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Effect of installation advancement ratio on two-way cyclic response of a single-helix screw pile for offshore wind

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ABSTRACT: Screw piles have been proposed as a silent and efficient type of foundations and anchors for offshore renewable energy application (e.g. floating wind). For large screw piles, conventional pitch-matched installation (advancement ratio, AR = 1.0) may be impractical due to the prohibitively high installation crowd force. By over-flighting (AR < 1), it is possible to reduce installation crowd force to zero and create pull in forces, as well as improving in-service tensile (both monotonic and cyclic) response at expense of reduced compressive response. For some applications e.g. serving as a foundation of a jacket structure, the pile may be subject to two-way cyclic loading. This study uses centrifuge tests to illustrate symmetric two-way, i.e. being in tension and compression alternatively, cyclic performance of a screw pile installed in sand, with effects of variation of advancement ratio being considered. Compared to previous one-way tensile cyclic tests, change of direction of displacement accumulation creates a more abrupt accumulation for the two-way loading cases depending on the magnitude of the load applied. The optimal AR value for two-way cyclic performance (AR = 0.5 in this study) is higher than that seen as optimal (AR = 0.25 in this study) for purely one-way tensile cyclic performance, as a balance of compressive and tensile response is needed. In all cases though, over-flighted installation it is observed to have a beneficial effect on cyclic performance.

Keywords: screw pile, helical pile, cyclic loading, installation effect, floating wind

1 INTRODUCTION

Screw piles (also referred as to helical piles or anchors) 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 e.g. anchoring floating devices such as floating turbines or wave energy converters (Jawid et al. 2024).

Conventional onshore screw piles have helix diameter (D_h) ranging from 200 mm to 800 mm with shaft diameter (D_s) being up to 300 mm and with pile length (L) being up to 10 m creating hundreds of kN of tensile capacity (Q_t). To install those piles, required crowd force and torque are typically up to hundreds of kN and kNm, respectively (Perko 2009). Transition of screw piles from onshore to offshore may involve significant size upscaling where both D_h and D_s are measured in terms of meters and L is tens of meters. This upscaling may need installation crowd force and torque measured in terms of MN and MNm, respectively (Cerfontaine et al. 2022; Davidson et al. 2022).

To reduce installation crowd force and torque, an over-flighted (advancement ratio, AR < 1.0) installation approach has been proposed to replace the conventional pitch-matched (AR = 1.0) approach:

$$AR = \frac{\Delta z}{p_h} \quad (1)$$

where Δz is vertical penetration per rotation during installation and p_h is the helix geometric pitch. It has been shown in centrifuge tests that reducing AR during installation can significantly reduce installation crowd force even to zero i.e. the piles can pull and rotate themselves into ground without applying crowd force at the pile head (Cerfontaine et al. 2023). The over-flighted installation can also improve tensile response although at expense of reduced compressive capacity, due to soil below the helix moving upwards increasing soil density and stress above the helix (Sharif et al.

2021a). This variation of loading response encourages use of over-flighted installation approaches on screw piles where tensile response is more critical such as pile anchors for floating offshore wind. This is in contrast to standard guidance e.g. BS8004 (British Standards Institution 2015) which suggests that only perfect or pitch matched installation (AR = 1.0) leads to optimised in-service performance.

Nonetheless, design of offshore piles/anchors has to consider cyclic loading. The beneficial effects of over-flighted installation on cyclic tensile performance of Screw piles still requires investigation. Recently, by means of an extensive experimental centrifuge study, Wang et al. (2025) have shown that, for a given cyclic loading regime which resulted in cyclic failure (permanent displacement accumulation reaches $10\%D_h$) within 20 cycles for AR = 1.0, piles installed at AR = 0.5 and 0.25 can last for much greater cycle numbers. As well as being deployed as anchors, screw piles are also expected to carry two-way cyclic loading when used for foundations in jacket structures. However, the effect of the reduced compressive performance induced by over-flighting on two-way (compressive and tensile) cyclic response remains unclear. This study conducts two-way cyclic loading tests on a screw pile installed in sand at different AR values. The results are compared to previous one-way tensile cyclic tests of the same pile.

2 CENTRIFUGE EXPERIMENT

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 N = 80 (Klinkvort and Hededal 2013; Li et al. 2010; Wang et al. 2025). Such a scaling factor results in parameter scaling as shown in Table 1.

Table 1 Centrifuge scaling factors in this study

Parameter	Prototype scale / model scale
Lenth	*1/N*
Force	*1/N²*
Torque	*1/N³*

Installation at 1g can create a softer/lower capacity pile loading response compared to conducting installation and loading test in one continuous centrifuge flight, due to the different post-installation stress field around the pile (Ko et al. 1984). To create in-fight installation, 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. More details of the actuator can be found elsewhere (Davidson et al., 2018).

2.2 Soil properties

Medium-dense dry sand beds ($D_r \approx 50\%$, 434 mm deep) were created by dry pluviation of HST95 sand (Lauder 2010) in a 500 mm × 800 mm × 550 mm strong box. 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 2.

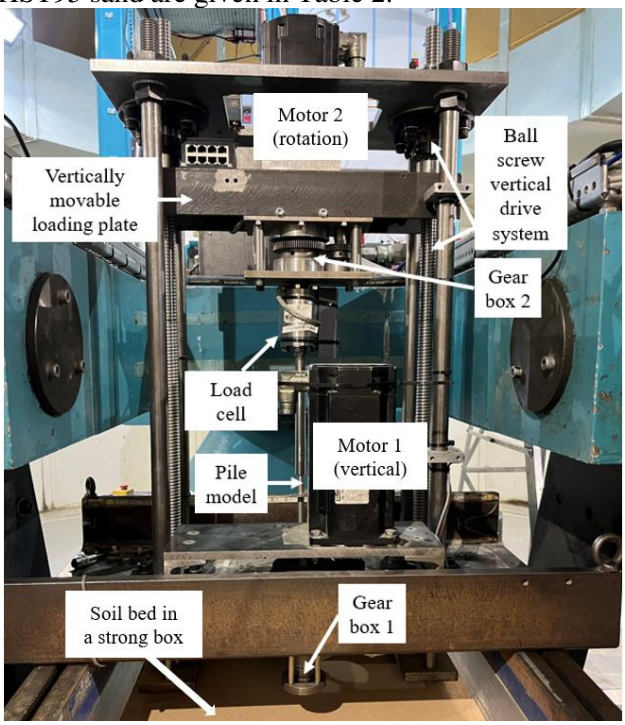

Figure 1 Image of the screw pile centrifuge testing equipment mounted on a model sand container

Table 2 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/m³]	γ_{dry}	16.0
Saturated unit weight [kg/m³]	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 of a solid core with 0.88 diameter (D_s), and a helical plate with 1.7 m diameter (D_h), 1.4 mm thickness and 0.56 m helix pitch (p_h) (prototype scale). 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. 2023; Sharif et al. 2021a; Sharif et al. 2021b). This pile has also been extensively tested under one-way tensile cyclic loading (Wang et al. 2025).

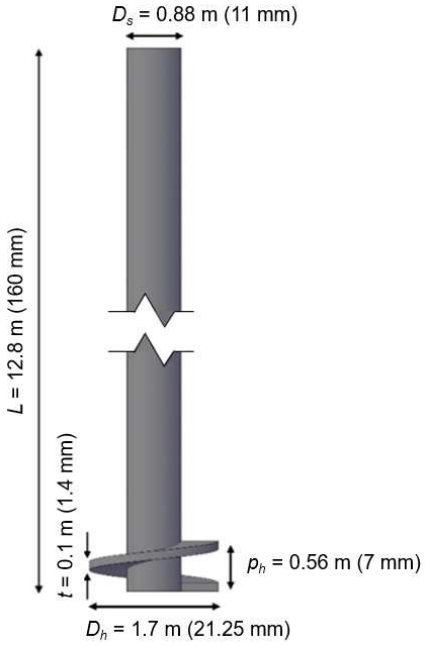

Figure 2 Schematic diagram of the screw pile model investigated (model scale in brackets)

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).

2.4 Pile installation

From this point onward, all test results are presented and discussed at prototype scale. Installation at AR = 1.0, 0.5 and 0.25 were conducted. Pile installation was conducted at a rotation rate of 3 revolutions/min (RPM) and then vertical penetration rates can be determined using Eq. (1). Installation crowd force and torque are shown in Figure 3 and Figure 4, respectively. Installation at AR = 1.0 seems impractical since it resulted in up to 10 MN crowd force where such large reaction force would be challenging for offshore installation. Installation at AR = 0.5 created a 'zero crowd force' condition. For AR = 0.25, tensile force was generated by the pile. In this case, the actuator provided no compressive force but needed to resist the tensile force.

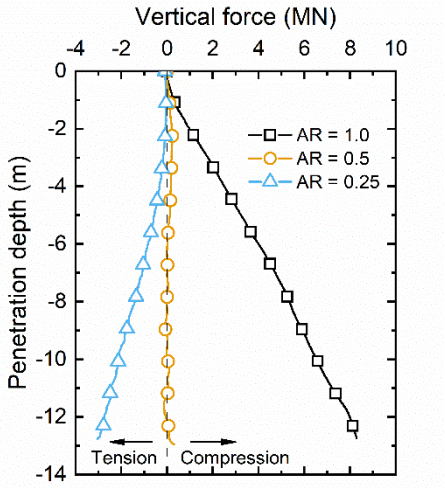

Figure 3 Effect of installation advancement ratio on installation crowd force

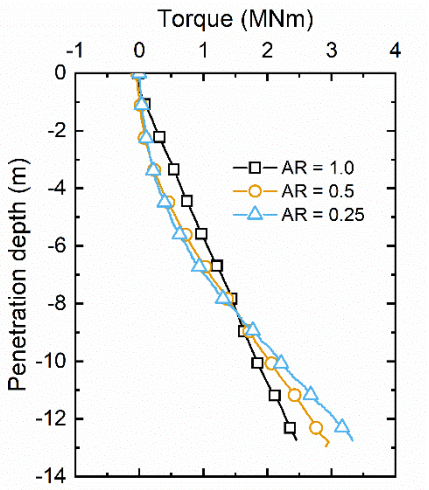

Figure 4 Effect of installation advancement ratio on installation torque

2.5 Monotonic loading test

Installation loading was conducted followed by loading in a single non-stop centrifuge flight.

To determine the tensile capacity, a monotonic uplift test was conducted where the pile was pulled out to a displacement of at least 0.4 D_h at a constant rate of 1 mm/min (at model scale). Figure 5 shows the force – displacement response during monotonic tension tests post installation at AR = 0.25 to 1.0. The tensile capacity Q_t was defined as resistance at displacement of 0.1D_h. e.g. 5.7, 6.8 and 7.6 MN for AR = 1.0, 0.5 and 0.25, respectively. It is attributed to the increased

soil stress and density above the helix resulted by over-flighting during installation.

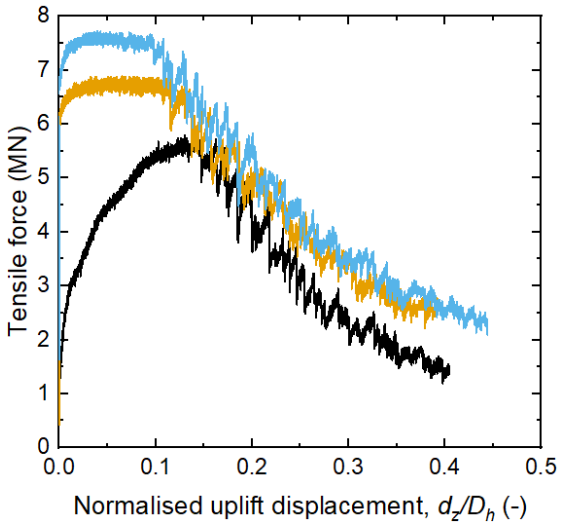

Figure 5 Effect of installation advancement ratio on monotonic tensile response

2.6 Cyclic loading test

Sinusoidal cyclic loading was adopted in this study. Loading parameters are explained in in Figure 6. One-way loading tests were conducted previously (Wang et al. 2025) and the cyclic loading amplitude Q_{cyc} was equal to the average loading Q_m = 1.6 MN. The adopted Q_{cyc} was equal to 21% to 28%Q_t for AR = 0.25 to 1.0. This loading regime resulted in significant displacement accumulation allowing easy comparison between AR values. The two – way loading regimes in this study adopted the same Q_{cyc} = 1.6 MN for direct comparison to one - way, with an average loading Q_m = 0 i.e. the loading was symmetric two-way loading. Cyclic loading was stopped after a permanent displacement (either compressive or tensile) of $0.1D_h$.

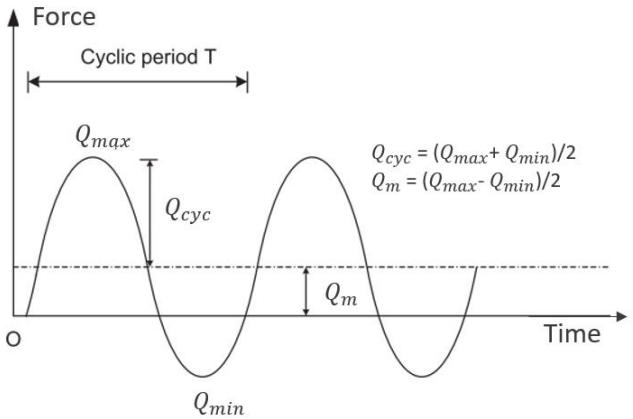

Figure 6 Form of sinusoidal cyclic loading regime and explanation of typical terminology

3 RESULT OF CYCLIC TESTS

Figure 7 compares displacement accumulation during one-way and two-way cyclic loading after installation at different AR values. For one-way tensile loading, decrease of AR leads to reduced displacement accumulation d_{acc}. At AR = 1.0, d_{acc} reaches $0.1D_h$ after about 10 cycles, while to reach this d_{acc} it requires 500 and 900 cycles for AR = 0.5 and 0.25, respectively.

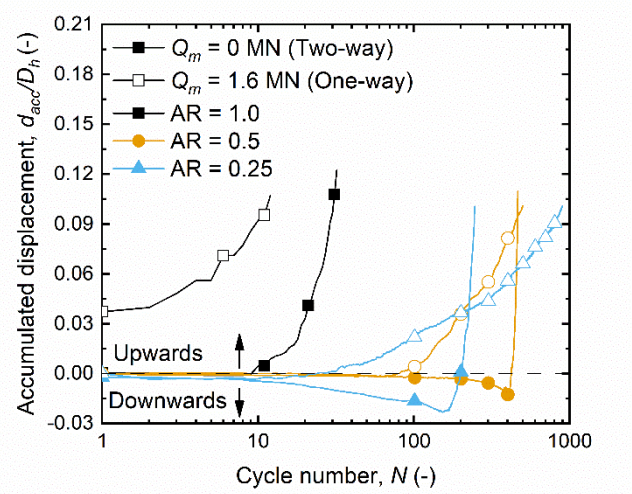

Figure 7 Effect of cyclic loading direction and installation AR on displacement accumulation [one – way data from Wang et al. (2025)]

For the pile installed at AR = 1.0, two-way loading appears to reduce displacement over the one-way loading and the accumulation displacement is constantly upward throughout cycling. For the over-flighted piles (AR = 0.5 and 0.25) subject to two-way loading, the accumulated displacement is slowly developed, downwards first until a certain number of cycles at which point the displacement reverses and there is a very "brittle" pull-out. This is in contrast with the constantly upward accumulated displacement for one-way cases where two-way cases seem less affected up to a certain cycle number for AR = 0.5 which is typically associated with a neutral installation behaviour (i.e. zero crowd force). Thus, caution may be required for screw piles which are designed to carry two-way cyclic loading as the failure is more abrupt than in one-way loading.

The direction of displacement accumulation for two-way cyclic cases is related to installation induced soil states around the helix. For pitch-matched (AR = 1.0) screw piles, relatively high stress and density of soil is created below the helix, resulting in higher compressive loading stiffness (capacity) over tensile stiffness (capacity) (Davidson et al. 2022; Perko 2009). Thus, the pile installed at AR = 1.0 tends to be displaced upwards subject to symmetric two-way

cyclic loading (Figure 7). With reduction of installation AR, post-installation soil density and stress below the helix tends to be decreased with those above the helix being increased (Sharif et al. 2021a), potentially resulting in the tensile response being stiffer than the compressive response (Cerfontaine et al. 2022). Consequently, the over-flighted pile (AR = 0.5 and 0.25) tends to be displaced downwards subject to symmetric two-way cyclic loading and the lower AR value corresponds a greater downward displacement accumulation (Figure 7). With increasing cycle number and accumulation of downward displacement, however, soil stress and density above the helix may decrease and soil may even 'collapse'. This is likely to reduce tensile loading stiffness and capacity. Once the tensile stiffness (capacity) becomes lower than compressive stiffness (capacity), the upward displacement accumulation starts to be developed as per the case for AR = 1.0. Additionally, the reduced soil resistance above the helix results in high rates of upward displacement accumulation and thus the abrupt failure for AR = 0.5 and 0.25 (Figure 7).

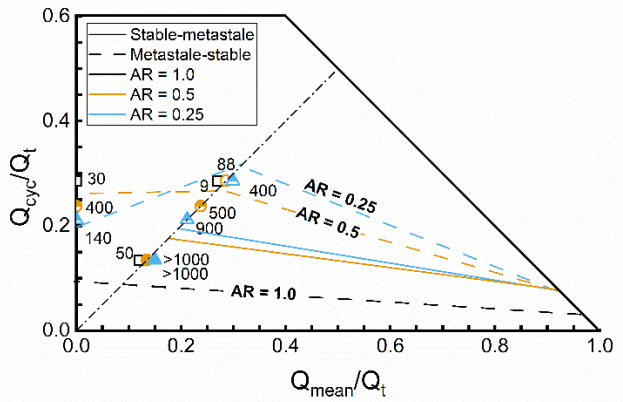

Figure 8 Cyclic interaction diagram for one-way and two-way loading considering AR effects (numbers besides datapoints denote cycle number to failure)

Pile axial cyclic performance is typically regarded as i) stable, if no failure (d_{acc} reaches $0.1D_h$) happens with in 1,000 cycles, ii) meta-stable, if failure happens between 100 to 1,000 cycles, and iii) unstable, if pile fails within 100 cycles (Jardine and Standing 2012; Schiavon 2016). Adopting the criteria, the interaction diagram, summarised by Wang et al. (2025) based upon one-way tensile cyclic reponse, is updated including two-way response (Figure 8). It suggests that, when the pile is designed to carry predominately two-way cyclic loading, installation at an AR value of 0.5-0.6 is recommended, as it balances compressive and tensile response. This is in contrast with one-way tensile loading, where the optimised performance is associated with lower AR values. In addition, an AR value of 0.5-0.6 appears more practical for offshore applications, as it minimises the required vertical installation force (Figure 3), which is advantageous in environments where generating a large reaction force is not feasible.

In all cases though, over-flighted installation is observed to have a beneficial effect on cyclic performance.

4 CONCLUSIONS

In this paper, centrifuge experimental results considering two-way cyclic loading tests on a screw pile installed in sand are presented. Effects of variation of installation advancement ratio (AR) on the cyclic response was considered. Comparison between the two-way cyclic performance and previous one-way tensile cyclic performance was made.

Over-flighted (AR < 1.0) piles exhibit improved response than pitch-matched (AR = 1.0) piles in terms of both one-way tensile and symmetric two-way cyclic performance, as well as monotonic tensile performance. Over-flighted installation also benefits from the reduced installation crowd force.

One-way tensile loading tends to result in upward displacement accumulation, contrasting with symmetric two-way cyclic loading where accumulated displacement is developed downwards first before reversing suddenly with significant increased displacement accumulation rates. Thus, the abrupt failure for two-way cyclic loading regime needs to be considered. This will though be affected by the cyclic loading magnitude/pile capacity which could be tuned to avoid such a situation.

In all cases though over-flighted installation it is observed to have a beneficial effect on cyclic performance, compared to AR = 1.0.

This study is limited to full drained conditions and medium-dense sand. Future studies could extend the findings by exploring the effects of drainage conditions and soil relative density on the cyclic response of screw piles.

AUTHOR CONTRIBUTION STATEMENT

Wei Wang: Conceptualization, Formal analysis, Writing- Original draft. **Michael Brown**: Conceptualization, Writing- Reviewing and Editing, Supervision. **Yaseen Sharif**: Methodology, Writing- Reviewing and Editing **Craig Davidson**: Methodology, Writing- Reviewing and Editing, **Matteo Ciantia**: Supervision, Writing- Reviewing and Editing.

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