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CENTRIFUGE TESTING OF LARGE SCREW PILE GEOMETRIES FOR OFFSHORE APPLICATIONS

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ABSTRACT. Screw piles have been recognised as an innovative solution to support offshore jacket structures or mooring lines for floating platforms (e.g. wind turbines, wave energy converters). Their main advantage is a low noise/low vibration installation process and a potentially enhanced tensile capacity. The two main challenges for design are the prediction of installation requirements (torque and force) and the uplift capacity of the piles. This work investigates the effect of successive uplift phases at intermediate depths during the installation of a screw pile in dense sand, as a means of reducing the installation requirements. The modification of the uplift capacity at the final deepest depth and the installation requirements are considered in detail. Centrifuge tests have been undertaken at the University of Dundee, where an actuator has been developed to conduct installation and testing of model piles in-flight. Results show that the uplift capacity is reduced due to the previous uplift phases, but only by 10 to 20% of to a virgin installation to the final depth. The reduction in the installation requirements is of the same order of magnitude. A torque correlation factor was calculated for each test and was shown to be dependent on the relative embedment depth.

Notation

Dc	[m]	Core diameter
D_h	[m]	Helix diameter
Dr	[-]	Relative density
F_c	[MN]	Axial installation (crowd) force
F_y	[MN]	Uplift force
H	[m]	Embedment depth of the helix
K_t	[m^{-1}]	Torque correlation factor
K_t^*	[-]	Dimensionless torque correlation factor
N_γ	[-]	Dimensionless uplift bearing factor
T	[MNm]	Installation torque

1. Introduction

Many applications in offshore geotechnical engineering require foundations/anchors with a significant tensile capacity, such as tension-leg platforms for floating wind turbines (Oguz et al., 2018), foundations supporting jacket structures for wind turbines (Davidson *et al.*, 2018), wave energy converters (Gaudin et al., 2018) or aquaculture enclosures (Huang et al., 2008).

Screw piles are a promising anchoring or foundation solutions for these applications (Byrne *et al.*, 2015), consisting of one or several helices attached to a steel core (Perko, 2009). Screw piles are literally screwed into the ground by applying a torque, generating less nuisance for marine mammals than conventional pile driving. The uplift capacity is mainly provided by the embedded helix which provides a larger long-term capacity than piles, which resist applied load through shear mobilisation along the shaft and their own self weight.

Although screw piles have attracted more attention in recent years (Harnish *et al.*, 2017; Schiavon *et al.*, 2017; Cerfontaine *et al.*, 2020), their behaviour is still not particularly well understood for this application. Many questions and challenges remain unanswered, especially how their installation requirements can be lowered for large dimension screw piles (Davidson *et al.*, 2019). The prediction and verification of the screw pile capacity in tension is also critical (Harnish *et al.*, 2017; Cerfontaine *et al.*, 2019).

This work investigates through small-scale centrifuge tests the behaviour of a single screw pile which has been tested in pull-out in dense sand, then reinstalled to a greater depth. The incentive to study this problem is threefold:

a) *Post-failure capacity*. It gives an insight into the capacity that could be expected from an anchor that has reached ultimate capacity in the past but must be maintained at the same installed location. This could also be justified by the necessity to increase the anchor capacity after a service period or an excessive displacement due to cyclic loading (Schiavon *et al.*, 2017).
b) *Installation requirements*. Introducing uplifting phases during the installation has the potential to release and lower the large crowd force that may need to be applied during installation.
c) *Cost of testing*. Applying a succession of uplift phases during the installation of a pile at a single location could reduce the cost of these tests and be applied as quality control in the field.

2. Centrifuge testing

Centrifuge modelling has been recognised as an efficient and accurate way of modelling the behaviour of foundations and investigating their capacity (Garnier *et al.*, 2007). Previous work has shown that 1g installed and in-flight installed piles do not behave in the same manner when tested laterally (Klinkvort *et al.*, 2013) and axially. This suggests that both installation and loading phases of screw piles should be undertaken in-flight (at corresponding prototype g or stress level). Subsequently, a suitable actuator was developed at the University of Dundee (Al-Baghdadi *et al.*, 2016; Davidson *et al.*, 2018) to undertake both installation and loading in a single phase in-flight.

2.1. Loading system

The equipment developed at the University of Dundee enables an accurate displacement along two degrees of freedom (Figure 1): vertical displacement and rotation. The vertical displacement is controlled via a geared belt-driven ball screw system powered by a master servo-motor (AKM54H), allowing a maximum displacement of 30mm. The rotation is provided by a second (slave) servo motor (AHM53H) connected to the screw pile via a 4:1 ratio gearbox to increase the available torque to 41Nm. A custom F310-Z combined torque transducer and axial loadcell was mounted to the gear-box of the slave motor to measure the installation torque and crowd force as well as the force during tension/compression tests. The loadcell can measure torque to 30 Nm and axial force to ±20 kN.

A SR002 8 channel slip ring was installed on a shaft extension above the loadcell. This slip ring was designed for low voltage, signal carrying applications and has particularly low electrical noise of less than 10 mΩ at 5 rpm. Axial displacement data was measured with a WPS-500-MK30 draw-wire sensor, with back-up recording provided by the encoded servo-motors.

Data from the loadcell and draw wire were acquired with a MicroAnalog 2 modular instrument data acquisition system (DAQ), with amplification factors of 1 for the draw wire and 200 for the loadcell. The servo-motors were supplied with a 3-phase alternating current which can introduce electrostatic and magnetic noise, from capacitive coupling and the flow of electric current respectively, into a strain gauge-based device such as the F310-Z loadcell. The DAQ system has very effective screening of such noise and was able to consistently record high quality, low-noise data. Furthermore, shielded cable was used for all instruments to reduce electrical noise. Labview 2013 software was used to provide a graphical user interface and control system for the servo-motors. Live data from the DAQ was monitored for the duration of the centrifuge test.

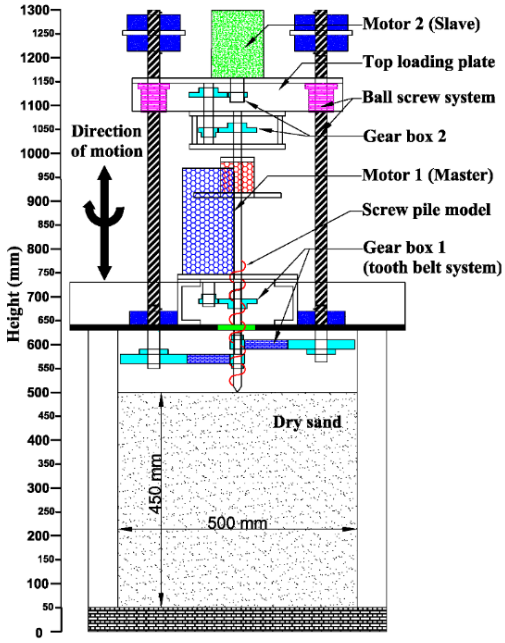
2.2. Soil properties and sand bed preparation

All tests used the fine-grained quartz HST95 sand. This material has been widely used at the University of Dundee and has been well characterised (Al-Defae *et al.*, 2013; Jeffrey *et al.*, 2016). The relevant sand properties are summarised in Table 1.

Table 1 HST95 sand properties at an average relative density of 76%, based on (Al-Defae et al., 2013)

Property	Unit	Value
Effective particle size, d_{10}	mm	0.09
Average particle size, d_{50}	mm	0.14
Uniformity coefficient, C_u	-	1.9
Dry density, ρ_d	kg/m³	1710.4
Critical state friction angle, ϕ'_{crit}	°	32.0
Peak friction angle, ϕ'_p	°	44.2
Peak dilation angle, ψ'_p	°	15.0
Steel-sand friction angle, δ'_{crit}	°	24.0

Figure 1 Schematic diagram of the screw pile centrifuge test mounted on a strong-box (Al-Baghdadi *et al.*, 2016)



The sand bed was prepared by dry pluviation in a strong box whose internal dimensions were 500 × 800 × 550mm. The pluviator has been described and characterised in (Jeffrey *et al.*, 2016). The preparation of a very dense sand was targeted (73-80% average relative density) as this corresponds to an upper bound for the force and torque requirements necessary during the installation of a given pile geometry in sand. The sand layer had a thickness of 400mm. The dimensions of the container are such that two tests can be undertaken in each box, during two successive flights, without creating significant boundary effects. The shortest distance to the box walls was larger than 10 times the helix diameter, which complies with the recommendations of Bolton et al. (1999).

General scaling laws and practical recommendations were respected to ensure the representativity of centrifuge tests at prototype scale (Garnier et al. 2007). The dimension of the helix/plate (D_h) to the mean grain size (d_{50}) is larger than 50. In addition, the effective helical radius proposed by (Schiavon *et al.*, 2016), $w = (D_h - D_c)/(2\ d_{50})$ must be large enough to ensure that a sufficient number of sand particles are in contact with the helix. This ratio is equal to 37 in this study, which is slightly lower than the lowest ratio studied by Schiavon et al. (2016), but was deemed acceptable. In addition, the helix pitch to d_{50} ratio is larger than 50, allowing the movement of all particles through the helix during the installation process.

2.3. Screw pile design

The geometry of the screw pile is similar to previous studies undertaken at the University of Dundee either in the centrifuge or numerically (Davidson *et al.*, 2018; Cerfontaine *et al.*, 2020). The uplift capacity of this screw pile was shown to be sufficient for offshore renewable energy applications such as wind or wave energy devices. It can be used as a pile to found jacket structures in moderate water depths (50-80m) (Davidson *et al.*, 2018) or to anchor floating platforms (Cerfontaine *et al.*, 2019). The dimensions of the pile are reported in Table 2. The pile tip was design flat, to mimic a plugged tubular pile in the field. The centrifuge was spun such that the average gravity over the sand bed increased to 50g.

Table 2 Screw pile dimension at model (1/50th) and prototype scales

Parameter	Model [mm]	Prototype [m]
Length, L	162.5	8.12
Core diameter, D_c	11.0	0.55
Helix diameter, D_h	21.25	1.06
Helix mid-depth, H	155.0	7.75
Helix pitch, p_h	7.0	0.35
Helix plate thickness, t_h	1.4	0.07

2.4. Installation & loading procedure

It is recommended in the literature that screw piles must be installed in a pitch-matched manner (Perko, 2009), i.e. with the helix describing a true helical movement in the ground, limiting the disturbance within the surrounding soil. Therefore, the helix should penetrate the soil over a distance equal to its pitch (p_h) for each revolution. This was achieved by imposing a rotation rate equal to 3RPM and a penetration rate equal to 21mm/min, the helix pitch (p_h) being equal to 7mm at model scale.

Four tests are presented in the following. In two of them (B & D), the screw pile was installed up to a relative embedment ratio (H/D_h) equal to 7.4 and pulled out at the rate of 1 mm/min up to 10mm at model scale. In the two other tests, the anchor was embedded up to one (C) or two (A) intermediate positions, uplifted until a peak load was reached, and installed downwards again. The final depth was identical in all cases and its relative embedment ratio (H/D_h) was equal to 7.3. The different tests are summarised in Table 3

Table 3 Summary of the tests: relative density (Dr) and helix relative depth (H/D_h) during the uplift steps

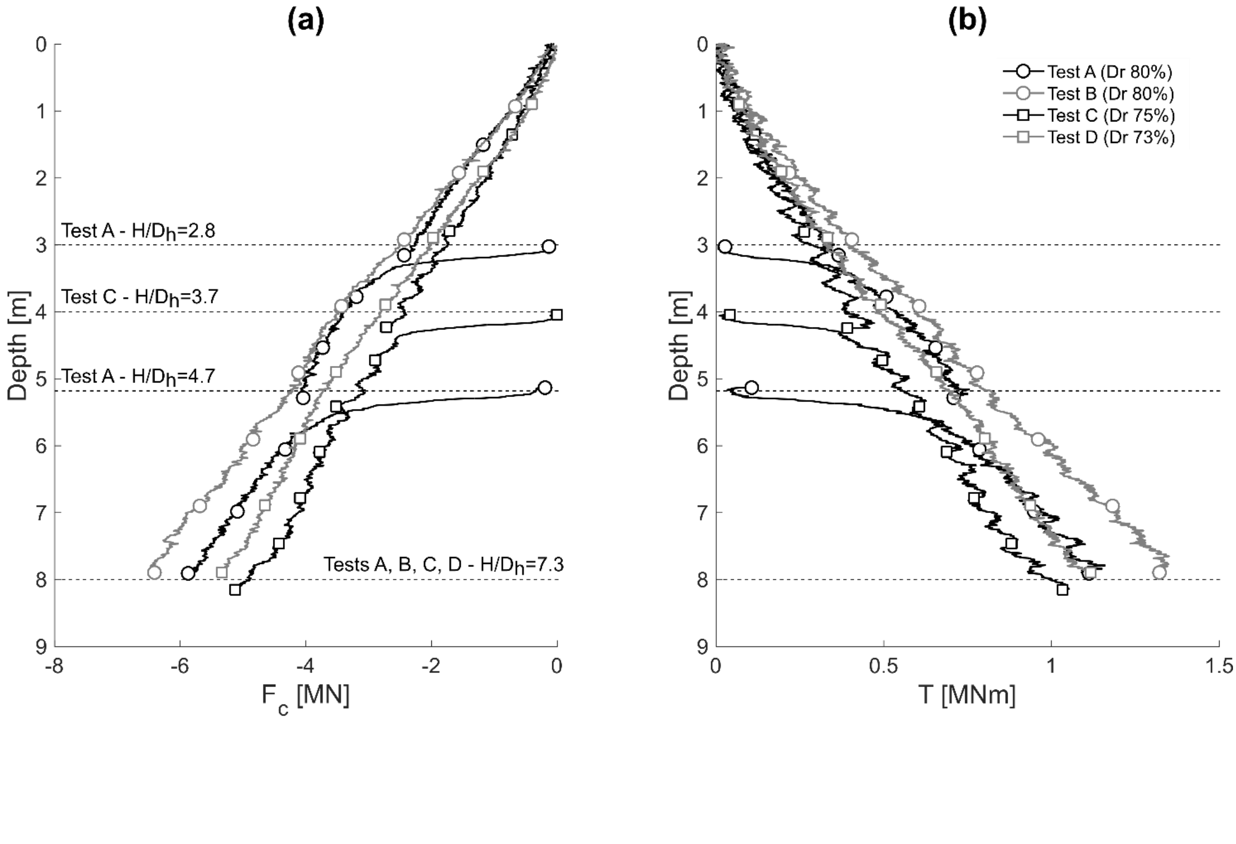
Test ID	Dr [%]	Step	H/D_h of uplift steps [-]
Test A	80	A1	2.8
		A2	4.7
		A3	7.1
Test B	80	B1	7.1
Test C	75	C1	3.7
		C2	7.3
Test D	73	D1	7.1

3. Results

3.1. Installation requirements

The crowd force (F_c) and the torque (T) necessary to install the screw piles at the required depth are given in Figure 2 for all tests. The installation requirements are initially relatively consistent, the higher density samples requiring larger force and torque to be installed at the same depth following recommendations of pitch matched installation. In both tests (A & C) where intermediate pull-out phases were undertaken, the crowd force F_c is slightly lower (8-15%) at the final depth, in comparison with the single step installation (B & D, Figure 1(a)). In both tests, the divergence between the single step and multiple step tests occurs after the intermediate uplift phase

Figure 2 Installation requirements (crowd force F_c and torque T) as a function of depth for the four tests and position of the different intermediate uplift phases (tests A & C), Dr is the relative density corresponding to each test



(A1, A2 or C1). A similar trend can be observed for the torque requirement.

3.2. Load-displacement relationship

An example of the load-displacement relationship is given in Figure 3. Both stiffness and maximum uplift force increase as a function of the relative embedment depth. The displacement necessary to mobilise the maximum load increases similarly.

3.3. Uplift capacity

The uplift capacity was determined as the maximum pull-out load ($F_{y,max}$) measured in the load-displacement relationship (Figure 3), irrespective of the displacement necessary to reach this load. This definition allows for a comparison with the limit analysis semi-analytical solution proposed by Giampa *et al.* (2017) and is based on a fully formed failure mechanism. The maximum load was found for each test and is reported as a non-dimensional bearing factor N_γ in Figure 4. This bearing factor is defined as

$$N_\gamma = \frac{4\,F_{y,max}}{\gamma'\,H\,\pi D_h^2} \quad (1)$$

where γ' is the effective unit weight of the sand and H is the embedment depth.

The comparison of N_γ calculated from the centrifuge tests are consistent with the semi-analytical solution, fully described in (Giampa *et al.*, 2017). This solution has been computed with parameters (peak friction and dilatancy angles) corresponding to the maximum (80%) and minimum (73%) relative densities measured in the different sand boxes. In test A, the intermediate uplift capacity (A2, H/D_h = 4.7) does not seem to be affected by the previous uplift (A1, H/D_h = 2.8). However, a comparison of the capacity at the largest relative embedment ratio (A3, H/D_h = 7.3) with a virgin screw pile installed at the same depth (B1) shows a significant reduction. The reduction was approximately 21% and 15% for test A and test C respectively.

3.4. Torque correlation

A torque-uplift capacity correlation is often used for the design or quality control of screw pile capacity (Tsuha *et al.*, 2010). This correlation factor (K_t) is usually expressed as a linear relationship between the uplift capacity and the torque necessary to install the screw pile (Perko, 2009). The correlation factor value is usually assumed to be a unique single value for a given pile geometry and soil conditions. A non-dimensional definition of this factor (K_t^*) was proposed by Byrne *et al.* (2015)

$$K_t^* = \frac{F_{y,max} \times D_h}{T_{max}} \quad (2)$$

where $F_{y,max}$ is the uplift capacity at a given depth and T_{max} is the torque necessary to install the pile at this depth.

The correlation factor has been calculated for all uplift capacities in tests A-D. Results are reported in Figure 5 and Table 4 where the dimensional correlation factor was also provided. This figure shows that although a single pile has been used and the soil conditions do not vary significantly, the K_t factor is not unique but its distribution follows a remarkably linear trend with increasing embedment ratio. If only the uplift capacity at the largest position is considered (~H/D_h =7.4), the scatter is much lower, as K_t varies between 2.86 and 3.29 (average 3.06). As a comparison, the dimensional correlation factor reported by (Perko, 2009) can be made non-dimensional as

$$K_{t,p}^* = D_h \frac{\lambda_k}{D_c^{0.92}} \quad (2)$$

Figure 3 Force (F_y) displacement (u_y) relationships for tests with multi-stage (A) and singe (B) uplift (Dr = 80%)

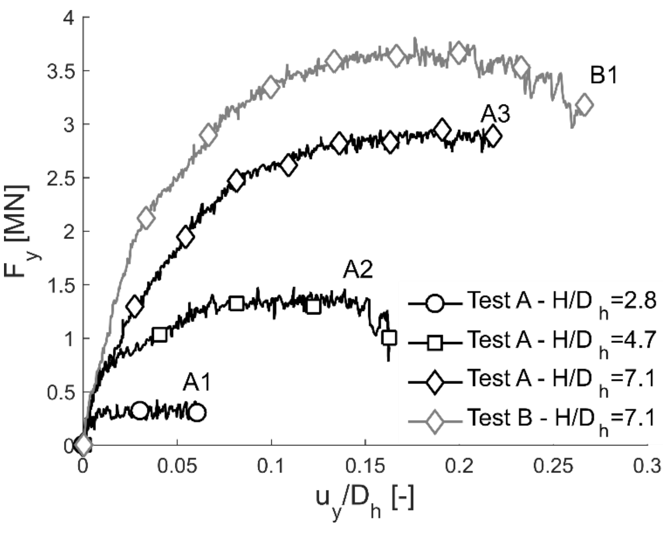
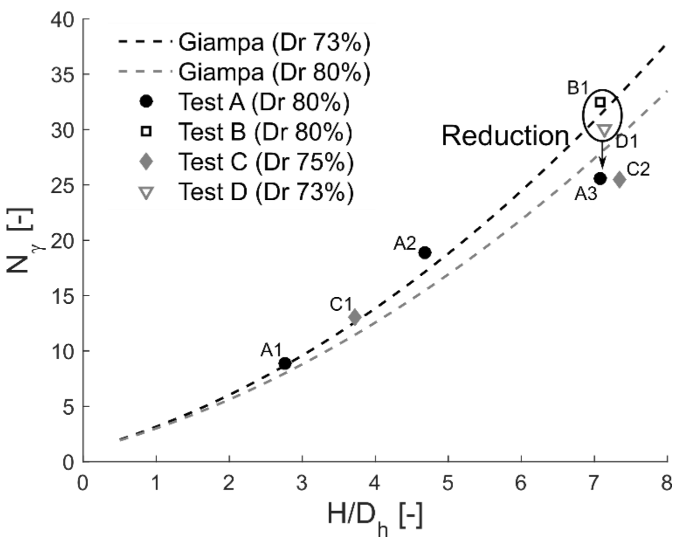


Figure 4 Normalised bearing capacity (N_γ) as a function of the relative embedment ratio (H/D_h) and comparison with the semi-analytical solution proposed by Giampa et



where $\lambda_k = 1422$ mm$^{0.92}$/m is a fitting factor. All the centrifuge data lie well below this empirically defined correlation factor.

Table 4 Dimensional (K_t) and non-dimensional ($K_t^*, K_{t,perko}^*$) torque-capacity correlation factors

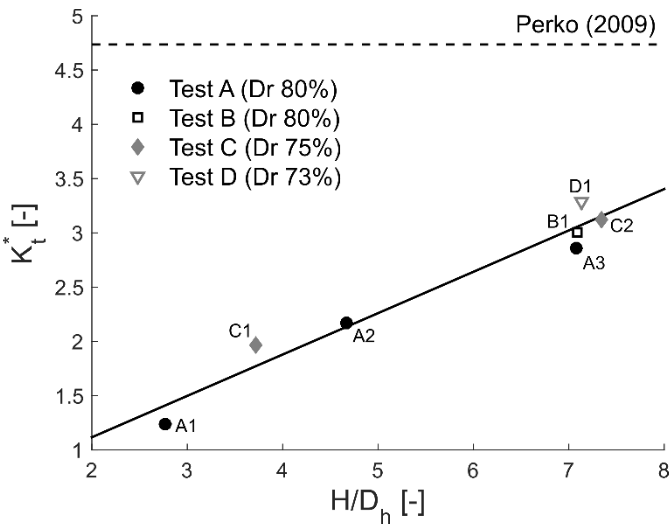
	A1	A2	A3	B1	C1	C2	D1
K_t^* [-]	1.16	2.04	2.69	2.83	1.85	2.94	3.10
K_t [m^{-1}]	1.24	2.17	2.86	3.00	1.97	3.12	3.29
$K_{t,p}^*$ [-]				4.73			

3.5. Discussion

The intermediate uplift steps have only a slight effect on the installation requirements of screw piles, although some reduction for torque and force was observed after intermediate uplift tests. It is believed that the uplift test can release a part of the large compression force 'accumulated' as the pile is installed within the ground and this would be greater at the intermediate depth compared to the shallow depth. However, further research is necessary to investigate such an effect and reduce the potential heterogeneity due to the soil bed preparation. In addition, the uplift tests were associated with very large uplift loading and displacement. Another way of optimising the installation may be to apply a larger number of steps, but associated with much lower displacements.

The bearing factors of the different tests are globally consistent with the semi-analytical prediction method proposed by Giampa *et al.* (2017), indicating a predominantly shallow failure mechanism. The uplift capacity at the deepest embedment depth seems to be reduced by the intermediate steps, although only by a limited amount. From a practical point of view, it means that any screw pile that had prematurely reached ultimate behaviour at a shallow depth could be reinstalled deeper and the uplift capacity available could be predicted as a virgin pile, whose capacity is reduced by 10 to 20%. From a theoretical point of view, it is likely that

Figure 5 Non-dimension torque-capacity correlation as a function of the relative embedment ratio (H/D_h)



the intermediate failure mechanism will create shear planes within the ground, as investigated by Cerfontaine *et al.* (2020). These intermediate shear planes can be reactivated during further loading of the pile, leading to a different failure mechanism in comparison with a virgin pile. Although the current procedure allows more data to be obtained for a single screw pile test, the uncertainty on the pile capacity reduction makes the interpretation of the ultimate capacity more difficult.

The torque (non-)dimensional correlation factor (K_t or K_t^*) is usually considered as a constant value for given pile geometry and soil conditions. Some correlations have been introduced which are only a function of the shaft diameter (Perko, 2009). Such correlations have also been deemed acceptable for large pile geometries (largest D_h = 0.61m, largest D_c = 0.22m, tension test) (Harnish *et al.*, 2017). However, it has been demonstrated that the correlation factor increases with the D_h/D_c ratio (Al-Baghdadi, 2018) and not only the shaft diameter (transition from a flow around mechanism to an uplifting mechanism). Results presented here also exhibit that the torque correlation factor scatter is largely reduced if a depth dependence is introduced. This makes sense as the uplift capacity is only a function of the helix diameter (at shallow depths), while the torque necessary for installation depends on both the shaft and the helix properties.

Screw pile geometries used for offshore applications are likely to be much larger, with lower D_h/D_c ratios and embedded at a shallower depth than usual onshore screw piles. Due to their large size they are also likely to be at lower H/D_h ratios than are typically encountered onshore. This will result in shallow uplifting failure mechanisms in tension as described in (Cerfontaine *et al.*, 2020). Current use of K_t from onshore practice does not recognise these controls on pile performance thus rendering the use of this design/verification approach misleading with the potential to reduce the actual factor of safety on site. Therefore, the usual torque correlation techniques cannot be applied directly and more refined models should be applied to obtain accurate results. They also need to identify other controls such as pile pitch, advancement ratio and soil conditions as identified by (Lutenegger, 2019).

4. Conclusion

Centrifuge testing of screw piles embedded in dense sand has been undertaken to investigate their behaviour while subjected to several uplift steps during their installation. This was done to see if large installation forces and torques could be reduced to aid installation and reduce plant demands. The pile models have been installed at 50g to simulate very large geometries necessary for offshore applications. The uplift capacity has been tested at intermediate depths, before the final embedment depth is reached.

It was shown that the final uplift capacity is decreased with respect to a virgin installation at the same final depth. However the loss of capacity is limited to 10-20%. Therefore, the capacity of existing or failed anchors can be increased by re-installing them deeper. The installation requirements were shown to decrease by the same order of magnitude due to the intermediate uplift phases. This reduction is not sufficient to optimise the installation process. Finally, non-dimensional torque-correlation factors were established. It was shown that this factor was not unique but depth-dependent and requires further investigation prior to use in pile capacity verification.

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