Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Measurement of installation torque using an instrumented screw pile

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ABSTRACT: The development of large screw piles for use as anchors and foundations of offshore wind infrastructure is ongoing. Further research is required into the parameters required to optimise the performance of such screw piles during installation and axial loading. The use of instrumentation in centrifuge modelling of screw piles is uncommon and typically restricted to measurements of the axial load via strain gauges installed at discrete intervals on the model pile. The installation torque of these large screw piles is significant, and it is necessary to fully understand the contribution of the different components of the screw pile to the total required installation torque and to improve the prediction of the installation requirements. This paper presents the development of a two-helix model screw pile for centrifuge testing which was instrumented with strain gauges to enable the measurement of installation torque above both helices and below the upper helix of the pile. Results are presented from the centrifuge test programme in sand which show the torque required to install the pile at three different installation advancment ratios.

1 INTRODUCTION

The continued expansion of the offshore wind sector has prompted research into foundation systems which can be efficiently deployed in large quantities, be installed quietly, and provide suitable in-service performance against the substantial axial and lateral loads (Davidson et al., 2020). Screw piles, comprising of one or more helical plates attached to a tubular shaft, have been proposed as a potential solution to all of these requirements (Cerfontaine et al. 2023b and Lloyd's Register 2024).

Screw piles are commonly used onshore as foundations and anchors in a wide range of applications (e.g. guyed tower anchors, light pole and solar panel foundations, underpinning, etc.) are typically small with shaft (D_s) and helix (D_h) diameters of 64 – 200 mm and 150 – 400 mm respectively (Perko, 2009). Installation of such piles is typically done using plant/equipment such as excavators fitted with a rotary head. Current industry guidance on the installation of screw piles states that each rotation of the pile should lead to a vertical penetration equal to one helix pitch, p, ($\pm 0.15\,p$) (BS 8004:2015, 2015 and Perko, 2009) in an effort to minimise soil disturbance. This method is also known as pitch-matched installation.

Until recently, much of the literature on the installation requirements of screw piles has focussed on screw piles applicable for onshore applications. Analytical solutions have been developed to predict the installation torque (Ghaly and Hanna, 1991, Ghaly et al., 1991, Perko, 2000), but it is the empirical relationship between installation torque and axial capacity, developed by Hoyt and Clemence (1989) that has been widely adopted by the onshore screw pile industry. More recently, installation torque prediction methods based on the cone resistance (q_c) data from Cone Penetration Tests (CPT) have been proposed (Davidson et al., 2020, Bittar et al., 2024, Gavin et al., 2013, Spagnoli, 2016, Tsuha and Aoki, 2010).

Davidson et al. (2020) reported results of the installation torque, force, and vertical capacity from centrifuge tests of screw piles designed to sustain the compressive loads of an 8 MW turbine supported by a four-legged jacket in 80 m water depth. These data showed that a screw pile with shaft and helix diameters of 0.88 and 1.7 m required up to 6.7 MNm torque and 20 MN of vertical force at 13 m depth when installed using pitch-matched parameters in very-dense sand (83 % relative density, D_r). These loads exceed existing plant capabilities meaning that either more smaller piles in groups may be required (Jawid et al.,

2026) or the installation of larger piles needs to be optimised.

Investigations using Discrete Element Modelling (DEM), centrifuge and 1g approaches (e.g., Bradshaw et al. 2019, Sharif et al. 2021, Cerfontaine et al. 2021a, Cerfontaine et al. 2021b, Cerfontaine et al. 2022, Cerfontaine et al. 2023a, Sharif 2024, Wang et al. 2025) have reported the effects on the installation torque and force when non-pitch-matched installation approaches were used to install screw piles into sand. In these studies, the installation rate was described in terms of the advancement ratio (AR) which is the ratio between the vertical penetration per revolution (Δz) to the helix pitch (p) as per Equation 1. Each of these investigations reported that decreasing the AR reduced the vertical force and torque needed during installation while increasing the axial tensile capacity of the pile. For example, using the same screw pile as described previously from the work of Davidson et al. (2020), Sharif et al. (2021) reported up to 35 % and 96 % reductions in installation torque and force while the tensile capacity increased by up to 120 % (depending on relative density and AR).

Cerfontaine et al. (2023a) described how lower ARs result in the upwards movement of soil particles, increasing the stress above the helix and creating a downward reaction force on the pile, reducing the installation force. At AR 1, the soil particle movement is downwards, leading to a high-stress area below the helix and pile tip with consequentially higher installation forces.

$$AR = \frac{\Delta z}{p} \qquad (1)$$

The omission of the effects of the advancement ratio in currently available methods for predicting the installation parameters and axial capacity should be addressed. Data are required to develop such methods, and while the centrifuge and field studies detailed above provide the total magnitudes of the installation requirements, they do not give sufficient insight into the contribution of each component of the screw pile (i.e., the helix, shaft, tip, etc.).

While the DEM simulations reported by Sharif et al. (2021), Sharif (2024), and Wang et al. (2025) do provide this detail, data from physical tests was also deemed necessary to develop updated prediction methods, beginning with the installation torque.

Few centrifuge tests have been conducted using instrumented models and those that have (e.g., Urabe et al. (2015) and Schiavon et al. (2016) only measured the axial force at discrete positions on the models. Therefore, a double-helix screw pile was designed, fabricated and instrumented with strain gauges to measure the torque at three locations on the pile, in addition to the pile head.

This paper details the development of the instrumented pile and presents installation torque data from centrifuge tests of the pile at three different advancement ratios in dense sand.

2 METHODOLOGY

Details of the scaling laws, preparation and properties of the sand, model screw pile, actuation system, and data acquisition equipment are presented in this section.

2.1 Scaling laws and drainage conditions

All tests presented were conducted using the 3m radius beam centrifuge, at the University of Dundee (UoD) in uniform beds of dry sand where fully drained conditions were assumed throughout (i.e., no excess pore pressure). Dry sand testing is cost and time efficient and has been shown by Li et al. (2010) to provide the same results as drained saturated tests.

A scaling factor of N = 50 was chosen for all tests and all results presented are at prototype scale following the scaling laws shown in Table 1.

Table 1. Centrifuge scaling laws for conversion between model and prototype scale values (Muir Wood, 2004).

Model parameter	Scaling law	This study
Lengths and displacements	N_L	1/50
Acceleration and gravity	N_G	30.9
Mass density	N_ρ	1.6
Torque	$N_\rho\ N_G\ N_L^4$	$1/80^3$
Stress	$N_\rho\ N_G\ N_L$	1

2.2 Centrifuge testing equipment

The model screw pile was installed during the centrifuge flight using a bespoke two-axis actuator designed and fabricated at the UoD. This equipment provides control of the vertical displacement and rotation speed during installation of the pile allowing for different advancement ratios. Details of the development of the actuator are available in Al-Baghdadi et al. (2016), and Davidson (2025), Davidson et al. (2018).

The actuator is mounted to a model container (Figure 1) with internal dimensions of 800mm long, 500 mm wide and 500 mm deep. Thus, the minimum distance from the edge of the pile helix to the horizontal boundary of the model container was 7.3 D_h.

The data acquisition and control system uses a National Instruments CompactRIO 9047 to control the two Kollmorgen AKM servo motors and record analogue measurements from the sensors. A Novatech F310-Z ±20 kN / ±40 Nm loadcell/torque transducer was used to measure the force and torque at the pile head. Vertical displacement of the actuator was measured with the Micro-Epsilon WDS-750-P60-CR-P draw wire transducer. Strain gauges were used to measure the torque on the instrumented model pile (further detail in Section 2.4).

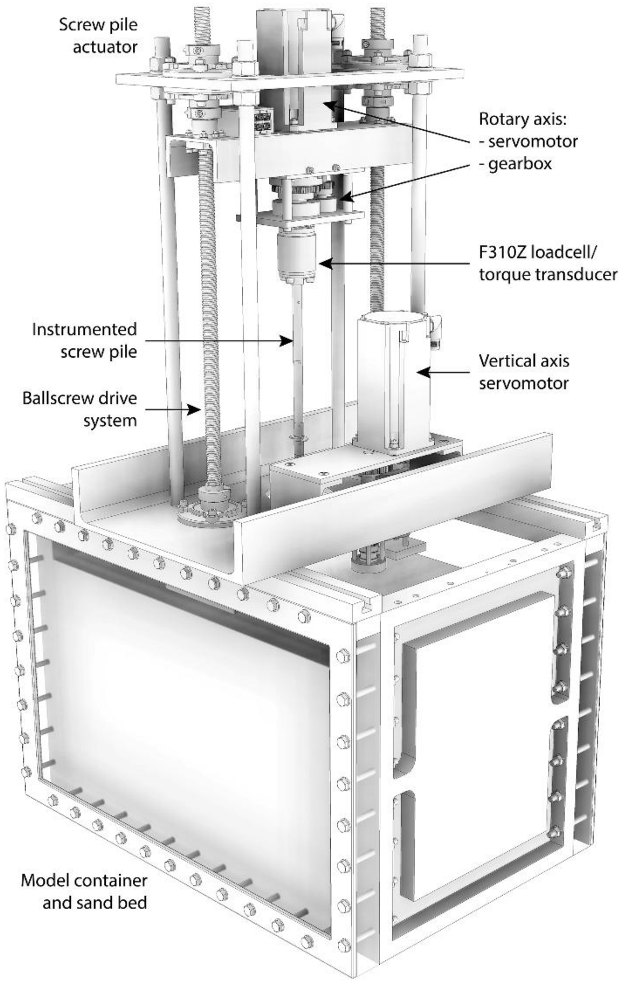


Figure 1. Perspective schematic view of screw pile actuator mounted on model container.

2.3 Sand bed properties and preparation

As for similar previous centrifuge tests of screw piles at the UoD (e.g. Al-Baghdadi 2018, Davidson et al. 2020, Cerfontaine et al. 2023a, Wang et al. 2023, Wang et al. 2025), dry HST95 sand was used for all tests reported here. This sand is a fine-grained quartzitic sand with D_{10} and D_{50} particle sizes of 0.10 and 0.14 mm respectively (Lauder et al., 2013). Relevant properties of HST95 are presented in Table 2.

Table 2. HST95 sand properties (Al-Defae, 2013, Lauder, 2010).

Property	Value
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Angle of dilation* at D_r = 79%, ψ (°)	16.1
Peak friction angle* at D_r = 79%, ϕ'_{pk} (°)	44.8
Maximum dry unit weight, ρ_{max} (kN/m^3)	17.58
Minimum dry unit weight, ρ_{min} (kN/m^3)	14.59

**Inferred from best-fit peak strength relationship from direct shear tests for data at effective stresses between 50-200 kPa and critical state friction angle, at 79 % relative density (Al-Defae et al., 2013).*

The sand beds were carefully prepared to 434 mm depth using a slot pluviator system, to control the relative density. The pluviator consists of a tapered hopper with a slot at the base which can be varied in width. To obtain the 79% relative density of the sand beds in the tests reported, the width of the pluviator slot and the speed at which it translated along the rails in a reciprocal manner were set to 1.2 mm and 250 mm/min, respectively.

2.4 Model instrumented screw pile

Centrifuge testing of screw piles at the UoD to date has been with non-instrumented models and measured the torque and force at the pile head only. Therefore, an instrumented model screw pile was designed and fabricated to satisfy the following goals:

- Have geometry representative of a screw pile for offshore wind loading conditions.
- Be appropriately sized to accommodate strain gauges for instrumentation.
- Designed to protect the strain gauges and their wires.
- Be structurally competent under relatively high torques.

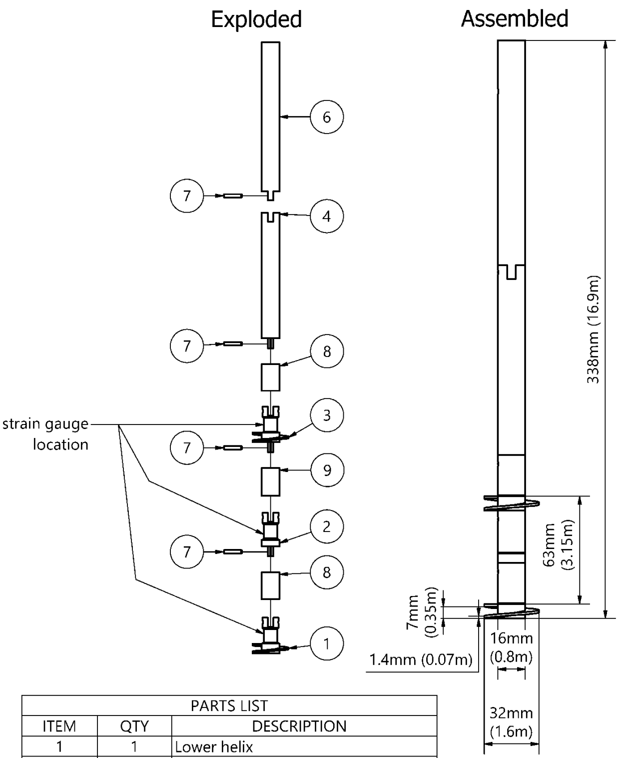
The resulting screw pile was a double-helix design with full Wheatstone-bridge strain gauges for measuring torque at three locations, namely directly above and below the upper-helix and above the lower-helix.

Figure 2 presents details of the model instrumented pile.

HBM XY7 350Ω strain gauge rosettes arranged in a full Wheatstone-bridge configuration were mounted to the pile in the location shown in Figure 2. These 9.9 x 8 mm rosettes dictated the minimum dimensions of the pile. To maintain uniform interface properties between the pile and soil, the gauged section was protected using a steel sleeve (

Figure 2) instead of an epoxy coating and the wires were routed through the hollow shaft of the model. Using sleeves for the protection of the gauges meant that the model had to be fabricated in sections and assembled. To join each part together and ensure a close fit to transmit the torque and force applied to the pile without deformation or failure, an Oldham style coupling was used. This uses a tenon and slot configuration which was pinned together. All components were fabricated from high strength EN24t steel.

The approach described above was improved design over an earlier model that used threaded connections between the parts which were restrained by set screws. This connection method was not sufficiently rigid and further tightened from torque generated during installation of the pile, affecting the measured torque.



PARTS LIST		
ITEM	QTY	DESCRIPTION
1	1	Lower helix
2	1	Inter-helix
3	1	Upper helix
4	1	Upper shaft A
6	1	Upper shaft B
7	4	Pin
8	2	Sleeve (helix sections)
9	1	Sleeve (inter-helix)

Figure 2. Schematic diagram of the instrumented screw pile assembly and components (Prototype dimensions shown in brackets).

The XY7 strain gauge rosettes feature a 45° foil pattern designed for measuring torque. The gauges on each of the three instrumented sections of the model were calibrated before assembly of the pile. This was achieved by mounting each section in turn to the F310Z transducer on the actuator, manually applying a load and recording the measured voltage. The calibration factor for each section was determined from the slope of the measured voltage versus the torque measured from the F310Z transducer.

2.5 Test programme

Three centrifuge tests of the instrumented screw pile reported in this paper. The tests were completed in uniform, dry sand at 79 % relative density at advancement ratios of 1.0, 0.5 and 0.1 in line with centrifuge testing by Cerfontaine et al. (2023a) and similar to further centrifuge testing reported in Wang et al. (2025) as well as DEM simulations by Sharif et al. (2021).

3 RESULTS AND DISCUSSION

The installation of the instrumented screw pile in the three tests described provided continuous measurement of the installation torque at four locations on the pile. The torque at each location was deconvoluted by subtracting the measured value from the gauges below, e.g. the upper helix torque was calculated by subtracting the torque reading of the gauges below the helix from that of the gauges above the helix. The screw pile design and size of the gauges precluded measurement of the torque from the tip of the pile shaft which means the torque measured by the lowermost gauges includes the contributions from the lower helix and pile tip.

Data from the three tests are presented in Figure 3 where torque from each location on the pile is shown for each of the three AR values. Additionally, the sum of the torque measured from the three strain gauges on the pile is presented for comparison to the torque measured by the transducer at the pile head. In each test, the summed value very closely matches the pile head torque up to a normalised depth (penetration depth (z) divided by helix diameter (D_h)) of at least 2.

This match demonstrates firstly, that the strain gauges on the pile were effective at measuring the torque. Secondly, assuming that the difference between the total pile head torque and the summed torque from the instrumented pile was equal to the torque contributed by the shaft above the uppermost helix, this section generally contributed the least torque to the total value.

In contrast to the low magnitude and variablity with AR of torque on the upper shaft, the torque measured at the inter-helix shaft location was dependant on the AR as shown in Figure 3 and Figure 4, ranging from

9.4 % to 32.6 % for AR 1 and 0.1. This is likely the result of the changing stress field in the soil as discussed by Sharif et al. (2021) and Cerfontaine et al. (2023a). DEM simulations by Wang et al. (2025) of a double-helix pile with geometry similar to the instrumented pile showed a similar trend of inter-helix shaft torque increasing as AR was reduced.

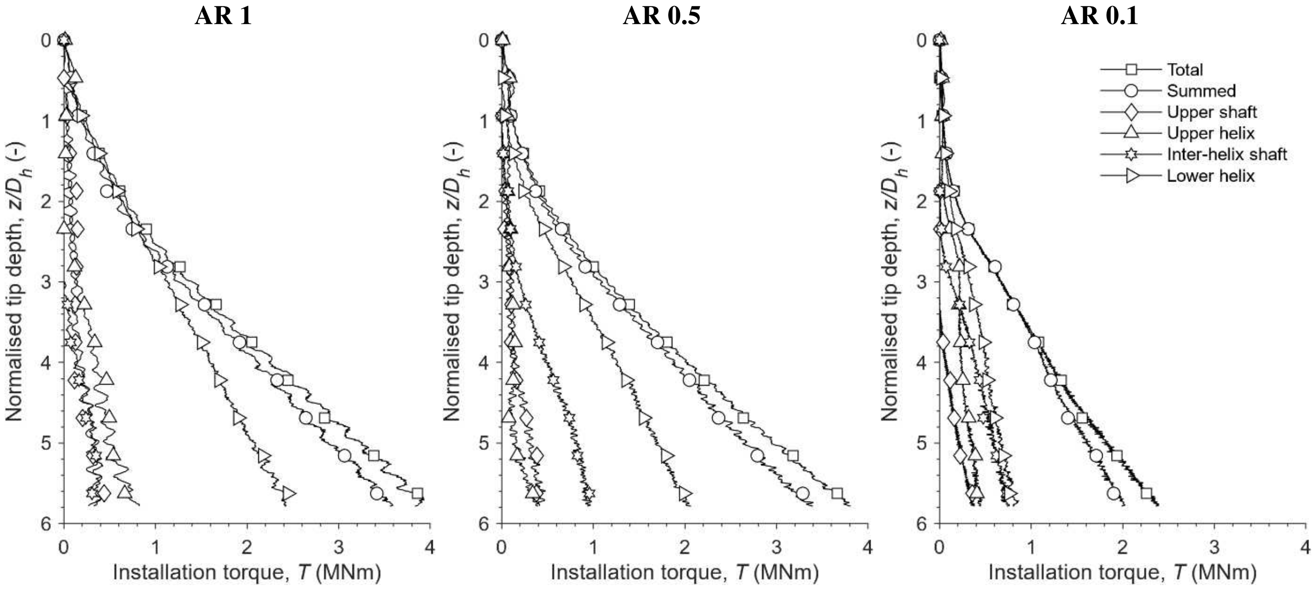


Figure 3. Measured installation torque of the instrumented screw pile in dense sand at a) AR 1, b) AR 0.5, and c) AR 0.1.

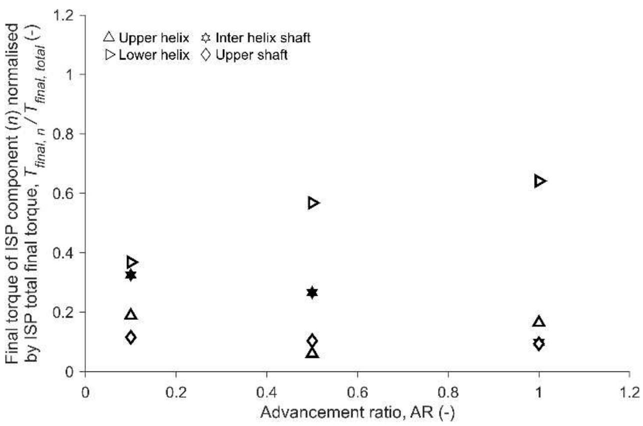


Figure 4. Final torque of the instrumented screw pile (ISP) components normalised by the total final torque.

The combined torque from the lower-helix and pile tip were the greatest contributor to total torque at all advancement ratios (36.9 – 46.2 % for AR 0.1 and 1). Additionally, there is a clear trend of torque increasing at this location on the pile as AR increases (Figure 3), which again is likely due to the increased stress below the helix at higher ARs.

The effect of higher stress between the helices was evident in changes to the surface finish of the model pile after testing which is shown in Figure 5. The image shows there is a distinct difference in the colour and lustre of the pile shaft from left to right (i.e, shallow to deep). From the pile tip to ~120 mm above the upper-helix (installed depth of 6.25 to 9.25 m), the surface is dark and matte, above which the appearance transitions to match the original machined finish at the pile head. Measurements of the average surface roughness (R_a) were conducted using a Taylor Hobson Surtronic Duo - Handheld Surface Roughness Meter with the stylus of the instrument aligned to the long-axis of the pile. The results of these measurements are shown in Figure 6 where a difference in R_a of 0.8 microns is evident between the pile tip and upper shaft.

This non-linear change in average surface roughness indicates that the change in radial stress on the shaft was also non-linear with depth as might be expected. DEM simulations by Sharif (2024) showed an increase in radial stress for a distance of 3 D_h above the helix at lower AR installations which is similar to the observations presented here. Although there is a measurable difference in surface roughness of the shaft between the helices compared to above the upper helix, the critical state interface friction angle is not significantly affected. Using the relationship presented by HSE (1997) between the critical state interface friction angle and the normalised surface roughness (Rn), a change in the critical state interface friction angle of 0.3° would be expected under the same stress conditions.

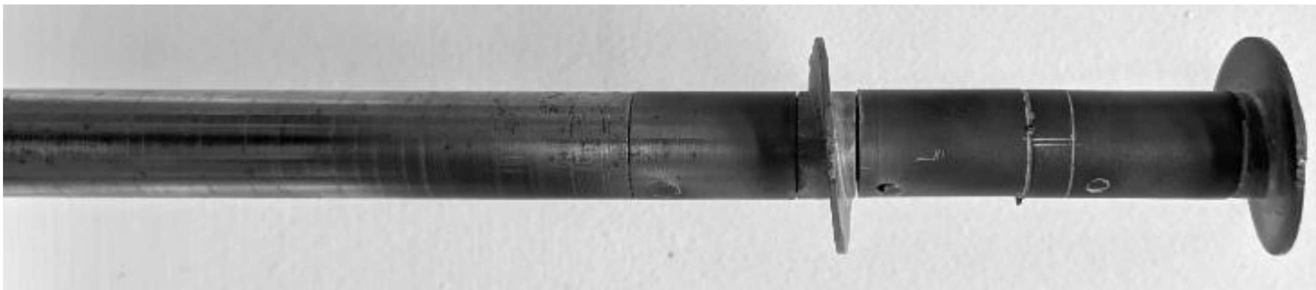


Figure 5. Photograph of the instrument screw pile after reported centrifuge tests showing change in surface appearance.

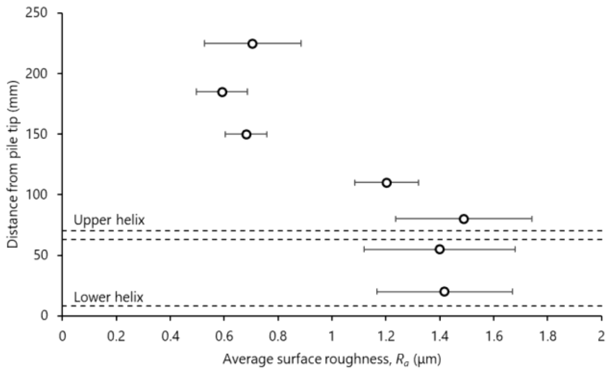


Figure 6. Average surface roughness profile of the instrument screw pile after reported centrifuge tests.

$$R_n = \frac{R^{0.2-D_{50}}}{D_{50}} \quad (2)$$

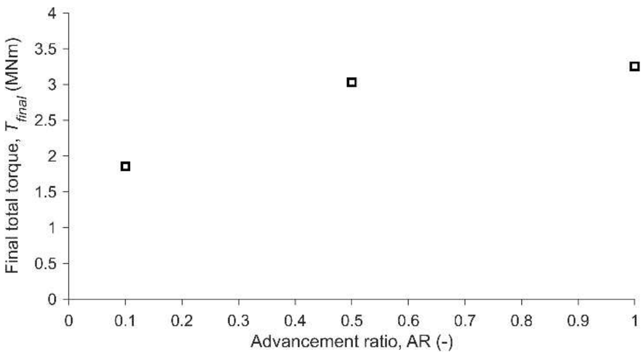


Figure 7. Final total installation torque (averaged over final 1.5 D_h depth).

The last point of discussion is that of the effect of the advancement ratio on the total torque. Figure 7 shows that the torque averaged over the final 1.5 D_h, equal to 2.4 m (as used by Bustamante and Gianeselli, 1982, Gavin et al., 2013, Spagnoli, 2016, and Al-Baghdadi 2018) of penetration decreases by 43 % as AR is reduced from 1 to 0.1. Cerfontaine et al. (2023a) conducted an extensive series of centrifuge tests of a single-helix, closed-ended screw pile in medium-dense and dense dry sand. They reported a decrease in final installation torque of 29.3 % in dense sand as AR reduced from 1 to 0.1. Similarly, the double-helix screw pile DEM simulations by Wang et al. (2025) in medium-dense sand shows a reduction of 39.2 % between tests at AR 0.25 and 1. These findings are in agreement with those observed from the centrifuge tests of the instrumented pile.

The data reported here and from additional tests in medium-dense and loose sand will be used to develop an AR inclusive CPT-based torque prediction method for future publication.

4 CONCLUSIONS

Research into the development and application of screw piles as foundations for offshore wind energy structures is ongoing. Recent developments have shown that reducing the advancement ratio below 1, as currently prescribed in industry guidance, can reduce the installation requirements, including the torque. Therefore, existing torque prediction methods, all of which do not incorporate the effect of the advancement ratio need to be updated.

To do so, data are required on the contribution of each part of the screw pile to the total torque. While DEM simulations can provide such data, physical tests are also needed for validation. This paper has presented details of a newly developed instrumented double-helix 1/50th scale model screw pile designed to measure torque at four locations during centrifuge tests.

Results from installation of the pile into very-dense sand at 79 % relative density at advancement ratios of 1.0, 0.5, and 0.1 have been presented. These data show that the total torque is dependent on the advancement ratio, with the final torque (average torque over the final 1.5 helix diameters of penetration) decreasing by 43 % as AR reduced from 1 to 0.1. The combined torque from the lower helix and pile tip contributed the most to the total torque at all ARs, while the shaft above the upper helix contributed the least.

Data from the tests presented will be used to develop an advancement ratio inclusive CPT-based torque prediction method (Davidson, 2025) which will be useful in further development of screw piles as offshore foundations in the wind energy sector.

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