Centrifuge modelling of screw piles for offshore wind energy foundations

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ABSTRACT: Screw piles (helical piles) can provide a viable, cost-effective and low-noise installation alternative to increasing the size of existing foundation solutions (e.g. monopiles) to meet the demand for the advancement of offshore wind energy into deeper water. Significant upscaling of widely used onshore screw pile geometries will be required to meet the loading conditions of a jacket supported offshore wind turbine. This increase in size will lead to greater installation force and torque. This paper presents preliminary results from centrifuge tests investigating the requirements to install screw piles designed for an offshore wind energy application using specially developed equipment. Results indicate that the equipment is suitable to investigate these screw pile requirements and that significant force is required for such upscaled screw piles, with 19 MN vertical force and 7 MNm torque for the standard design. Optimization of the screw pile geometry, reduced these forces by 29 and 11 % for the vertical and rotational forces respectively.

1 INTRODUCTION

Recently, the development and installation of offshore wind energy has increased greatly and this trend is expected to continue for the foreseeable future. Overall in the UK, wind turbines are currently installed in water depths up to 40 m, with 81 % of all turbines supported by monopiles and 6.6 % by jackets (Wind Europe 2017). As companies look to further develop wind energy resources, wind farms will have to be sited in deeper water. Utilizing monopiles in deep water, of around 25m, raises concerns over their in-service performance and ability to manufacture very large monopiles (Golightly 2014).

An alternative solution is to expand the use of jacket structures. Typically, jackets are founded on long steel piles, driven with pile driving hammers, causing significant levels of noise above (Marine Management Organisation 2016) and below the water surface (Bruns et al. 2014). This has led German authorities to impose strict hydro sound limits, as underwater noise levels during piling operations are considered disruptive to many marine mammal species. Mitigation of the noise through techniques and equipment such as bubble curtains and sound dampers (Bruns et al. 2014) and in extreme cases large physical barriers is possible but expensive.

Screw piles have been proposed as a replacement for conventional straight-shafted piles for jacket supported wind turbine foundations (Byrne and Houlsby 2015, Spagnoli and Gavin 2015), as they offer several advantages. Firstly, installation is achieved through continuous simultaneous application of vertical crowd and rotational forces. This eliminates problems associated with pile driving hammers as the rotational installation method is significantly quieter (Byrne and Houlsby 2015, Knappett et al. 2014). Secondly, the superior axial capacity, compared to straight-shafted piles, generated by the helical plates and the soil trapped (soil-soil shear) between them is a significant advantage in resisting the substantial environmental loads acting on the jacket and turbine. Thirdly, screw piles can potentially reduce the amount of steel required for the foundations due to improved efficiency of the load carrying mechanisms, leading to cost savings for a wind farm project.

Rotating a screw pile into the soil generates large amounts of torque from the frictional resistance on the soil-steel interface. This is an important factor in the development of screw piles for offshore wind applications and is an active area of research (Schiavon et al. 2016, Spagnoli et al. 2016, Tsuha 2016). Numerous analytical and empirical methods (Hoyt and Clemence 1989, Ghaly and Hanna 1991) are available to predict the installation torque, which are derived from observations on small onshore piles and may not be applicable to the larger screw piles required for offshore projects. Methods correlating torque to Cone Penetration Test (CPT) data are also available (Spagnoli 2016, Al-Baghdadi et al. 2017).

With offshore screw pile installation torque predictions of 5 MNm (Byrne and Houlsby 2015) or greater, the need for reliable and accurate design methods is paramount in anticipating and potentially minimizing the required torque. Additionally, optimization of the screw pile design should be undertaken to reduce the torque and material requirements for a given pile capacity where possible. There is an absence of literature on the design and performance of large-scale screw piles with variable shaft geometry. To address this issue, a series of centrifuge tests were conducted using novel equipment to explore the optimization of a screw pile designed for deep-water offshore wind energy foundations.

The work presented in this paper was conducted as part of the EPSRC project EP/N006054/1: Supergen Wind Hub Grand Challenges Project: Screw piles for wind energy foundations. This project is developing understanding of large scale screw piles through a combination of physical modelling (University of Dundee), field testing (University of Southampton) and advanced numerical modelling using the material point method (Wang et al. 2017) to simulate the effects of screw pile installation, ahead of performance analysis with traditional finite element techniques (Durham University).

2 MODEL SCREW PILE DESIGN

To investigate the optimization of a realistic screw pile design, which could be used for an offshore wind energy development, in terms of the installation torque and force (crowd) required, two screw piles were designed for a theoretical loading scenario.

2.1 *Loading scenario*

It is expected from an economic perspective that jacket supported turbines will be deployed in water depths of 45 to 80 m, between the proven capability of monopiles and future floating structures. Using a worst-case design approach, loads were calculated for an 8 MW turbine on a jacket in 80 m of water on homogenous sand with the properties discussed below.

Environmental loads were calculated using DNV (2007) methods and the parameters in Table 1, representing conditions with a 1 % exceedance level. Loads were assumed to act in unison diagonally across the jacket (from corner to corner) to calculate the upwind tensile and downwind compressive loads. A pinned jacket-pile connection was assumed. A steel density of 7700 kg/m^3 was applied for the dead weight calculations. The turbine and jacket design and the calculated loads, with a factor of safety of 1.35, are summarized in Figure 1 and Table 2 respectively.

Table 1. Aerodynamic and hydrodynamic properties for loading calculations.

Parameter	Value
Reference wind speed (m/s)	32.7
Reference wind speed elevation (m)	10
Air temperature (°C)	5
Kinematic viscosity of air at 5° (m^2/s)	13.60x10^{-6}
Density of air at 5°C (kg/m^3)	1.226
Significant wave height (m)	11.5
Wave period (s)	15
Storm duration (hours)	3
Sea water temperature (°C)	5
Kinematic viscosity of water at 5°C (m^2/s)	1.56x10^{-6}
Density of sea water at 5°C (kg/m^3)	1027.6
Sea water current speed (m/s)	0.6

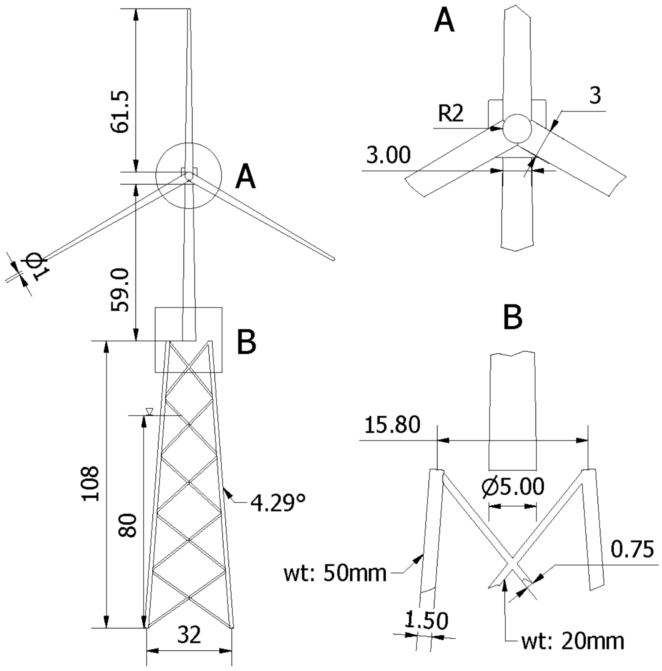

Figure 1. Schematic of conceptual 8 MW wind turbine and steel jacket in 80 m water depth (dimensions in metres).

Table 2. Loads acting on screw pile (negative value indicates tensile load)

Load Direction	Upwind	Downwind
Horizontal (MN)	6.28	6.28
Vertical (MN)	-26.14	34.85

2.2 *Screw Pile Designs*

Two screw piles were designed to suit the loads and soil properties previously defined, using a single pile at each corner of the jacket, to provide a worst-case design. However, it is likely that a multiple screw pile template would be used at each corner of the jacket to reduce installation requirements.

The following approaches to calculate the appropriate capacities were used: tensile resistance from the multi-helix method in Das and Shukla (2013); cylindrical shear method in Perko (2009) for compressive capacity; analytical methods in Fleming et al. (2008) for the lateral capacity, with contributions from the helices to the lateral capacity neglected (Perko 2009). The first design had uniform core and helix dimensions, while the second, optimized design, had reduced core and bottom helix diameters (Figure 2 and Table 3). Morais and Tsuha (2014) demonstrated a substantial reduction in installation torque of small diameter onshore screw piles with a section of reduced core diameter compared to designs with a uniform core diameter.

Figure 2. Photograph of optimized (upper) and standard uniform (lower) screw piles tested in the centrifuge.

Table 3. Screw pile dimensions in metres at prototype scale (mm at model scale of 1/80th).

Parameter		Uniform screw pile	Optimized screw pile
Length, *L*		13 (162.5)	
Core diameter, d_c	Upper	0.88 (11)	
	Lower	0.88 (11)	0.60 (7.5)
Helix diameter, D_h	Upper	1.70 (21.25)	
	Lower	1.70 (21.25)	1.34 (16.75)
Pitch, *p*	Upper Lower	0.56 (7)	0.56 (7.5)
Thickness, *t*	Upper Lower	0.11 (1.4)	0.11 (1.4)
Helix spacing ratio, S/D_h		2	2

Reduction of the core and helix diameters in the optimized version was possible because of the substantial axial bearing capacity generated in compression by the lower surface of the helix and solid pile base. In the uniform design, the axial compressive capacity far exceeds the required amount from Table 2. Thus, the diameter was reduced to match the loading conditions. As the screw pile was calculated to fail with a 'long pile' mechanism under lateral loading, the core diameter was reduced below the hinge point, while maintaining the necessary capacities and torsional resistance. It is acknowledged that a more robust and practical design could be achieved by introducing the step change in pile core diameter at the position of the upper helix rather than above it as adopted here. Alternatively, a transitional change in diameter could be used rather than a stepped approach. The large core diameter was required to deal with the significant bending moments associated with the jacket structure loading regime (lateral loading) and demonstrates one of the significant changes in geometry required for offshore deployment compared with onshore, where maximum core diameters are typically 406 mm (Tappenden and Sego 2007). Al-Baghdadi et al. (2015) investigated placing helices close to the top of the screw pile (and seabed surface) but found that although increased lateral capacity could be generated (up to 22 %), the helix was most efficient just below the seabed surface making it prone to being uncovered due to scour.

3 CENTRIFUGE TESTING EQUIPMENT

3.1 *Installation and loading system*

Previous investigations of the effects of installing model piles at 1g before subsequent testing at high-g levels observed significant differences in the response of the model pile compared to in-flight installation and testing (Klinkvort et al. 2013). Therefore, equipment was developed at the University of Dundee which is capable of installing and testing screw piles in one continuous centrifuge flight (Al-Baghdadi et al. 2016), at up to 60g (Figure 3).

The testing equipment allows for very precise bi-directional axial displacement (up to 300 mm) through a geared belt-driven ball screw system, powered by a AKM54H servo motor (Motor 1 in Figure 3). Rotation was provided by a second (slave) servo motor (AKM53H) connected to the screw pile via a 4:1 ratio gearbox to increase available torque from 10 Nm to 41 Nm. A custom F310-Z combined torque transducer and axial loadcell was mounted to the gearbox 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.

As the loadcell was mounted directly above the screw pile and rotated during the installation phase, this created a challenge regarding handling of the loadcell cable. The initial process in Al-Baghdadi et al. (2016) to control the cable under high-g conditions during a screw pile installation was to allow the cable, which was pre-wound around the loadcell, to unwind as the loadcell rotated and collect at the base of the rig. This approach was quickly found to be flawed, as on several occasions the cable became entangled with the screw pile because of the increased self-weight under high-g conditions (leading to aborted tests).

An alternative approach was adopted by Al-Baghdadi et al. (2016) which reversed the initial method by winding the cable on to the loadcell, from a pre-coiled position, through a large plastic funnel and cable sleeve to control the position of the cable. A large diameter plate added below the loadcell created a spool for the cable to wind on to.

Although this method worked for the initial testing program, a third system was implemented for this project which was considered more robust and eliminated any concerns over the handling of the loadcell cable without affecting the quality of the data. Although other researchers have used different designs (Tsuha et al. 2007), 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.

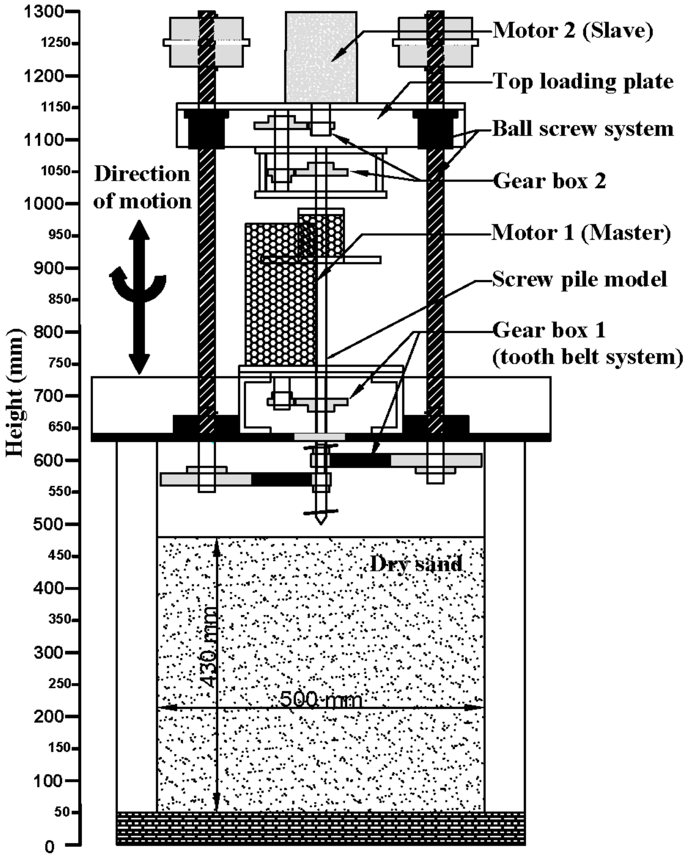

Figure 3. Schematic diagram of the screw pile centrifuge testing equipment mounted on a model container (800 mm long) (Al-Baghdadi et al. 2016).

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 Micro Analog 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.

3.2 *Soil Properties*

All tests used dry HST95 fine-grained quartz sand. The physical properties of this sand, summarized in Table 4, have been characterized at the University of Dundee (Al-Defae 2013, Jeffrey et al. 2016).

Table 4. HST95 sand material properties (Al-Defae 2013).

Property	Value
Grading description	Fine
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Typical interface friction angle, δ'_{crit} (°)	24
Angle of dilation*, ψ (°)	16
Maximum dry density, ρ_{max} (kN/m^3)	17.58
Minimum dry density, ρ_{min} (kN/m^3)	14.59

* As measured at 80% relative density (Al-Defae 2013).

3.3 *Model Container and sand bed preparation*

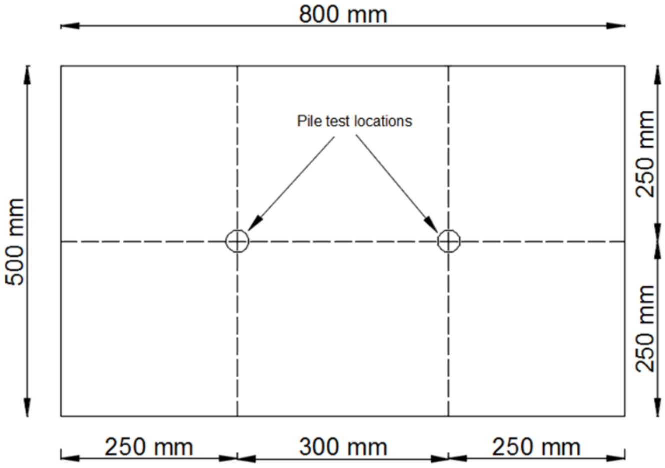

Figure 4. Plan locations of the centrifuge pile tests in the sand container.

A container with internal dimensions of 500x800x550 mm (Figure 3) was used for both tests. Sand was prepared to a depth of 430 mm and relative density of 81 % using an air pluviation system described by Jeffrey et al. (2016). Such dense to very dense sands are commonly encountered offshore Europe and represent a worst-case condition for installation forces. The container size allows for two tests in a single test bed (by moving the actuator between separate centrifuge flights) without creating any boundary effects. The shortest distance to the container boundaries from the test locations (Figure 4) was greater than 10 times the largest helix diameter (Phillips and Valsangkar 1987, Bolton et al. 1999).

Grain size effects were also considered, with a minimum value of 53 satisfying the smallest pile diameter (7.5 mm) to d_{50} particle size ratio of less than 50 recommended by Garnier et al. (2007).

3.4 *Screw pile installation*

The parameters used to install screw piles are critical to their in-service performance, as over-rotating (augering) during installation can reduce tensile capacity (Perko 2009). Therefore, screw piles should be installed to penetrate the soil by an amount equal to at least 80 % of the helix pitch per revolution (Perko 2009). This was achieved by using displacement controlled installation such that sufficient vertical force was applied to install the screw pile by 7 mm per revolution at a vertical rate of 21 mm/min.

4 RESULTS AND DISCUSSION

Two centrifuge tests were performed to measure the installation torque and crowd force of the standard and optimized screw piles designs at 50g. The results of both tests are shown in Figure 5 at prototype scale.
To compensate for the dry soil conditions, the test data was scaled by a factor of 80 to simulate the design soil conditions of saturated soil behaving in a fully drained manner (Li et al. 2010).

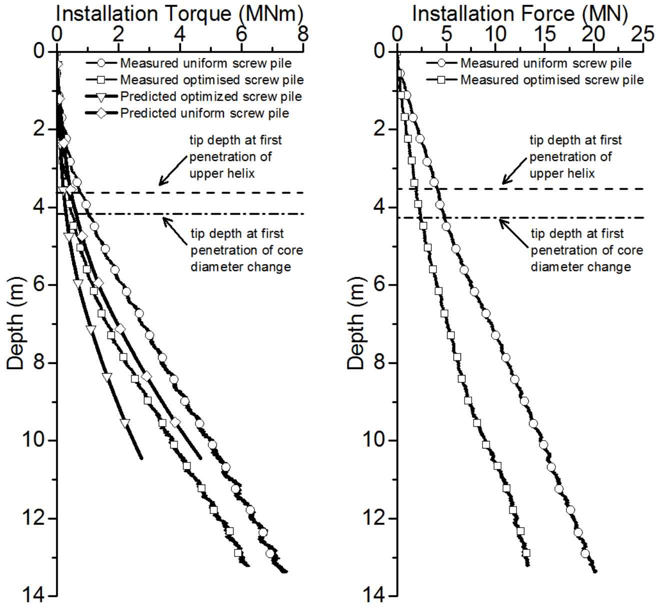

Figure 5. a) Vertical installation force and b) installation torque for uniform and optimized screw pile designs.

The crowd and torque of the uniform and optimized screw pile designs were successfully measured in the centrifuge tests, indicating that the equipment is suitable for further investigating the magnitude of the full-scale screw pile installation requirements. The equipment also allows for the investigation of pile geometry optimization and its effect on torque and crowd force. It is apparent from Figure 5 that the magnitude of both the torque and crowd force during installation are significant (V_{max} = 19 MN, T_{max} = 7 MNm) for the standard uniform pile. To put this in context, an onshore screw piling system based on an excavator mounted torque head, may be capable of only generating a torque of 250 kNm and vertical force of 257 kN, although casing rotators are capable of supplying torque of around 5 MNm and crowd force of 1.2 MN. The solid screw pile core design, reflecting a worst-case scenario, also influenced the large installation forces, but it is expected that full-scale, hollow core, screw piles would behave in an unplugged manner during installation, thus reducing the torque and crowd force.

The results from this preliminary testing (Figure 5) of the optimized design show that this approach was effective in reducing the final crowd force and torque values by 29 % and 11 % respectively. Furthermore, optimization of the screw pile design reduced the surface area and volume by 11 % and 18 % respectively, which could present a substantial saving of material and costs across a large array of turbines, while still achieving the in-service structural requirements.

These findings are comparable to those of Morais and Tsuha (2014) who observed a 33 % reduction in installation torque for a screw pile with a 28 % smaller surface area, during field scale tests of screw piles with uniform and reduced core diameters.

Figure 5 also includes a torque prediction for each test using the CPT correlation by Al-Baghdadi et al. (2017) with the rotation reduction factors equal to one and q_b equal to q_c. For the depth covered by the CPT data, the torque prediction matches the observed torque reasonable closely, although there is a slight under-prediction in this case, it is suggested that this method is appropriate for estimating the installation torque of large scale screw piles in sand.

5 CONCLUSIONS

As offshore wind energy progresses into deeper water, new foundation solutions are required. Steel jackets founded on screw piles are one such solution, with screw piles offering quiet installation and potentially superior capacity compared to straight shafted piles.

Centrifuge testing of model scale screw piles offers an alternative to large scale field testing, of which there is very limited existing research, especially for large or novel geometries. Centrifuge tests of two screw pile designs, in dense sand, were conducted to investigate the full-scale installation force and torque requirements of screw piles designed to sustain the loads of a jacket supported turbine.

The results show that equipment specially developed at the University of Dundee can successfully capture the installation data of model scale screw piles along with the subtle changes to the geometry, intended to optimize the design. It is apparent that the torques and vertical forces generated during installation are very significant and one or two orders of magnitude greater than those used onshore. Armed with this information, offshore contractors will have insights into the requirements for installation equipment development or installation strategies (screw pile groups) to minimize installation requirements.

Further centrifuge tests of additional designs in various sand densities are planned to continue the investigation into the behavior of large screw piles.

6 ACKNOWLEDGEMENTS

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