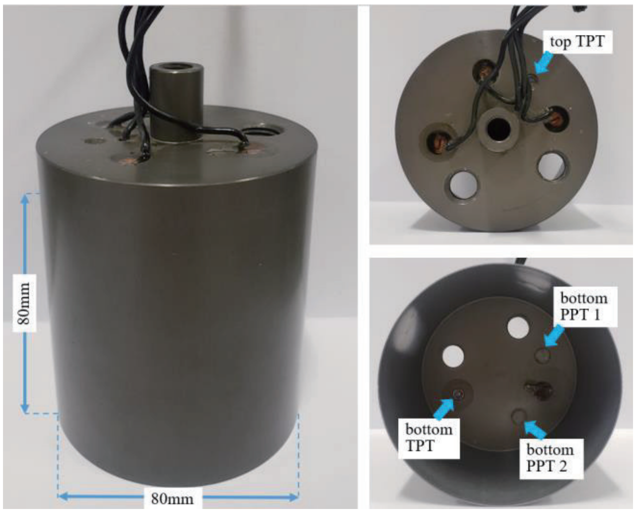

Fig. 1. Suction bucket model.

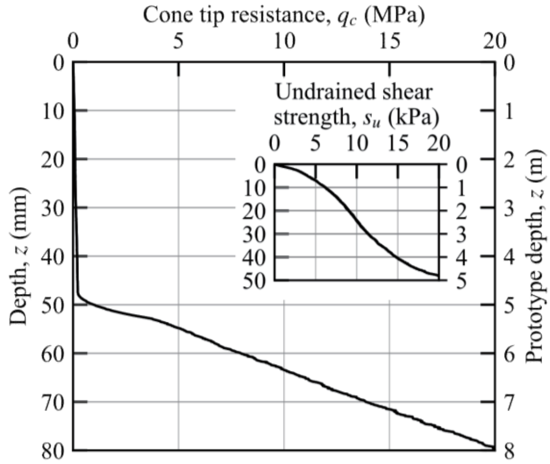

Fig. 2. Depth profiles of cone resistance and undrained shear strength.

2.2 Sample preparation and characterization

The sample was prepared in a sample container (or 'strongbox') measuring 390 mm (width) × 650 mm (length) × 325 mm (depth), as a 50 mm layer of kaolin clay overlying a 90 mm layer of silica sand. The coefficient of vertical consolidation of the clay is estimated to be about c_v = 5 m^2/year (at stress levels relevant to these experiments), whereas c_v > 300 m^2/year for the sand (when saturated with the 100 cSt pore fluid). Hence the drainage response is expected to be undrained in the clay and drained in the sand for the loading conditions applied in these experiments (described later).

The sand layer was prepared by dry pluviation targeting a relative density of 90%. Saturation was carried out from the base of the sand using cellulose ether (Methocel^{TM}) with a viscosity of 100 cSt, such that at the testing acceleration of 100g, the permeability is the same as in the equivalent (water saturated) prototype. The clay was prepared as a slurry with a water content of 282%, and after mixing under a vacuum for 24 hours, was transferred to a separate, identical strongbox and loaded under oedometric conditions in a consolidation press to a final pressure of 250 kPa. After consolidation, the strongbox was disassembled and a ~50 mm thick clay layer was cut from the surface of the consolidated clay sample and placed on top of the saturated sand. A ~120 mm layer of free water was maintained above the sample over the course of testing.

Sample characterisation was carried out using model scale CPT and T-bar (in clay only) penetrometers. Figure 2 shows depth profiles of undrained shear strength, s_u, in the clay layer derived from the T-bar, and of cone tip resistance, q_c, in the underlying sand layer. Sand relative density of ~90% was determined from global measurements of the saturated sand mass and volume.

2.3 Testing procedure

The installation procedure follows that presented in Bienen et al., (2018a) and is only described here in brief. The model was initially penetrated under displacement control at a rate of 0.1 mm/s until the targeted penetration resistance of 70 kPa was reached, representing the applied stress from the self-weight of the bucket. The motor was than activated to turn the three-way valve, connecting the bucket to the syringe pump for suction installation. Suction installation was carried out at a piston displacement rate of 0.5 mm/s, achieving a bucket penetration rate of 0.2 mm/s (or a flow rate of 980 mm^3/s). The syringe pump piston was stopped when the bucket penetration stopped at a skirt penetration of 66.5 mm (model scale). The three-way valve was then operated to vent the bucket, before further installing the bucket under displacement control at 0.1 mm/s to achieve full top plate contact with the soil plug. The valve was then operated to seal the bucket and the applied stress was increased to 116 kPa, before commencing a pre-shearing stage of 400 cycles around 116 kPa with an amplitude of ±6 kPa, simulating the weight of the turbine and the bedding-in process prior to storm loading. Finally, the applied stress was reduced to the target mean stress of 0 kPa or 36 kPa, depending on the test, for the cyclic loading. The storm load sequence followed the same pattern as utilised in Low et al. (2020) (figure 3), which is based on a 6-hour duration storm load composition (Andersen, 1991). The largest load cycle occurs in the middle of the storm, and the subsequent load cycles (which are percentages of the maximum load) are placed around the peak load in a way to simulate the ramp -up/ramp-down of real storms.

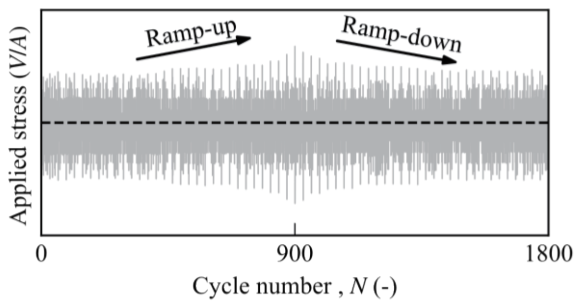

Fig. 3. Storm loading.

To investigate the effect of changes to mean stress, two tests with different mean stress levels were conducted: B1 at 0 kPa and B2 at 36 kPa. Four storm sequences were applied in each test. The cyclic loading amplitude was progressively increased in each sequence to explore load amplitude effects. A waiting period of 50 minutes was allowed between load sequences for pore pressure dissipation, accounting for calmer weather conditions between storm events. In both tests the cyclic loading frequency was 0.6 Hz. An upward movement of 0.1L (8 mm) was adopted as the failure criteria. Hence the actuator was programmed to switch to displacement control and hold position if this limit was reached during the cyclic loading. Table 1 presents the mean load and the maximum cyclic stress amplitude of each storm.

Table 1. Cyclic load test summary.

Test	Mean stress (kPa)	Sequence	Maximum cyclic stress ampl. (kPa)
B1	0	1st	56
		2nd	84
		3rd	112
		4th	168*
B2	36	1st	56
		2nd	84
		3rd	112
		4th	168

*Not achieved as the bucket failed prior to peak load.

After the cyclic loading sequence, the three-way valve was operated to vent the bucket, before extracting the bucket at 0.1 mm/s to access the tensile resistance. This extraction rate is expected to lead to an undrained response in the clay and a drained response in the sand.

3 RESULTS AND DISCUSSION

3.1 Installation and tensile resistance

The installation and tensile resistance with depth for both tests B1 and B2 are shown in Figure 4. Installation resistance increases sharply at around 48 mm for test B1 and 49 mm for test B2, indicating the boundary to the underlaying sand, as also suggested by the profile of cone resistance in Figure 2. The self-weight stress of 70 kPa was sufficient to penetrate through the clay layer, reaching the underlying sand. The gradient of penetration resistance with depth is observed to reduce at the early stages of suction installation (~ 51 mm). This indicates uplift of the clay plug, causing suction to be transferred to the underlying sand layer, with the associated seepage leading to a reduction in skirt tip resistance. Suction installation was halted when no further penetration was observed, which is likely to have been caused by contact of the clay plug with the invert of the bucket lid (as clay was observed in the tube to the syringe pump) preventing further suction transfer. As noted earlier in the paper, complete penetration, characterised by a sharp increase in penetration resistance, was achieved by further jacking the bucket into the soil until a depth of approximately 77 mm and 75.5 mm in tests B1 and B2 respectively. Commencement of jacking coincides with a significant increase in penetration resistance, confirming that clay plug uplift and, consequently, skirt tip resistance reduction, took place during suction installation.

During the vented extractions, zero excess pore pressure was measured at the lid invert, such that tensile resistance was derived solely from skirt friction. Figure 4 shows that the peak tensile resistance in Tests B1 and B2 are 24 kPa and 44 kPa respectively. The lower peak tensile resistance in test B1 is due to the higher upward movement during cyclic loading in this test, which led to a shallower embedment (and hence less skirt area in contact with the soil) at the start of extraction. Despite these differences the extraction curves align reasonably well.

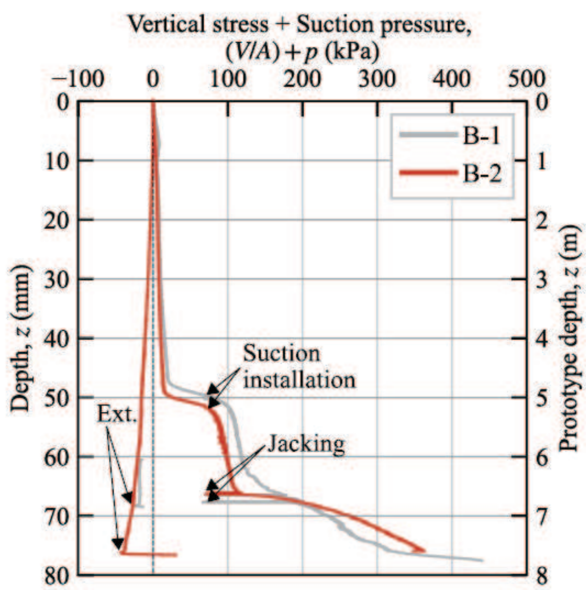

Fig. 4. Installation and extraction resistance.

3.2 Response under cyclic vertical loading

Figure 5 shows the evolution of applied stress, excess pore pressure and displacement for tests B1 and B2. During the 1st and 2nd storm, the response in test B1 was mainly elastic, despite the peak load in the 2nd storm reaching 1.9 times the tensile resistance (44 kPa). In the 3rd storm, the bucket experienced noticeable uplift as the storm intensity increased, although the resultant upward displacement after the storm was only 0.5% of the skirt embedment, which is likely to be tolerable in practice. A mean load of 0 kPa with excursions reaching up to 2.5 times the tensile resistance could be sustained. This contrast with previous tests in clay over sand where packets of uniform cyclic loading featuring up to 2222 cycles around a low compressive mean stress (8 kPa) caused the bucket to extract (Stapelfeldt et al., 2021) for tensile loads above the drained resistance. This suggests that storm cyclic loading may be less severe than packets of uniform cyclic loading, leading to reduced accumulated uplift. However, as a caveat, the models used in the two testing campaigns have different skirt length (and hence a different tensile resistance) and involved a different mean stress. Test B1 reached the failure criteria (0.1L of upward displacement) during the 4th storm, at which point the actuator was switched to displacement control to hold the position.

Adopting the compressive mean stress of 36 kPa in test B2 resulted in net settlement. Negligible movement was observed during the first two storms, but for the higher amplitude storms, the bucket experienced net settlement, even with tensile loads reaching up to 2.8 times the tensile resistance. This shows that the mean stress impacts the net displacement direction, consistent with findings for packets of uniform cyclic loading in clay over sand (Stapelfeldt et al., 2021).

Figure 6 also shows the influence of load history on the accumulation of displacement. In test B1, as the 3rd storm intensifies, bucket uplift starts to accumulate closer to the peak of the storm, where larger tensile loads are applied. However, as the storm intensity diminishes, this trend reverses, with net settlement taking place, despite the same loads being applied (as the storm is symmetrical). Although less obvious, similar behaviour can be observed in test B2 during the 4th storm, where settlement occurs as the storm intensifies, followed by a reduction in the rate of settlement as the storm intensity reduces. The implication of these observations is that displacement accumulation in a given cycle cannot be determined solely by the load characteristics, as it is also affected by the loading history.

Figure 6 shows the stress amplitude and excess pore pressure during the 3rd storm prior to the peak load, when uplift occurred in test B1 and negligible displacement occurred in test B2. Excess pore pressure at the lid invert cycles with the applied load in both tests, indicating an undrained response at the lid invert. This agrees with observations in sand (Bienen et al., 2018b) and clay over sand (Stapelfeldt et al., 2021) for uniform cyclic loading.

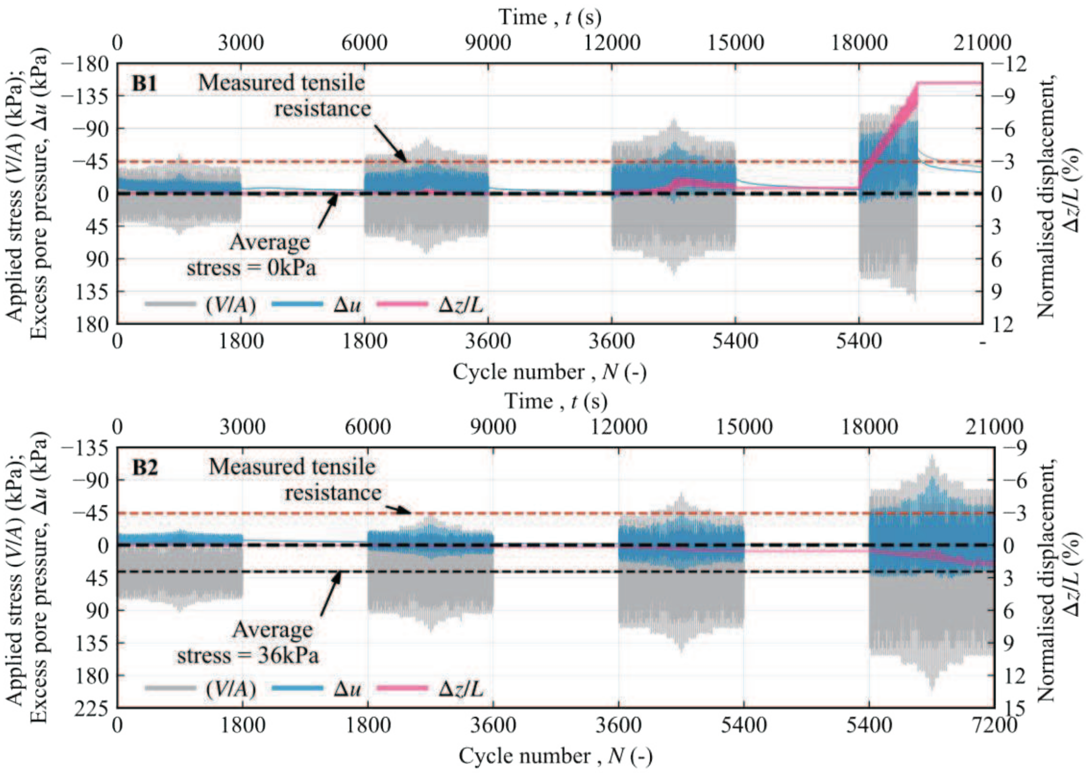

Fig. 5. Applied stress, excess pore pressure and accumulated displacement for tests B1 (above) and B2 (below).

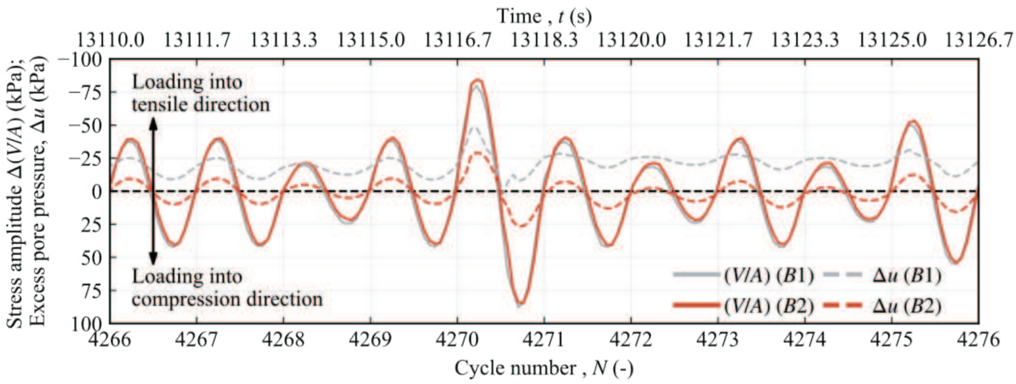

Fig. 6. Response to cyclic loading – 3rd storm intensification phase.

During the 3rd storm, excess pore pressure cycles around 0 kPa in test B2 while in test B1 it cycles around -25 kPa. The accumulated negative excess pore pressure at the lid invert during test B1 is likely to be related to the plug uplift, as pointed out in Stapelfeldt et al. (2021). Although further investigation is needed, this seems to be a key aspect to understand the response of suction buckets in clay over sand.

4 CONCLUSION

This paper provides experimental evidence of suction bucket response in clay over sand subjected to realistic storm loading.

Results show that a 0 kPa mean stress with excursions into tension of up to 2.5 the measured tensile resistance can be withstood. Comparisons with previous reported results (Stapelfeldt et al., 2021), where packets of uniform cycles loading were applied, suggests that storm loading conditions are less severe in terms of accumulation of displacement. Furthermore, under the same sequence of cyclic loading, a zero average stress leads to a ratcheting response, where the bucket loses embedment, whereas under a compressive average stress the bucket experiences settlement, agreeing with observations for packets of uniform cyclic loading (Stapelfeldt et al., 2021).

The accumulation of displacement in clay over sand appears to be dependent on loading history. The effect of the loading history was particularly noticeable for the bucket loaded with 0 kPa mean stress and when larger loads were applied.

Negative excess pore pressure accumulates at the lid invert when the bucket experiences uplift. This seems to be related to the plug being uplifted during the cyclic loading, which may be a key aspect of the suction bucket response in clay over sand. This shows that the load-transfer mechanism in clay over sand is complex and further investigation is needed.

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