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Centrifuge modelling of two-way axial cyclic response of screw piles for offshore wind

W. Wang
University of Dundee, Dundee, United Kingdom, 2422030@dundee.ac.uk

M. J. Brown, Y. U. Sharif, C. Davidson
University of Dundee, Dundee, United Kingdom, m.j.z.brown@dundee.ac.uk, y.sharif@dundee.ac.uk, c.s.davidson@dundee.ac.uk

M.O. Ciantia
University of Dundee, Dundee, United Kingdom, m.o.ciantia@dundee.ac.uk
University Milano Bicocca, Milano, Italy, matteo.ciantia@unimib.it

ABSTRACT: Screw piles have been proposed as an innovative silent foundations/anchor solution for offshore renewable energy applications such as fixed or floating wind. Such application requires a deeper understanding of the influence of increases pile size and offshore loading conditions on performance of screw piles. To date two-way axial cyclic response of screw piles has not received sufficient attention, which may be encountered in offshore jacket structures. This investigation conducted both one-way tensile and two-way cyclic loading tests on a screw pile designed for offshore wind turbines using a geotechnical centrifuge. The results suggest that, when the cyclic amplitude is the same, the two-way loading regime can lead to permanent displacement accumulation at a lower rate than that of the one-way loading case, although it may cause a softer post-cyclic monotonic tensile response.

1 INTRODUCTION

Screw piles (also referred as to helical piles) consist of one or several helices connected to a central straight shaft or core and are typically installed by applying torque and vertical (crowd) force simultaneously at the pile head. This type of piles has been widely used onshore and recently has been proposed as an innovative silent solution for foundations/anchors for offshore renewable energy applications (Cerfontaine et al., 2023b, Lloyd's Register, 2024, Spagnoli and Tsuha, 2020).

One concern regarding the transition of screw piles from onshore to offshore use is the uncertainty raised by increasing their size. The screw piles used onshore are typically up to 0.4 m helix and 0.2 m shaft diameter and 6 m in length, resulting in tensile capacities up to hundreds of kN. To achieve a tensile capacity of the order of MN and sufficient lateral capacity for offshore applications, the helix diameter may need to be greater than a 1 m with a total pile length of tens of meters.

Davidson et al. (2022) proposed some potential screw pile designs for offshore wind applications and tested them in a geotechnical centrifuge. Based on the test results, they corrected existing capacity design methods which focus on small sized screw piles used onshore. This previous work has subsequently been followed by exploration of potentially improved pile geometries and installation methods in terms of enhanced monotonic capacity and reduced installation requirements (Cerfontaine et al., 2022, Cerfontaine et al., 2023a, Sharif et al., 2021a, Sharif et al., 2021b, Wang et al., 2023a).

For offshore applications, displacement or serviceability limits may prove more challenging to achieve and the effect of cyclic loading may be more critical concern than monotonic capacity. For onshore use of screw piles, cyclic loading is usually encountered when the piles are used as anchors for e.g. guy lines of transmission towers and wind turbines (Cerato and Victor, 2009, Schiavon et al., 2019). Therefore, previous studies predominately focused one-way tensile response. The purely tensile cyclic response of the upscaled screw piles has also been investigated with a focus on influence of installation method (Wang et al., 2024b). However, the screw plies are also expected to carry two-way cyclic loading when installed as deep foundations for jacket structures. This paper presents preliminary results of two-cyclic response of an upscaled screw pile measured during centrifuge testing with comparison to a one-way cyclic tensile loading case.

2 CENTRIFUGE MODELLING

2.1 Centrifuge setup and testing actuator

Pile testing was conducted in a strong box filled with dry sand on the University of Dundee's 3m radius geotechnical beam centrifuge at 50g. Testing in dry sand aimed to simulate drained conditions and the same effective stress regime at 80g in saturated sand so the scaling factor in this study was 80 (Davidson et al., 2022, Li et al., 2010).

Installation at 1g can create a softer pile loading response compared to conducting installation and loading in a continuous centrifuge flight, due to the different post-installation stress field around the pile. To create reasonable real-world post-installation stress, this study used a purpose built two axis actuator controlled by two servo-motors, which precisely control the rotational and vertical displacement as shown in Figure 1 and allow full in-flight installation and testing.

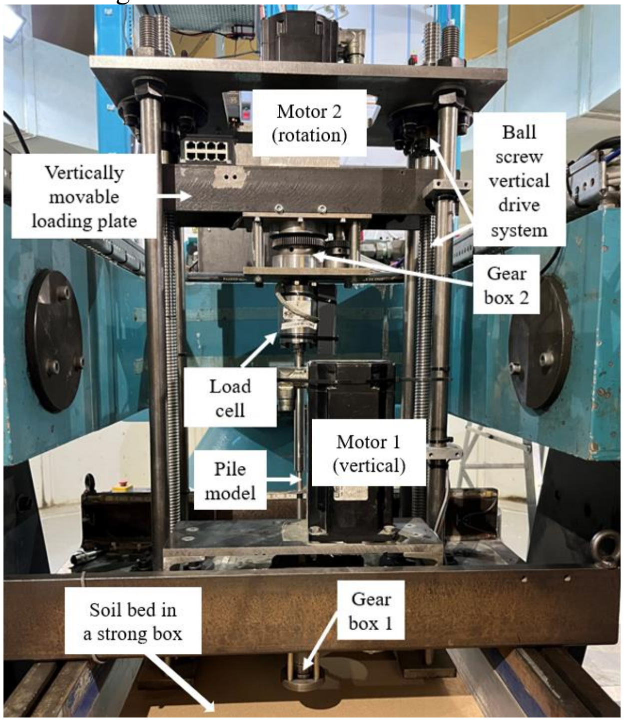

Figure 1 Image of the screw pile centrifuge testing equipment mounted on a model sand container.

This actuator was originally designed by Al-Baghdadi et al. (2016) and evolved in several later studies (Davidson et al., 2022, Cerfontaine et al., 2023a, Davidson et al., 2018). It allows for up to 400 mm bi-directional axial displacement through a geared belt-driven (Gearbox 1) ball screw system, powered by a AKM54H servo motor (Motor 1). Rotation at the pile head was provided by a second servo motor (AKM53H) connected to the screw pile via a 4:1 ratio gearbox (Gearbox 2) to increase available torque from 10 Nm to 41 Nm. A custom F310-Z combined torque transducer and axial loadcell was mounted below the gearbox of Motor 2 to measure the installation torque and crowd/vertical force as well as the force during post-installation in-service tests. The loadcell can measure axial force up to 20 kN and torque up to 30 Nm. Axial displacement data was measured with a WPS-500-MK30 draw-wire sensor, with back-up recording provided by the encoder of the servo-motors. A SR002 8 channel slip ring was installed on a shaft extension above the loadcell to avoid cables getting entangled with the screw pile during the rotary installation. Output voltages form the loadcell and draw-wire were recorded at a frequency of 250 Hz using a data acquisition system based on National Instruments 9047 CompacRIO operating in hybrid mode with 9022 input modules and Labview 2018 software.

2.2 Soil bed properties

Medium-dense soil beds ($D_r \approx 50\%$, 434 mm deep) were created by dry slot pluviation of HST95 sand (Lauder, 2010) in a 500 mm × 800 mm × 550 mm strong box. The sand was pluviated to slightly above the target height, and then the sand surface was levelled carefully. HST95 sand is a fine-grained quartz sand that has been extensively used and characterized at the University of Dundee for laboratory testing. Properties of HST95 sand are given in Table 1.

Table 1 Properties of the HST95 sand (adopted from Lauder (2010) and Al-Defae et al. (2013))

Properties	Symbol	Value
Effective particle size [mm]	d_{10}	0.090
Mean particle size [mm]	d_{50}	0.141
Particle specific gravity [-]	G_s	2.63
Minimum void ratio [-]	e_{min}	0.467
Maximum void ratio [-]	e_{max}	0.769
Dry unit weight [kg/m^3]	γ_{dry}	16.0
Saturated unit weight [kg/m^3]	γ_{sat}	19.7
Critical state friction angle [°]	φ_c	32
Peak friction angle [°]	φ_p	39.0
Peak dilation angle [°]	ψ_p	8.6
Steel-sand interface friction angle [°]	δ	24

2.3 Pile model

The single-helix pile model (see Figure 2) comprised a solid core with an 11 mm diameter (D_s), and a helical plate with 21.25 mm diameter (D_h), 1.4 mm thickness and 7 mm helix pitch (p_h) (model scale). The ratios of D_s / d_{50} = 78 and = (D_s - D_s) / 2 = 36 are above the recommended minimal value of 35 and 16, respectively, to avoid any particle size effects (Garnier et al., 2007, Rafsanjani et al., 2021).

A single helix allows preliminary understanding of cyclic performance without potential complicated interaction between helices occurring during installation and loading tests. In addition, adopting more than one helix at a small spacing may have detrimental effects on tensile capacity and may not be favourable design for practice (Wang et al., 2024a). The single helix also reduces torque requirements for installation.

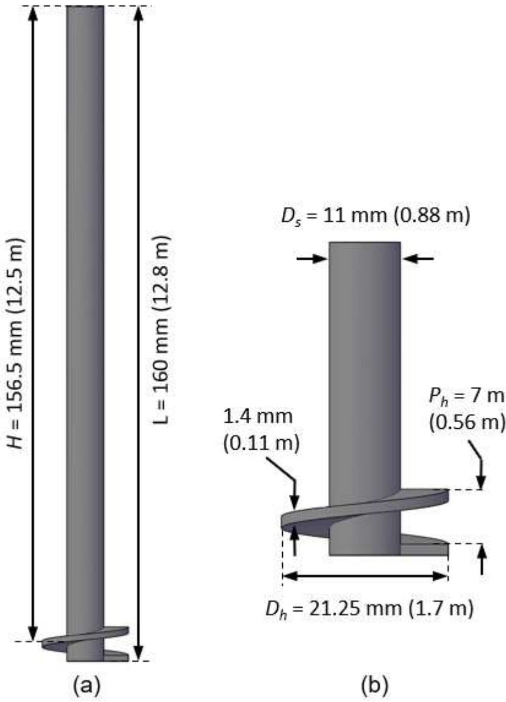

Figure 2 Screw pile model (a) whole pile model; (b) local detail of the helix region (prototype dimensions in brackets)

The solid pile core was adopted to avoid structural failure and to simulate assumed worse case pile plugging during installation. Therefore, the straight shaft section of this pile should be considered as rigid. The helix embedment depth was chosen to be $H = 7.5D_h$ which is just above the transition from shallow to a deep failure mechanism (Cerfontaine et al., 2019).

This pile geometry was originally designed as a footing of a four-leg jacket structure supporting an 8 MW wind turbine (Davidson et al., 2022) and has been widely used as a benchmark for screw pile studies at the University of Dundee (Cerfontaine et al., 2023a, Sharif et al., 2021a, Sharif et al., 2021b, Wang et al., 2023a).

Figure 3 shows the plan view of the soil container with test locations. The soil container allows two tests conducted in a single soil bed without any boundary effects. The minimal distance from the pile to any edge of the box or to another test location was 250 mm or $11.7D_h$. The minimal vertical distance from the pile end to the box bottom was 270 mm or $12.8D_h$.

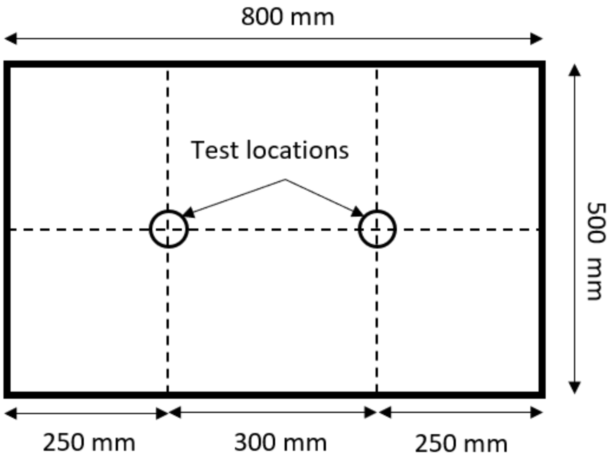

Figure 3 plan view of the soil container with test locations

2.4 Pile installation

The pile installation of each test scenario was conducted at a rotation rate of 3 revolutions/min (RPM). Onshore industrial guidelines, e.g. British Standards Institution (2015), require the installation of screw piles conducted following a pitch-matched manner, where advancement ratio AR = 1.0 (see eq. 1) with a tolerance of ± 0.2:

$$AR = \frac{\Delta z}{p_h} = \frac{2\pi v}{\omega p_h} \tag{1}$$

where Δz is increase of pile penetration depth per pile rotation, p_h helix geometric pitch, v and ω vertical and rotational velocity of installation, respectively. Installation at AR = 1.0 results in the helix movement tracking its geometry and is thought to minimise the soil shearing induced by helix.

One of the concerns of the pitch-matched installation is potentially prohibitive requirement of vertical force in offshore environment where it is difficult to provide adequate reaction force (Davidson et al., 2022, Wang et al., 2023b). Over-flighting, e.g. adopting lower AR values during installation can reduce the installation vertical force, which can also improve tensile response at expense of reduced compressive capacity/stiffness due to the different post-installation stress field (Cerfontaine et al., 2022, Cerfontaine et al., 2023a, Wang et al., 2023b).

As a starting point of two-way cyclic loading, this study considered installation at AR = 1.0 as recommended by existing standards. The installation vertical velocity was fixed at 21 mm/min to secure an AR = 1.0 condition associated with a rotational rate at 3 RPM. After the pile was installed to the target depth, the rotational motor was switched off to simulate the disconnection between pile head and installation equipment as per field practice. The installation behaviour of tests involved in this study can be found elsewhere (Wang et al., 2023b).

2.5 Loading test

The loading tests were conducted immediately following installation in a single non-stop centrifuge flight as mentioned previously.

To determine the tensile capacity prior to cyclic loading, a monotonic uplift case was conducted where the pile was pulled out to a displacement of at least 0.2 D_h at a constant rate of 1 mm/min (at model scale). The actuator allowed loading tests with the rotational motion being either on or off. The fixed-rotation condition is more likely to apply to jacket structures and therefore was adopted in cyclic loading in this study. The free-rotation condition, where the pile could potentially rotate during loading tests, applies to anchors for floating wind. To investigate if a pile had the potential to screw itself out of the ground during vertical tensile loading and also to determine the effect of connection details to such a pile in-service, monotonic tension tests were conducted using both the fix and free head condition. Figure 4 shows that the influence of free or fixed rotation on the pile head was negligible on tensile monotonic response. The tensile capacity Q_t was defined as resistance at displacement of $0.1D_h$. i.e. 5.2 MN. In contrast, Figure 4 also shows that tensile capacity of a push-in straight-shafted pile (SSP) with the same shaft diameter (11 mm at model scale) was only 1.13 MN, reduced by 80% compared to the screw pile.

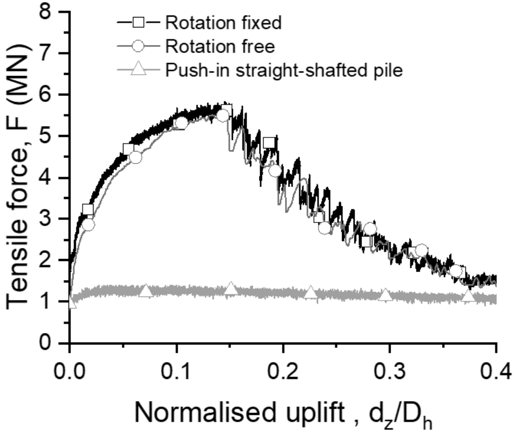

Figure 4 Monotonic uplift response with screw pile head rotation fixed and free compared with a straight-shafted pile.

To apply the vertical cyclic loading to the screw pile, a proportional-integral-derivative (PID) controller built in Labview 2018 was used. A user configurable signal generator was used to create the sinusoidal loading pattern and was the input for the setpoint for the PID controller. To ensure a smooth and accurate loading operation the force feedback system and motor commands were generated and updated at 250 Hz. This allowed for quick automated correction to be made to the displacement of the pile which ensured the target load/setpoint was achieved. The maximum allowable velocity of the motor was 25 mm/min and the velocity achieved was typically less than 10 mm/min.

Sinusoidal cyclic loading at a frequency of 0.1 Hz was adopted in this study. The two loading regimes have the same cyclic amplitude Q_{cyc} = $28.6\%Q_t$ (1.6 MN). It should be noted that the applied Q_{cyc} = 1.6 MN was over 50% of tensile capacity of the SSP and therefore the SSP is not expected to last under this loading level for even a single cycle. The mean loading Q_{mean} of the one-way input was also 28.6% Q_t resulting in the minimal loading Q_{min} being zero, while the two-way input is symmetric with Q_{mean} = 0.0. Cyclic loading was stopped after a permanent displacement of $0.1D_h$, which was assumed to be the criteria of serviceability limit state (SLS), was reached. After the cyclic loading, the piles were monotonically uplifted at a constant velocity of 1 mm/min (at model scale) to determine the variation of tensile capacity.

Table 2 summaries cyclic loading scenarios conducted in this paper.

Table 2 summary of cyclic loading tests in this paper

Test ID	Amplitude, Q_{cyc}/Q_t	Mean value, Q_{mean}/Q_t
One - way	28.6%	28.6%
Two - way	28.6%	0.0%

3 RESULTS AND DISCUSSION

3.1 Displacement accumulation

Figure 5 shows that, for the one-way loading test, permanent displacement started to accumulate from the first cycle and reached $0.1D_h$ after 8 cycles, whilst the two-way testing needed around 10 cycles to initiate displacement accumulation which reached $0.1D_h$ after 30 cycles. The one-way and two-way cyclic loading were stopped after 12 and 32 cycles and $0.108D_h$ and $0.121D_h$ permanent displacements were accumulated, respectively. Although the displacement accumulation developed quite fast, an improvement over the SSP should be noted since the SSP could not last even a single cycle.

The reduced displacement accumulation due to two-way loading may be attributed to the large soil stress below the helix and low soil stress above generated during installation (Sharif et al., 2021a). This resulted in a much stiffer compressive response than the tensile response. Although the compressive capacity was not determined in this study, centrifuge tests on this pile in a denser soil bed (D_r = 86%, also installed at AR = 1.0) showed the compressive capacity being more than twice that of the tensile capacity (Davidson et al., 2022). At a fixed $Q_{cyc} = 28.6\% Q_t$, reducing Q_{mean} from $28.6\% Q_t$ (one-way) to 0.0 (two-way) means that the stiffer compressive response was more influential and the pile experienced less softer/more critical tensile loading. Therefore, less displacement was accumulated in the two-way case.

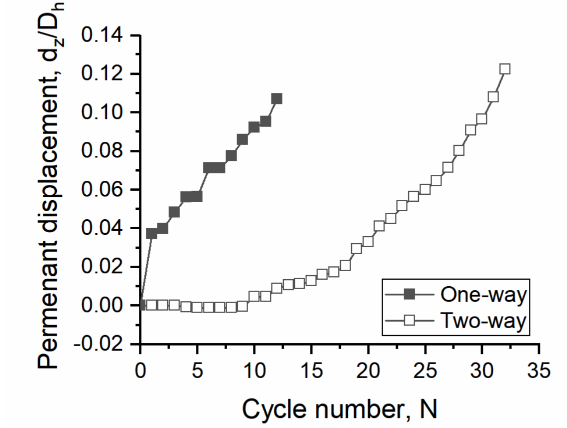

Figure 5 Comparison of displacement accumulation induced by one-way and two-way cyclic loading

3.2 Post-cyclic tensile response

Figure 6 shows that, after the one-way cyclic loading, the tensile capacity was reduced to 4.6 MN by 20.6% without loss of stiffness. In terms of the two-way case, a greater capacity degradation occurred (to 3.1 MN by 46.6%) with a significantly softer /less stiff – displacement behaviour.

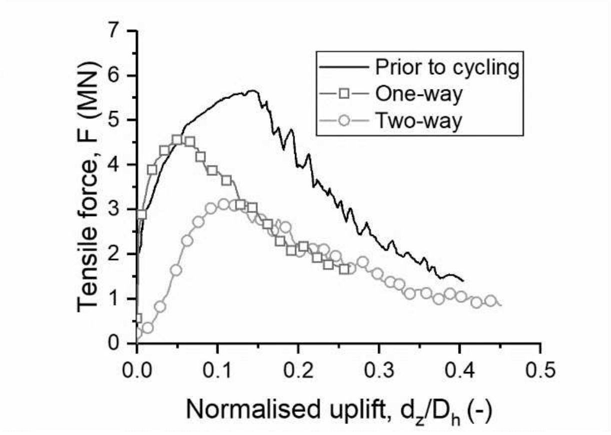

Figure 6 Comparison of monotonic tensile loading response prior to and after one-way and two-way cyclic loading

Wang et al. (2024b) suggested subject to one-way tensile cyclic loading that the capacity degradation linearly increased with displacement accumulation. In the two cyclic tests in this study, similar magnitudes of displacement were accumulated (0.108 D_h and 0.121 D_h), but much more significant capacity and stiffness degradation was observed in the two-way case. In this case this suggests that that two-way loading is more detrimental in terms of post-cyclic response.

The more significant capacity degradation due to two-way loading may be as a result of the loading phase transformation of the helix from tensile to compressive which aggravates soil stress reduction above the helix. But it should be noted that in the two-way case a higher number of loading cycles was conducted. Therefore, the comparison of post-cyclic capacity is not completely fair and it would be more appropriate to compare at similar cycle numbers.

4 CONCLUSIONS

One-way tensile and two-way cyclic loading tests, in which the loading amplitude was the same, were conducted on a screw pile designed to be used for fixed offshore wind turbine jacket structures. The installation of the pile followed a pitch-matched approach. It was found that the two-way loading regime led to displacement accumulation at a lower rate, although at the same permanent displacement the two-way case exhibited a more significant capacity degradation. Further instrumented tests or numerical modelling are required to understand the difference in mechanisms between one-way and two-way cyclic loading on the screw piles. In addition, the pitch-matched installation approach may be not practical for offshore applications. Therefore, the effects of installation methods also require further study. It is also noted that this study adopted dry sand to model drained conditions. The potential effects of excess pore pressure at higher loading frequencies or in finer grained soils requires further investigated.

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