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Physical modelling of deep screw piles in medium-dense sands for floating wind applications

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ABSTRACT: This paper presents centrifuge testing to investigate the uplift capacity of a "deep" screw pile installed in medium dense sand whilst varying the advancement ratio (AR) during installation. Although tested as individuals these piles are designed to form part of a group of nine piles designed as a single mooring point for floating wind applications. Previous research on the uplift capacity of large screw piles for offshore application has focussed on shallow failure mechanism where the failure surface propagates towards the soil surface inclined at the dilation angle. However, there is limited research on the deep failure mechanism of large screw piles when subjected to uplift loading. It is thought that "deep" screw piles may generate larger uplift capacity due to an increase in helix depth and the added contribution (often ignored onshore) of skin friction occurring along the longer pile shaft. Physical centrifuge modelling was used to investigate the uplift capacity of a deep screw pile at various advancement ratios (ARs). The tested screw pile had an embedment ratio of 17.5. The AR was varied below the industrial guidelines known as pitch-matched installation. The results indicated that by reducing the AR (known as over-flighting) to 0.5 and 0.25, the uplift capacity increased by 53% and 40% respectively, whilst also reducing the installation crowd force and even generating pile self-pull-in.

1 INTRODUCTION

The first recorded use of screw piles was in 1836 by Alexander Mitchell for marine applications (Little, 1961). Since then, screw piles have mostly been used in onshore related problems such as foundations for telecommunication towers and bridges (Harnish and El Naggar, 2017) at a relatively smaller size. However, due to their significant uplift capacity and silent installation, they have been proposed as possible alternatives to straight shafted piles (SSPs) as anchors for Floating Offshore Wind Turbines (FOWTs) (Lloyd's Register, 2024; Al-Baghdadi, 2018; Byrne and Houlsby, 2015; Davidson et al., 2022; Cerfontaine et al., 2020; 2023a).

Screw piles typically consist of a hollow slender shaft with one or multiple helices welded or bolted to the lower portions of the shaft. The installation method involves applying a combined rotational force and a compressive force which are termed torque and crowd force, respectively.

The mode of installation of screw piles is best described by the advancement ratio (AR). This term (i.e., AR) was first defined by Bradshaw et al. (2019) as the vertical distance per rotation over the helix depth and is expressed as:

$$AR = \frac{\Delta z}{P_h} \tag{1}$$

wherein Δ_z is the vertical penetration distance per full rotation; P_h is the helix pitch (or depth) (shown in Figure 1). Industrial guidance on the recommended AR is equal to 1 ± 0.2 and is termed pitch-matched or 'perfect' installation (BSI, 2015; Perko, 2009; Lutenegger, 2019). However, recent studies in dry sand have shown that by reducing the AR (known as over-flighting) there is a reduction in the measured installation vertical (crowd) force (F_z) and a significant increase in the subsequent in-place uplift capacity. This change in installation behaviour is AR dependant where the surrounding soil during installation is progressively compressed by the vertical movement of the soil particles through the helix which increases the residual stress, changes the soil relative density (D_r) around the helix, and creates a tensile pull-in installation force (Cerfontaine et al., 2023b). The increase in capacity, residual stress and reduction in compressive crowd force when varying the AR was observed in DEM simulations conducted by Sharif et al. (2021).

When a screw pile is subjected to uplift, the failure mechanism is described in two ways: shallow and deep. The change in mechanism depends on the soil relative density and the ratio of the pile embedment (H) to the helix diameter (D_h). Typically, in the literature, an embedment ratio (H/D_h) of less than 7 is considered shallow, whereas an embedment ratio greater than 10 is considered deep (Perko, 2009). A transitional mechanism may form between this range. The majority of research on the uplift capacity of large screw piles for offshore applications has focused on the shallow mechanism; whereby, the failure surface propagates towards the soil surface at the dilation angle (Cerfontaine et al., 2020; Giampa et al., 2019) as pile helix diameters are much larger than those onshore. Perko (2009) postulated that the deep behaviour mechanism involves failure locally around the helix and shaft resulting in similar bearing capacity factors in both compression and tension loading and is more common in smaller onshore piles.

Although deep screw piles may have relatively smaller helices, they should be considered as an alternative anchor foundation for FOWTs as they may provide larger capacities, significantly reduce the installation requirements, and may be suited for screw pile groups (Bradshaw et al., 2022) for fixed or anchored structures e.g., replacement for a single larger anchor or pile. There is, however, limited research on the deployment of smaller, deeper anchors in groups and more work is required to provide insight for industry adoption in this area.

The purpose of this study is to provide some confidence for the industry in this technology by conducting physical centrifuge modelling to investigate the uplift capacity of a deep screw pile installed in medium-dense sand (55%) at AR = 1.0, 0.5 and 0.25 characterised initially as single piles. In the future, this work will be extended to investigate the behaviour of groups of "deep" screw piles as anchorage for floating wind.

2 METHODOLOGY

2.1 Centrifuge modelling

The tests for this paper were conducted using the University of Dundee's Actidyn C67-2 3m radius geotechnical beam centrifuge. Each test was conducted in the same 500mm × 800mm × 550mm strong box which was filled with dry sand. It has been shown that the same effective stress in saturated sand can be achieved by altering the g-level with respect to the scaling factor (Davidson et al., 2022; Li et al., 2010). The approach taken in this study was as follows: a scaling factor of 1:30 was used to calculate the model scale dimensions of the pile model; and each test was conducted in dry sand at $19g$ which exhibited the same effective stress of saturated sand at the scaling factor ($30g$).

The equipment used in this study was designed specifically to install and load a screw pile in one flight (single centrifuge operation) (Al-Baghdadi, 2018; Al-Baghdadi et al., 2016; Davidson et al., 2022). Two-servo-motors allowed for precise control of the vertical and rotational displacement. A WPS500-MK30 draw wire was used to measure the axial displacement. A loadcell, from Novatech Measurements Limited, with a torque capacity range of -40Nm to 40Nm and a force capacity range of -5kN to 5kN, was used to measure the installation requirements at the top of the pile model.

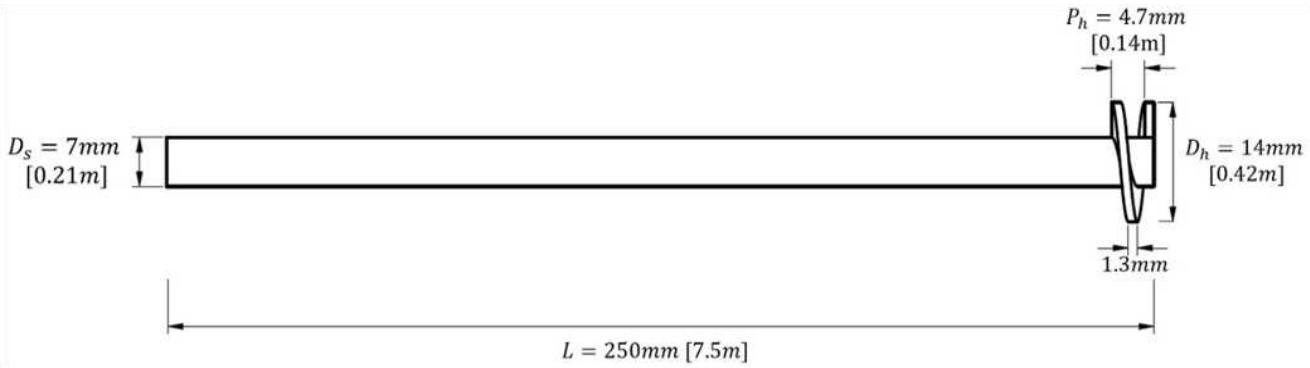

Figure 1. Schematic diagram of screw pile in model dimensions [prototype dimensions] (pile length is not drawn to scale

2.2 Pile model

The single-helix pile consisted of a 7mm (0.21m, prototype scale) shaft diameter (D_s), a 14mm (0.42m) helix diameter, 4.7mm (0.14m) helix pitch and is shown in Figure 1 with model and protype dimensions. The embedment ratio was equal to 17.5. Similar to previous work (Davidson et al., 2022), a solid shaft (fully plugged behaviour) was used to avoid structural failure (i.e., buckling), eliminate issues around particle scaling and plugging that are seen in open-ended piles (Deeks, 2008), and reflect upper bound installation requirements. The pile was 3D printed using the Standard SS 316L material which is low-carbon stainless steel material that offers excellent strength making it suitable for general prototyping. The pile was originally designed to be installed as part of a screw pile group of nine piles and a semi-analytical design method (Mitsch and Clemence, 1985) was used to calculate the dimensions. One helix was preferred, as it reduces the installation requirements and allows for a clear understanding of the uplift capacity of screw piles with large embedment ratios.

2.3 Soil bed preparation

Preparation of the soil bed included dry pluviation of HST95 sand in a strong box (500mm × 800mm × 550mm) to achieve medium-dense sand (D_r = 55%). During pluviation, the height between the pluviator and the strongbox was kept constant. The sand was pluviated above the target height of 434mm and was subsequently levelled off using a custom scraper. The sand used in all tests (HST95) is shown in Table 1 and has been characterised and widely used in previous work (Al-Defae et al., 2013; Lauder, 2010).

Table 1. HST95 sand properties (Lauder, 2010; Al-Defae et al., 2013)

Property (unit)	**Symbol**	**Value**
Effective particle size (mm)	d_{10}	0.09
Average particle size (mm)	d_{50}	0.14
Maximum particle size (mm)	d_{100}	0.213
Particle specific gravity (-)	G_s	2.63
Minimum void ratio (-)	e_{min}	0.467
Maximum void ratio (-)	e_{max}	0.769
Dry unit weight (kN/m^3)	γ_{dry}	16.15
Saturated unit weight (kN/m^3)	γ_{wet}	19.79
Peak friction angle, D_r = 55%, (°)	$\emptyset_{pk}$	40.0
Critical friction angle (°)	$\emptyset_{crit}$	32.0
Interface friction angle (°)	δ_{crit}	24.0

*Properties are from direct shear box tests at effective stresses (σ') between 5kPa and 25kPa conducted by Al-Defae et al. (2013).

Each soil bed preparation allowed for two tests. The second test was conducted after repositioning the actuator manually to allow for precise spacing of $10D_h$ (140mm) between the pile and the box boundary (or the second pile location) so that no interactions took place (Bolton et al., 1999). Pile model scaling effects were deemed negligible as the ratio of the helix diameter to the average grain size was approximately 99 which is larger than the threshold (58) given in Schiavon et al. (2016). Similarly, the effective helical radius (W), which accounts for helix and shaft and is defined as $0.5(D_h - D_s)$, was approximately 24, satisfying the recommendation of 16 given in Heshmati R. et al. (2021).

2.4 Pile installation and testing procedure

The pile was installed at AR = 1.0, 0.5 and 0.25. Each pile installation commenced after reaching the desired g-level (i.e., $19g$) and setting the force and torque readings to zero with the pile starting just above the sand surface prior to installation. Values pertaining to the selected AR (i.e., rpm, velocity, and number of rotations) were inputted into the bespoke Labview software to allow for seamless installation to the desired helix depth at model scale. The installed pile was tested by subjecting a uplift force at a constant velocity of 1mm/min. Due to zeroing the installation parameters prior to installation, the measured uplift force was only due to the resistance of soil.

3 RESULTS

The results from this point forward are shown and discussed at prototype scale only. The installation requirements and vertical (uplift) force figures were smoothed using a filter that involved fitting polynomials to the data in a least-squares approach (Savitzky and Golay, 1964) for presentation purposes and to identify trends with depth.

3.1 Installation

3.1.1 Crowd force observations

The measured installation vertical (crowd) force acting on the pile head is shown in Figure 2 in medium dense sand (55%) for installation at AR = 1.0, 0.5 and 0.25. A 252kN compressive crowd force was required to install the pile at the industry recommended AR (i.e., AR = 1.0, pitch-matched installation). This compressive crowd force is effectively one order of magnitude less than the measured crowd force values reported by Davidson et al. (2022) and Cerfontaine et al. (2023b) for large single screw piles designed to replace single driven pile jacket foundations.

Cerfontaine et al. (2023b) undertook several centrifuge tests showing that the crowd force is controlled by the surface area of the screw pile and thus, suggesting that this significant decrease is a result of the smaller shaft diameter of the pile tested in this study. The measured tensile (pull-in) crowd force for AR = 0.5 and 0.25 was 26kN and 116kN respectively. When decreasing the AR to 0.5 and 0.25 (over-flighted installation) the vertical direction of the crowd force changes from downward (compressive or push-in) to upward (tensile or pull-in), confirming the observation made by Cerfontaine et al. (2023b) that the installation behaviour changes when AR < 1, as the reaction compressive crowd force applied at the top of pile is less than the pull-in force generated at the helix when the surrounding soil is compressed during installation, resulting in a resultant force that is in tension.

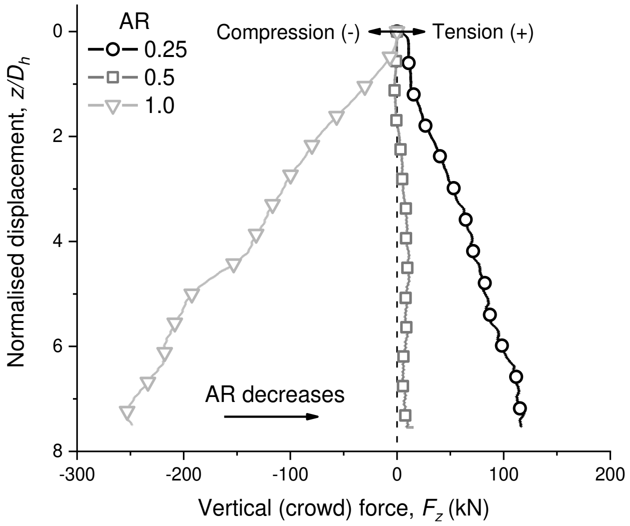

Figure 2. Measured vertical (crowd) force during installation in medium dense sand as a function of AR

3.1.2 Installation torque measurements

The measured installation torque (T) acting on the pile head is shown in Figure 3 in medium dense sand (55%) at AR = 1.0, 0.5 and 0.25. The largest torque required to fully install the pile was 40.1kNm observed when installed at AR = 0.5. This, coincidentally, is approximately half of the pitch-matched pile torque requirements which reached 22.2kNm. The measured installation torque for the pitch-matched pile (AR = 1.0) was also the largest for the first 2m but was surpassed by both over-flighted piles between 2m to 3m. At AR = 0.25, the final measured installation torque was 31.4kNm, which is approximately the mean of the final torque values for AR = 1.0 and 0.5. As shown in Figure 3, there is less variation in the final measured installation torque when compared with the installation crowd force whilst varying the AR. For pitch-matched (AR = 1.0), the measured installation torque increases linearly with depth; whereas, when the AR is reduced the measured installation torque becomes non-linear and was most pronounced at AR = 0.5. These results are also consistent with Cerfontaine et al. (2023b) and Wang et al. (2023). The Davidson et al. (2022) CPT-based torque prediction method was compared with the measured installation torque at pitch-matched (AR = 1.0) installation in medium dense sand and is also shown in Figure 3. The prediction method provided a final predicted installation torque of approximately 17.25kNm which was a relatively close match to the final measured installation torque value (22.2kNm).

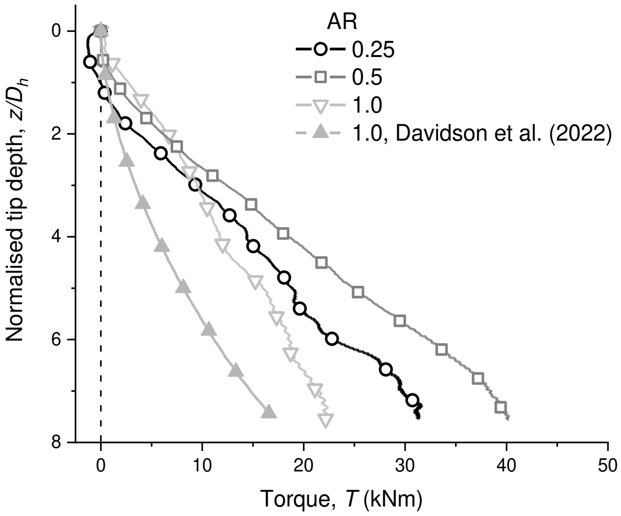

Figure 3. Measured installation torque during installation in medium dense sand as a function of AR

3.2 Uplift capacity

The relationship between vertical (uplift) force (F_u) and displacement (D_z) for all tests is shown in Figure 4 in medium dense sand (55%) at AR = 1.0, 0.5 and 0.25. Reducing the AR resulted in improved uplift performance of the pile with respect to the pitch-matched installation (AR = 1.0). The peak vertical force (or uplift capacity) of the pitch-matched (AR = 1.0) installed pile was 305kN. Whereas, when AR = 0.5 and 0.25 (over-flighting), the peak vertical force was 467kN and 416kN, indicating that by reducing the AR the peak vertical tensile force increased by 53% and 40% respectively. Figure 4 also shows that pile response is stiffer for the over-flighted piles (AR = 0.5 and 0.25). Due to over-flighting, the initial stiffness of both piles (AR = 0.5 and 0.25) was increased, showing a sharp rise to the peak vertical force at a displacement ($D_{z,max}$) of approximately $0.12D_h$ and $0.11D_h$ before beginning to soften. Whereas the pitch-matched pile (AR = 1.0) rises gradually to the peak vertical force at a displacement of approximately $0.18D_h$ before beginning to soften and reaching half of its peak vertical force at approximately $2D_{z,max}$.

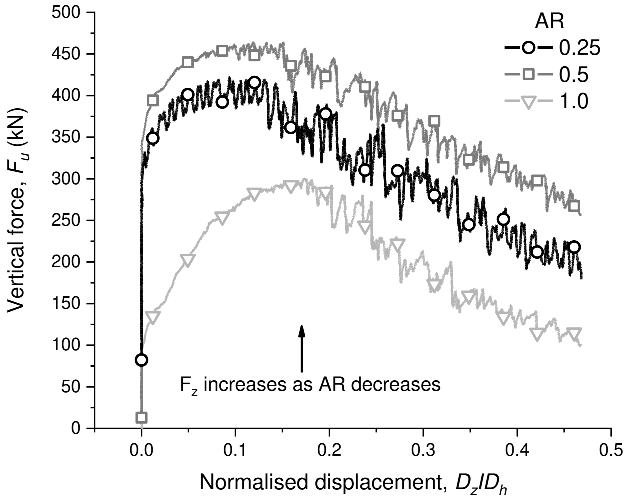

Figure 4. Measured vertical (uplift) force over normalised displacement in medium dense sand as a function of AR

The results are consistent with the centrifuge tests presented in Wang et al. (2023) and Cerfontaine et al. (2023b), as well as the numerical tests presented in Sharif et al. (2021). These studies contradict what is recommended in the industry with regards to optimum installation (BSI, 2015), but demonstrate that reducing the AR has a beneficial effects on the uplift capacity of the screw pile. This enhancement of the capacity is due to the change in the stress regime around the helix (Sharif et al., 2021) and has briefly been discussed in Section 1. Over-flighting also appears to provide additional benefits in the offshore environment where cyclic loading is of concern. Wang et al. (2023) showed that due to over-flighting (at AR = 0.25), the post-cyclic capacity of the pile remained higher than the pitch-matched pile (AR = 1.0) in both pre-cyclic and post-cyclic tests and piles were more stable and accumulated displacement at lower rates.

This pile geometry investigated was selected based upon capacity prediction from an existing semi-analytical design method (Mitsch and Clemence, 1985) which predicted a significantly greater peak vertical force (921kN) than the one seen in Figure 4 for the pitch-matched (AR = 1.0) installation (305kN). This overprediction may be due to several reasons: (1) these methods are based upon empiricism, utilising large datasets from field tests of smaller, shallower onshore screw piles; and, (2) the formulations of the semi-analytical design method use the limit equilibrium method which contains broad and unverified assumptions pertaining to the failure mechanism and stress distribution along the failure surface (Cerfontaine et al., 2019). A more up to date numerical design method for "deep" screw piles (Yuan et al. 2023) using the coupled Eurlerian-Langranian (CEL) approach was also modified after the centrifuge tests to predict the peak vertical force for this pile geometry. However, the numerical method overpredicted the peak vertical force.

4 CONCLUSIONS

A deep screw pile designed to be part of a group of nine piles was installed at AR = 1.0, 0.5 and 0.25 in medium-dense sand, and tested using the geotechnical beam centrifuge for installation (crowd) force, torque and vertical (uplift) force. It was found that, the installation crowd force and torque required to fully install the pile was significantly smaller than the pile geometries reported in previous studies, highlighting that the deployment of smaller screw piles in groups may be more feasible to install and anchor FOWTs than screw piles with larger geometries. The existing CPT-based torque prediction method (Davidson et al., 2022) was shown to reasonably match the results obtained from the centrifuge test at pitch-matched (AR = 1.0) installation. However, this prediction method works well for one AR (i.e., pitch-matched) and requires modifications to be used to predict installation torque for piles installed at ARs < 1. The effect of AR significantly reduced the installation crowd force while increasing the installation torque and uplift force of the deep pile. These results, however, should not be inferred to clayey soils, as varying the AR has not been investigated in this study for fine-grained soils. Existing methods to predict the uplift capacity of a deep screw pile were seen to be inaccurate, thus highlighting the need for new prediction methods for deeper piles that could be deployed in groups.

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