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Development of an inflight centrifuge screw pile installation and loading system

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ABSTRACT: To simulate the prototype installation behaviour of screw piles at realistic confining stress levels, a new installation and loading rig, consisting of two independently-controlled servo-motor drive systems was developed to allow screw pile models to be installed and axially load-tested inflight in one operation at 50 g. This system was developed around the Scalable Actuator Control System architecture (SACS) recently installed on the Dundee centrifuge, based around a National Instruments compactRIO controller with modularly scale-able servo drive interfaces. 1:50 scale model screw piles were manufactured from mild steel with 10 mm diameter cores with 25 mm diameter flanges welded on, representing a new generation of larger screw pile proposed for offshore marine renewable applications. These were installed up to 200 mm depth in dry dense sand to demonstrate the performance and capabilities of the new actuator. This paper details the design philosophy and operation of the servo motor actuation system for inflight screw pile installation.

1 INTRODUCTION

Screw piles (or helical piles) consist of one or more helical plates (or flanges) welded onto a hollow steel shaft (or core). This type of pile has been widely used onshore to resist tension and compression loads, and recently has been suggested to be used for offshore wind turbine foundation if significantly increased in size (Byrne & Houlsby 2015; Spagnoli & Gavin, 2015). Most previous studies on screw piles have used numerical modelling and/or 1-g small scale laboratory tests (e.g. Al-Baghdadi et al. 2015 and Knappett et al. 2014). Even where centrifuge testing has previously been undertaken, this has typically involved installation undertaken at 1-g and only load testing in-flight (Wang et al., 2013). Tsuha et al., (2007) improved on this with initial installation at 1-g and completion of installtion at 22-g prior to final testing inflight . These approaches though may limit the ability to predict realistic prototype installation torque levels which is essential to be able to design offshore rotary pile installers with sufficient capacity for the proposed new generation of larger screw piles. In this study, a new bespoke servo-actuator has been developed that can model the complete installation and pile testing processes as one inflight operation on the centrifuge.

Prior to beginning development of a new system, a review of existing centrifuge pile installation and actuation systems was undertaken. Many robotic systems have been developed for centrifuge modelling including single axis (vertical) and two- or three-axis movements (vertical and horizontal directions) to investigate sophisticated geotechnical problems. These systems have been used for simulating CPT tests, anchor pull-out, V-H-M foundation load testing, and deep excavation, amongst other geotechnical tests. Klotz & Taylor (2001) developed a single axis servo actuator at City University consisting of a servo motor, a gear box to increase the torque, and a ball screw system to covert the motor rotary motion into a linear motion for pile installation and test in flight with a 50 kN driving force and 400 mm stroke with penteration speeds between 0.25-1 mm/s at up to 200-g.

A 2D servo-actuator was developed by Haigh et al. (2010) for the Turner beam centrifuge in the Schofield Centre at the University of Cambridge and has been used to carry out cone penetration tests, pile tests under cyclic loads (axial and lateral) and deep excavation simulations. The actuator consisted of two servo controlled motors, ball screw systems that can translate the rotary motion into a linear motion, and two slide bearing rails to prevent rotation and allow the vertical movement of the carriage plate. This system allowed a high lead accuracy 0.025 mm per 300 mm, maximum stroke of 300 mm at up to 10 mm/s vertically, and tension and compression capacities of 10 kN at up to 50-g.

Tsuha et al. (2007) developed a bespoke device at what is now IFSTTAR to install and test small screw piles inflight at 22-g, consisting of a pilot motor, force sensor and dynamic torque meter, which were placed on top of an SV2 servo-controlled hydraulic jack (i.e. a hybrid electro-hydraulic system) with a capacity up to 3.2 kN and maximum speed 130 mm/s over 300 mm stroke. This device was capable of measuring torque up to 50 N.m with rotation speed between 0 - 5.2 rpm (Thorel et al., 2008).

Recently, Patra et al. (2014) developed a single axis servo actuator at the University of Dundee (UoD) based around a scalable architecture to allow further fully independent servo-controlled 'axes' to be added at a future date. In this work, the single axis drive was developed for anchor pull-out and penetrometer testing, having a capacity up to 50 kN and a maximum speed 3.1 mm/s over 300 mm stroke. This paper will detail how a second servo-electric drive axis was added, along with a framework and mountings to turn the two drive motors into a screw pile installer and vertical load tester, capable of displacement or force/torque control.

2 SERVO ACTUATOR DESIGN

The servo actuator described in this paper was designed to install and test large (high torque) 1:50 scale model screw piles inflight at 50-g. The installation of the screw pile inflight was considered the most difficult challenge as it involved controlled rotation of the multi-plate screw pile simultaneously with controlled vertical downward movement. Based upon experience from current onshore (displacement-controlled) field installation of similar piles, the rotational and vertical speeds need precise control based on the screw pile and soil properties to create minimum disturbance to the soil i.e. to avoid over- or under-flighting and also to control/minimize the vertical or "crowding load". Therefore, it was decided to use two independent servomotors manufactured by Kollmorgen to supply the rotational and vertical movement (AKM53H and AKM54H) due to their ability to provide precise control of velocity, angular position and acceleration (the servo actuator specifications are provided in Table 1). This was achieved by using a ball screw system with one of the servomotors ('master') to translate the rotary motion into a linear motion for vertical displacement as shown in Figure 1. The rotational degree of freedom was provided using the second servo motor ('slave') mounted on the top loading plate that rotated the multi-plate screw pile via a gearbox and a custom-built in-line combined torque/axial load cell (mounted above the screw pile model, and not shown for clarity in Figure 1).

Gears were used on both axes to increase the torque supplied by the servo motors. The main servo motor (master, vertical control) utilised a gear ratio of 1:6.67, while the second motor (slave, rotational control) utilised a gear ratio of 1:4 to increase the installation torque.

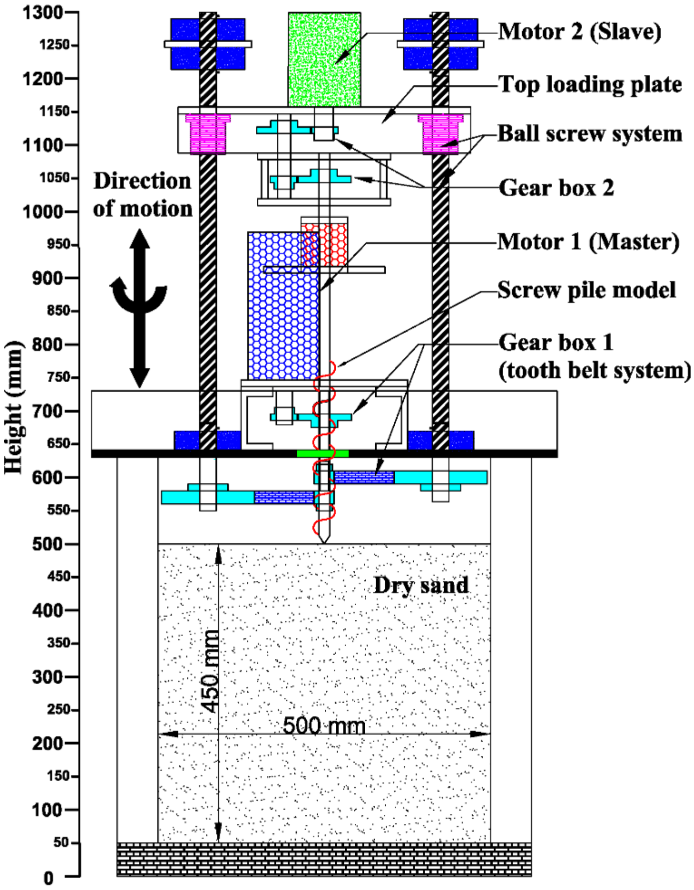

Figure 1. Schematic diagram of the screw pile centrifuge test setup with a new servo actuator placed on the container (note the screw pile consists of single plates rather than a continuous helical as shown).

Table 1. The Servo actuator performance specifications.

Specification	Vertical	Rotation
Stroke	300 mm	—
Max. Speed	1.67 mm/s	100 rpm*
Min. Speed	0.016 mm/s	1 rpm*
Capacity	± 10 kN	30 N.m

*rpm: revolutions per minute.

3 INSTRUMENTATION AND CONTROL

3.1 *Load cell*

A combined axial force and torque transducer (F310-Z), specially manufactured by Novatech Measurements Ltd, UK, was used to measure the force and torque during the installation and load testing (Figure 2). The transducer was rated to 20 kN axial force and torque of up to 30 N.m.

The load cell was mounted directly above the model screw pile to allow direct measurement of torque and axial load applied to the pile during installation and to allow load testing after installation in one operation.

Figure 2. Novatech F310-Z axial force and torque transducer.

3.2 *Draw-wire potentiometer*

A POSIWIRE WS31C draw-wire transducer with 750 mm long wire which was manufactured by Automation Sensor Measurement® (ASM) was used to record the linear displacement during the large displacement installation and subsequent load testing as shown in Figure 3. The cable of the draw-wire has a 1.2 N line tension and the transducer has analogue output with quasi infinite resolution. The servo motors additionally have position encoders which allows back-up monitoring of the displacement during the test.

Figure 3. Draw-wire potentiometer WS31C.

3.3 *Data acquisition system (DAQ)*

A Fylde micro analog 2 modular instrument system (FE-MM8) was used for data acquisition (DAQ) for the signals from the draw-wire and the axial force and torque transducers. This system has effective screening of electrical noise often encountered on strain gauge based transducer signals when used with three phase or high powered servo motor actuation systems, such as the ones used in the actuator. The DAQ unit was placed in the centrifuge cabin at the centre of the arm and connected to an onboard PC via USB, as shown in Figure 4. The DAQ unit used had four dual channel instruments cards (FE-366-TA), providing the ability to acquire (and excite at a switchable voltage between 5 – 10 V) up to 8 transducers simultaneously (10 V was used in this study). Onboard amplification was also possible in steps between 1-5000 (manual adjustment possible between discrete preset steps). In this study, the signal amplifications were set to 1 for the draw-wire transducer and 200 for the axial force and torque transducer.

National Instruments Labview software (version 13.0) was used to control the DAQ unit and the servo-motors (the latter via an NI compactRIO controller, described in further detail in the following section).

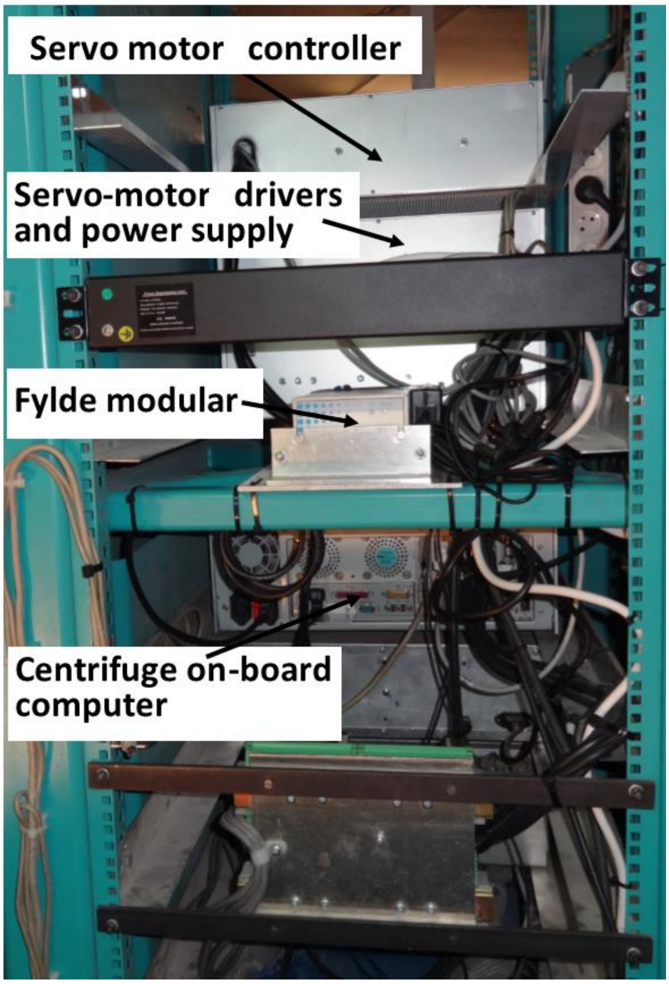

Figure 4. Fylde modular instrument positioned in the centrifuge cabin.

3.4 *Motion control*

An NI compactRIO controller (cRIO-9024), two 1-axis servo drive interfaces with dual encoder feedback (NI 9516) and two AKD analogue servo drives were used to control the servo-motors via Labview 2013. The software routine for the testing described in this paper allows independent control of drive to the two axes at controlled rate in both directions (forwards and reverse) under displacement control.

4 SCREW PILE TEST PROCEDURE

Proof testing of the installation and testing system included five centrifuge tests. The main purpose of these tests was to ensure the system's ability to carry out the installation and loading at 50-g. It was decided to do the test in steps of g level (i.e. 10, 20, 40 and 50-g) and carry out a multi-plate screw pile installation and test at each step. At each g-level the model pile therefore represents a different size prototype pile, with 10-g and 20-g being broadly representative of typical onshore piles (individual flange diameter = D_f = 250 – 500 mm) and 40-g and 50-g tests representing larger piles which might be required offshore (D_f = 1 – 1.25 m). The actuation system was carefully monitored during the centrifuge tests by using two GoPro HERO4 cameras positioned on the container sides and connected wirelessly to computers in the centrifuge control room. Also, the servo actuator was carefully inspected after each spin in order to confirm that no damage had occurred during the centrifuge tests.

The centrifuge tests were carried out in a steel container with internal dimensions of 800 mm long, 500 mm wide and 580 mm depth. The container was filled up to 450 mm depth with dry HST95 silica sand at 73% relative density using a manual sand pluviator. More details regarding HST95 silica sand properties can be found in Lauder et al. (2013). In order to minimize potential boundary effects, the distance from the pile tip at full installation depth (150 mm below the soil surface) to the container bottom was $12D_f$ which did limit the potential embedded length somewhat, and the distance from the pile centre to the nearest container side was 8 D_f.

The screw pile model was manufactured from mild steel with 25 mm diameter and 1.5 mm thick individual plates/flanges (helical plates), welded onto a 10 mm diameter steel shaft. The geometry of the screw pile model is summarized in Table 2. In this study, the ratio of screw pile core diameter (D_p = 10 mm) and flange diameter (D_f = 25 mm) to the average sand grain size (d_{50} = 0.12 mm) was more than 83 and 200, respectively.

Table 2. Screw pile model dimensions.

Screw pile model geometry	Dimensions (mm)
Shaft diameter, D_p	10
Flange diameter, D_f	25
Flange spacing, S	25
Flange number	6
Flange pitch, p	9.5
Flange thickness, t_f	1.4
Screw pile embedment length, L	150
Top flange depth below soil surface	12.5

The first centrifuge test was carried out at 10-g and the screw pile model was connected to the load/torque cell with the power communication cable pre-wound around the load cell. It was assumed that the cable would then unwind during the torque installation of the pile and would sit within the base C-channel that forms the bottom structural element of the actuation system (as had occurred during 1-g trials). However, during the first centrifuge spin the cable became trapped around the screw pile due to the increased self-weight of the cable. This problem was resolved by making the cable wind onto the load cell (rather than off it) from a pre-coiled arrangement on a platform next to the actuator and running the cable through a 23 mm diameter convoluted cable sleeving and a funnel. This arrangement is shown in Figure 5. Additionally, a 180mm diameter thin aluminium plate was connected to the bottom side of the load cell to keep the cable in place during the load test stage after it had been wound-on during installation. This technique was subsequently adopted for all centrifuge tests. Adopting this method though did induce a small additional torque on the torque cell which was found to be consistent and increase linearly as the test progressed. This was corrected for in all subsequent tests.

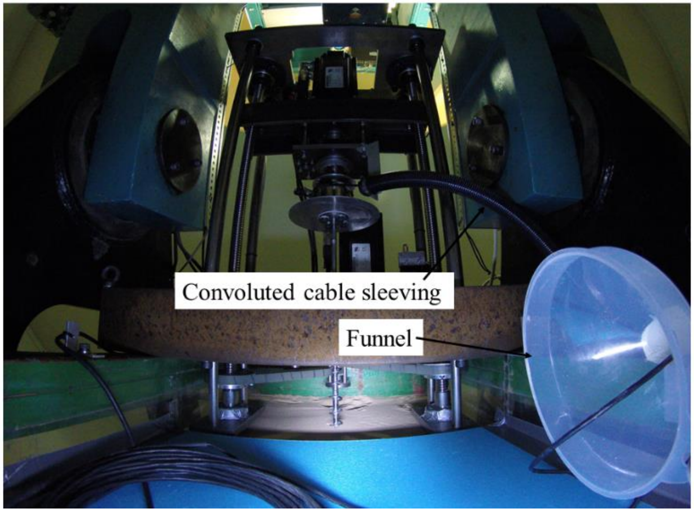

Figure 5. Screw pile installation in flight at 50-g.

5 CENTRIFUGE TEST RESULTS

Installation and load test results were obtained for three centrifuge tests at 20, 40 and 50-g. Test results for at 40-g are shown in Figures 6 and 7 which is divided into seven stages for discussion. In the first stage, the centrifuge started spinning and the tension load increased gradually as the suspended pile increased in weight. The hanging weight of the screw pile model, 180mm diameter cable collection plate (see above) and the connection elements was approximately 483 N at 40g. After the centrifuge stabilised at 40 g (stage 2), the screw pile was installed to 150 mm depth in stage 3. A few minutes after the installation ended (stage 4), the compression test was conducted up to a vertical displacement of 20% of the flange diameter (5 mm) displacement in stage 5. Some minutes after the end of the compression test (stage 6) a tension test was conducted in stage 7, again to 20% of the flange diameter (5 mm).

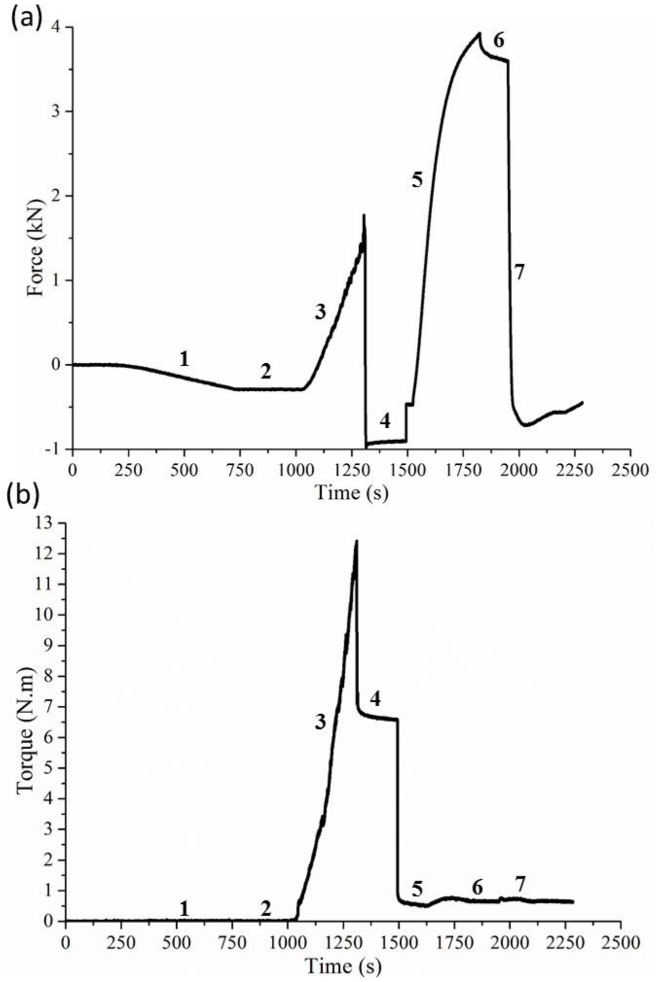

Figure 6. Screw pile centrifuge test at 40-g in dry dense sand (R_d=73%) at model scale (a) the force and (b) the torque measured during testing.

At prototype scale, the installation force and torque of the screw pile at a depth of 6 m was 3310 kN and 789 kN.m, respectively. Using a displacement of 10% D_f as a failure criteria, the ultimate compressive and tensile capacities were found to be 5079 kN and 1010 kN, respectively as shown in Table 2. From these figures, it would appear that the vertical installation force (crowding force) was approximately 35% of the ultimate compressive capacity and approximately 177% of the ultimate tension capacity. This can be attributed to the installation speed of the screw pile as it was kept constant at rate 30 mm/min vertically with rotation 3.2 rpm during the installation to be consistent with a vertical movement of one times the pitch of the screw pile flange (9.5 mm, Table 2) per revolution. This is a methodology typically used in onshore field installation and recommended by previous researchers (Perko, 2000 and Tsuha et al., 2012) to minimise soil disturbance during installation. In spite of following this procedure, the crowding load appears relatively large and will directly influence the measured torque (crowding loads are not normally measured in the field). Future tests will explore alternative installation procedures to potentially reduce this crowding load.

In the field, screw pile capacity is often correlated with installation torque by an empirical factor as proposed by Hoyt & Clemence (1989):

$$Q_u = K.T \tag{1}$$

where Q = screw pile capacity; K = empirical factor; and T = final installation torque. These parameters are summarized at prototype scale for the 40-g and 20-g tests in Table 3. It has been found that the empirical factor determined for the compression load is in good agreement with previous field test results in dense sand reported by Sakr (2010), where the compression empirical factor (K_c) varied from 6.5 to 9.6 with decreasing shaft and flange diameters from D_p = 0.508 m and D_f = 1.016 m to D_p = 0.324 m and D_f = 0.762 m, respectively Sakr (2010).

Table 3. Screw pile capacities at prototype scale.

g level	Flange Diameter D_f	Capacity in compressions Q_c	Installation Torque T	Empirical factor K_c
	m	kN	kN.m	m^{-1}
40g	1.0	5690	788.7	7.2
20g	0.5	1329	72.5	18.3

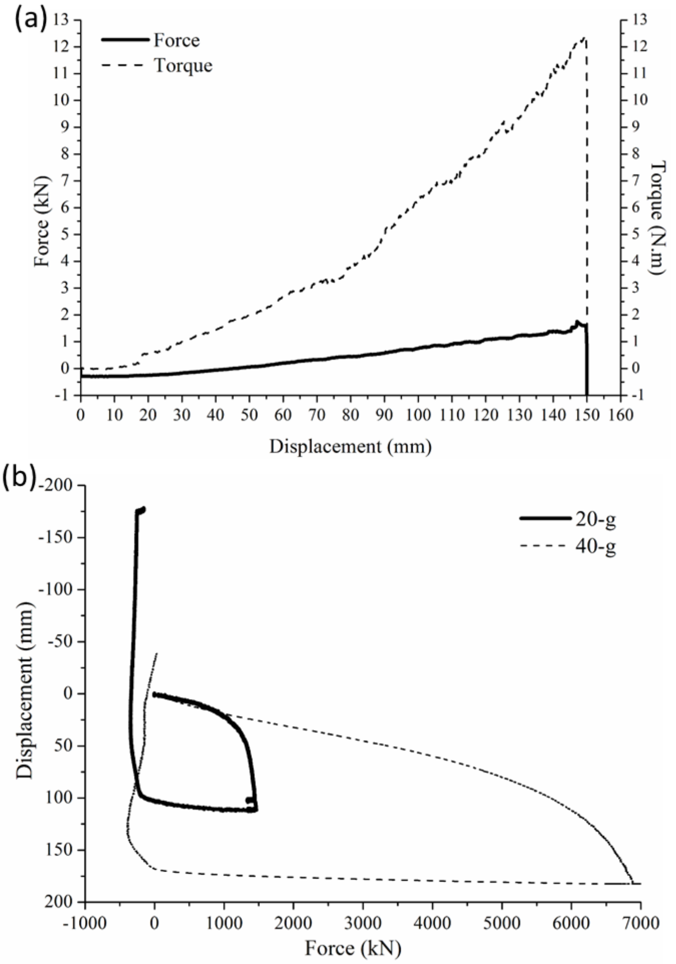

Figure 7. Centrifuge test results (a) installation force and torque with displacement at 40g at model scale (step 3) and (b) screw pile model force-displacement comparison at 20-g and

40-g in dry dense sand (R_d=73%) at prototype scale (steps 5, 6 and 7).

6 CONCLUSION

A new servo controlled actuation system has been developed at the University of Dundee to allow full installation and vertical load testing of model screw piles (with individual plates or flanges) in one continuous centrifuge in-flight operation. This single operation approach to screw pile installation and testing is considered fundamental to capture the effect of installation on final in-service pile performance and for quantifying the force-torque required for future field installation systems for larger, higher capacity piles. This system can apply a combination of synchronized vertical movement and rotational motion (via independent servo controlled motors) to allow controlled installation and testing of a screw pile (or other foundation and anchoring solutions). The servo actuation system has been designed to provide a maximum load of 10 kN in compression or tension and a maximum simultaneous torque of 30 N.m. The installation torque and force were recorded using a combined bespoke load cell capable of measuring both force and torque simultaneously thus allowing investigation of the torque required during installation and the influence of crowding loads. Initial results from the proof testing appear promising and will be used to validate the results of Finite Element analyses for capacity prediction and explore different installation rates and pile geometries. This will contribute to the ultimate aim of upscaling and optimising the design of screw piles as alternative offshore windfarm foundation solution.

7 AKNOWLEDGEMENTS

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