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# Optimised screw pile design for offshore jacket foundations in medium-dense sand

Cerfontaine, B., Brown, M.J., Davidson, C., Sharif, Y.U., Huisman, M., Ottolini, M.

**Abstract:** Screw piles are well suited foundations for offshore jacket structures, as they can be installed without significant underwater noise and have a large axial capacity. However, installation requirements for such large piles must be reduced to enable their installation in the field. This work combines geometry and installation optimisation to lower force and torque installation requirements. An original pile geometry, composed of a large diameter upper section connected to a smaller diameter lower section by a transition piece, was tested in a geotechnical beam centrifuge. The advancement ratio (AR), describing the relative vertical movement per pile rotation, was varied below the threshold usually recommended. Results show that a low AR reduces the pile penetration resistance and even generates some pull-in, while the torque remains almost unaffected. The torque is mainly associated with the upper section of the pile, which has a greater diameter to resist lateral loading in service. The pile capacity in tension generally increases as AR is reduced and reaches a maximum for  $AR = 0.5$ , while the compressive capacity reduces. It was shown that a simplified method can be used to estimate pile capacity, providing that some AR dependent reduction factors can be calculated or assumed.

**Keywords:** Offshore engineering, Anchors & anchorages, Centrifuge modelling, sand

# 1. Introduction

Screw (or helical) piles are a “silent” installation alternative to pile driving for offshore foundations (Spagnoli and Tsuha, 2020). Typical onshore geometries consist of a long shaft connected to several deeply embedded helices to enhance axial capacity (Perko, 2009). Screw pile lateral capacity is dominated by the shaft (or core) behaviour, with helices providing extra resistance (Al-Baghdadi *et al.*, 2017; Kwon *et al.*, 2019). However, increasing the shaft diameter or number of helices to meet offshore foundation needs creates greater installation requirements, i.e. installation torque and penetration resistance (Davidson *et al.*, 2020), which may not be easily applied by current installation vessels.

The advancement ratio (AR) is defined as the ratio between the vertical displacement of the pile per one rotation ( $\Delta z_h$ ) divided by the helix pitch ( $p_h$ ) (Bradshaw *et al.*, 2018)

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

Standards recommend that this ratio varies within  $1 \pm 0.15$  during installation (BS8004:2015, 2015), which is termed pitch-matched. It was shown experimentally (Cerfontaine *et al.*, 2021a) and numerically (Sharif *et al.*, 2021b) that relaxing this constraint in sands ( $AR \leq 0.85$ , termed pile overflighting) considerably reduces the vertical force necessary for installation.

Jacket structures supporting offshore wind turbine impose large axial and lateral loads to their foundations. A large screw pile shaft diameter would be necessary to resist those loads, which increases the pile penetration resistance (Davidson *et al.*, 2020). The objective of this work is to demonstrate that geometry and installation processes can be optimised to ensure the feasibility of screw piles. Centrifuge modelling of an original design, combining one helix, two shaft diameters and a bespoke transition piece, was undertaken to show the AR effect on installation requirements and resistance in both tension and compression.

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## 27 **2. Experimental set-up**

28 Two 3D printed stainless steel closed-ended screw pile models were tested in the geotechnical  
29 beam centrifuge at the University of Dundee (UK). Each model (see Table 1 for dimensions)  
30 is composed of lower and upper sections connected via a transition piece, while a helix is  
31 attached to the lower section (Figure 1). Two transition pieces were tested, a conical piece  
32 (named CTP, Figure 1b) and an internal helix (named IHTP, Figure 1a,  $D_h/p_h = 2.8$ ). The  
33 internal helix, identical to the lower helix, enables the sand to enter the pile upper section in an  
34 attempt to reduce installation requirements. The model pile was connected to an actuator  
35 capable of installing and loading the pile in a single centrifuge flight (Al-Baghdadi, 2018;  
36 Davidson *et al.*, 2020). Whilst spinning at 62g, installation of the pile was undertaken by  
37 imposing a constant rotation rate (3RPM) and using different vertical installation rates to  
38 achieve the required AR (equal to  $3 \cdot AR \cdot p_h$ ) until the target embedment depth (20m-30m at  
39 prototype scale) was reached. Tensile or compressive loading was then imposed at a constant  
40 vertical displacement rate (1mm/min) after a 5 minute resting period.

41 Medium-dense sand beds (43 m deep, average relative density 52%-57%) were created by  
42 dry pluviation of HST95 sand (properties in Table 2 (Al-Defae *et al.*, 2013; Robinson *et al.*,  
43 2019)) in a strong box (500 mm x 800 mm x 550 mm). Tests were undertaken in dry sand at  
44 62g, corresponding to a scale (N) 1:100 in an equivalent saturated sand behaving in a drained  
45 manner (Li *et al.*, 2010), which is the case here.

46 Further details regarding the testing rig, sample preparation and in-flight CPT can be found in  
47 Davidson *et al.* (2020). Fifteen tests were undertaken (Table 3), varying the pile geometry,  
48 embedment depth, advancement ratio and testing tensile or compressive resistance.

## 49 **3. Results and discussion**

50 Figure 2 shows installation requirements (vertical force in Figure 2a, torque in Figure 2b) as a  
51 function of the embedment depth, geometry and AR. Figure 2a shows that reducing the AR  
52 reduces the measured vertical force, from 21MN in compression (pitch-matched, AR = 1.0) to  
53 tension in the pile (overflighting, AR = 0.5). This behaviour is consistent with previous single

54 helix pile behaviour (Cerfontaine *et al.*, 2021a). It was shown numerically that helix overflighting  
55 forces sand particles to move upwards (Cerfontaine *et al.*, 2021b). However, the surrounding  
56 soil opposes this upwards movement and the reaction force acting on the helix creates tension  
57 in the pile (pull-in force). When the pile upper section penetrates the soil (from 10.5m depth),  
58 the pile penetration resistance increases due to the transition piece and larger shaft diameter,  
59 even if the helix pull-in continues to increase.

60 It was measured that the internal helix opening plugged during the installation (final plug height  
61 equal to 2.0m-2.5m). Plugging prevents the sand from entering the upper section. Therefore,  
62 the transition pieces have different penetration mechanisms, similar to a CPT device (for CTP)  
63 or to a cutting tool (for plugged IHTP). Figure 2a shows that penetration resistance of the CTP  
64 is greater than the IHTP, as the measured force is more in compression (Figure 2a , AR = 0.5,  
65 depth >10.5m). The torque is also lower for the IHTP (Figure 2b). The conical piece test was  
66 repeated in two successive sand beds to demonstrate the reproducibility of the results.

67 This relative insensitivity of the measured torque to AR (Figure 2b) is beneficial for design and  
68 application, as an error in the estimated or applied AR won't significantly affect the required  
69 torque, and hence lead to early refusal. The torque started to increase more importantly after  
70 the upper section penetrated (10.5m depth, Figure 2b), which can be related to a greater shaft  
71 diameter (lever arm, increased surface area) and the transition piece. At the end of installation,  
72 the torque varied between 21MNm and 24MNm for the IHTP, while the conical piece torque  
73 was 27MNm. These values are lower than the maximum that was deemed practically  
74 achievable with installation vessels.

75

76 Screw piles (with IHTP) were installed at AR ranging from 0.1 to 1.0 at a depth of 25m, then  
77 tested in tension or compression. Representative load-displacement relationships are shown  
78 in Figure 3. Capacity and initial stiffness of the pile tend to increase in tension as the AR  
79 decreases, while the opposite effect can be observed in compression, which is consistent with  
80 experimental and numerical results (Cerfontaine *et al.*, 2021a; Sharif *et al.*, 2021b). The  
81 prediction of foundation initial stiffness is critical in the design of offshore wind turbines, which

82 are dynamically sensitive. It was shown by Jalbi *et al.* (2019), that high vertical stiffness for  
83 jacket foundations is preferable to avoid low frequency rocking modes of vibration and  
84 susceptibility to resonance with the rotor frequency. Therefore, the pile initial stiffness  
85 enhancement due to overflying is beneficial for design. This enhancement of capacity and  
86 stiffness can again be explained by the overflying movement of the helix, which enhances  
87 soil density and the stress field above the helix and has the opposite effect underneath the  
88 helix. The effect on the pile shafts was not measured, but it could be expected that overflying  
89 increases the radial stress magnitude, hence the shaft vertical resistance (Cerfontaine *et al.*,  
90 2021b; Sharif *et al.*, 2021b). The pile behaviour only exhibits a well-defined peak in tension,  
91 hence the pile resistance (denoted  $F_{z,r}$ ) was calculated as the maximum force measured within  
92  $0.1D_h$  displacement.

93 Figure 4 shows a continuously decreasing compressive capacity with reduction in AR, while  
94 the tensile capacity of overflighted piles is always greater than the pitch-matched one, with a  
95 maximum for AR = 0.5. Tensile capacity is critical for jacket supported wind turbines (Davidson  
96 *et al.*, 2020). Therefore, the potential for tensile capacity increase with a reduction in AR will  
97 be beneficial, while the reduction in compressive capacity wouldn't necessarily affect the  
98 design. The torque at the end of installation is also reported in Figure 4, but does not show a  
99 clear trend, although it is maximum for AR = 0.5. The small difference between installation  
100 torques measured for tests at a same AR shows the good reproducibility of the results. The  
101 pile capacity after overflying installation (AR = 0.5) was measured at two additional  
102 penetration depths (20m and 30m). Figure 5 depicts that the change in compressive or tensile  
103 resistance from 20m to 30m depth is approximately twice the change in resistance due to AR  
104 variations. Therefore, including AR dependence in the pile capacity calculation has the  
105 potential to reduce the required pile penetration depth, hence the torque requirements saving  
106 time and money.

107

108 The pile axial resistance is due to the (upper) shaft and lower helix in tension, while the  
109 compressive capacity includes the transition piece contribution. The lower shaft contribution

110 can be ignored due to its relatively small diameter ( $D_{low}/D_h = 0.4$ ), short length and interaction  
 111 with the helix failure mechanisms (already included via Eq. (2)). Meyerhof and Adams (1968)  
 112 postulated that the bearing factor ( $N_\gamma$ ) for helix or plates in tension increases with depth  
 113 (shallow failure mechanism) until a certain depth, after which the bearing factor is constant  
 114 (deep failure mechanism). As a first approximation, the method proposed by Giampa *et al.*  
 115 (2017) was used to calculate  $N_\gamma$  (shallow mechanism)

$$\frac{F_h}{\gamma' z A_h} = N_\gamma \left( \frac{z}{D_h} \right) = 1 + 2F_{ps} \left( \frac{z}{D_h} \right) + \frac{4}{3} F_{ps} \tan \psi_p \left( \frac{z}{D_h} \right)^2 \leq N_\gamma \left( \frac{z}{D_h} = 6 \right) \quad (2)$$

116 where

$$F_{ps} = \tan \psi_p + \cos(\phi_p - \psi_p) (\tan \phi_p - \tan \psi_p) \quad (3)$$

117 and  $F_h$  is the helix capacity,  $\phi_p$  is the soil peak friction angle (see Table 2),  $\psi_p$  is the peak  
 118 dilatancy angle,  $\gamma'$  is the effective unit weight and  $A_h$  is the helix area. The deep bearing  
 119 factor was calculated by assuming the shallow to deep transition takes place at a relative  
 120 depth around  $z/D_h = 6$  in medium-dense HST95 sand (Cerfontaine *et al.*, 2019). Bearing  
 121 factors are potentially greater in compression than in tension (Lutenegger and Tsuha, 2015),  
 122 but they were considered identical here as there were no measurements available to  
 123 determine the helix contribution.

124

125 The upper shaft and transition piece contributions can be estimated based on the method  
 126 proposed by Lehane *et al.* (2007) for jacked piles. The compressive capacity of the transition  
 127 piece, considered as a fully plugged tip is

$$F_{tp} = 0.6 \bar{q}_c \frac{\pi}{4} D_{up}^2 \quad (4)$$

128 where  $D_{up}$  is the diameter of the upper section shaft and  $\bar{q}_c$  is the averaged cone penetration  
 129 resistance, extrapolated from (Davidson *et al.*, 2020). The shaft contribution is calculated by  
 130 integrating numerically the shear stress along the embedment depth

$$\tau_f = a \bar{q}_c \left[ \max\left(\frac{h}{D_{up}}, 2\right) \right]^{-0.5} \tan \delta_{crit} \quad (5)$$

131 where  $a$  is a drop index equal to 0.03 in compression and 0.022 in tension,  $h$  is the distance  
132 measured upwards from the base of the transition piece and  $\delta_{crit}$  is the interface friction angle.

133

134 The prediction of pile axial capacity is depicted in Figure 5 as a dashed line, which is consistent  
135 with pitch-matched installation (AR = 1.0) at 25m depth. Using results from Figure 4, it is  
136 possible to calculate an AR based reduction factor ( $f_{AR}$ ) to correct the results (solid line in  
137 Figure 5), which better approximates the centrifuge results (AR = 0.5). The proposed method  
138 gives an estimate for pile resistance, but more results are necessary to determine accurate AR  
139 correction factors. Firstly, pile jacking or helical pile embedment leads to different mechanisms  
140 during installation (see Cerfontaine *et al.* (2021b)). Secondly, the AR effect on the helix or the  
141 shaft resistances are probably different and function of many parameters, such as the  
142 embedment depth and pile and helix geometric properties.

143

144 Future research is necessary to determine correction factors for each contribution (shaft, helix,  
145 transition piece) and to optimise the transition piece to reduce installation torque. The use of  
146 DEM to investigate local mechanisms during installation (Cerfontaine *et al.*, 2021b) or loading  
147 (Sharif *et al.*, 2021b, 2021a) of screw piles can be used to enrich experimental findings and  
148 develop physically-based prediction methods. Finally, installation in the field will be undertaken  
149 at constant vertical force (pile and tool weight), with the AR adapting to maintain the vertical  
150 equilibrium. The effect of this mode of installation on the capacity needs further investigation.

151

## 152 **4. Conclusions**

153 An original screw pile design, composed of two parts of varying shaft diameter, was tested in  
154 a geotechnical centrifuge. It was shown that their penetration resistance can be reduced by  
155 geometry and installation optimisation, which enables their use as foundations for jacket  
156 structures supporting offshore wind turbines and minimises the reaction forces needed from



157 installation vessels. It was shown that reducing the advancement ratio during pile installation  
 158 strongly reduces the need for vertical reaction force, while the required torque was relatively  
 159 unchanged. The torque appears to be mostly due to the upper pile section, whose length and  
 160 transition piece should be optimised to reduce installation requirements, with the IHTP having  
 161 the lowest penetration resistance. The tensile resistance was always smaller than the  
 162 compressive capacity, but the tensile capacity increased with a reduction of AR, while the  
 163 compressive capacity decreased. An estimation method was proposed to calculate the pile  
 164 capacity in both tension and compression. Predictions were consistent with the capacities  
 165 measured experimentally, but more research is needed to derive AR-dependent correction  
 166 factors.

167

## 168 **5. Acknowledgements**

169

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 171 Research Council (EPSRC) (Grant no. EP/N006054/1: Supergen Wind Hub Grand Challenges  
 172 Project: Screw piles for wind energy foundations).

173

## 174 **6. Notation**

a	Stress drop index, from (Lehane <i>et al.</i> , 2007)
$A_h$	Helix surface (including shaft)
AR	Advancement ratio
$D_h$	Helix diameter
$D_{low}$	Diameter of the screw pile lower shaft
$D_r$	Relative density
$D_s$	Shaft diameter
$D_{up}$	Diameter of the screw pile upper shaft

$F_h$	Resultant force acting on the helix
$F_s$	Resultant force acting on the shaft
$F_{tp}$	Resultant force acting on transition piece
$F_z$	Total vertical force
$F_{z,r}$	Total vertical force at failure (within $0.1D_h$ ) in tension or compression
$L_{up}$	Length of the lower section shaft
$L_{up}$	Length of the upper section shaft
$N_\gamma$	Helix non-dimensional bearing factor
$p_h$	Helix pitch
$\bar{q}_c$	Averaged cone penetration resistance
$t_p$	Helix plate thickness
$T$	Total torque
$z$	Depth
$\alpha$	Angle of the conical transition piece, to the vertical direction
$\gamma'$	Buoyant unit weight (=dry weight in this study)
$\delta_{crit}$	Critical state interface friction angle
$\Delta z_h$	Vertical displacement of the helix after one helix revolution
$\tau_z$	Vertical shear stress

175

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## 8. Caption list: figures

Figure 1 Screw pile models used in the centrifuge and main geometric parameters. (a) Internal helix transition piece; (b) Conical transition piece.

Figure 2 Representative installation (a) vertical force ( $F_y$ ) and (b) Torque, as a function of depth, of the imposed AR and of the pile geometry.

Figure 3 Load-displacement relationship in tension or compression for piles embedded at 25m depth, as a function of the advancement ratio (AR)

Figure 4 Change in pile tensile or compressive capacity and change of torque at the end of installation as a function of the advancement ratio. Pile capacity is calculated as the maximum value within  $0.1D_h$  displacement from the end of installation (25m depth at prototype scale).

Figure 5 Evolution of the pile capacity in tension (T) or compression (C) as a function of embedment depth for AR =0.5 and prediction via a simplified approach. The horizontal lines indicate the range of variation of measured pile resistance as a function of the AR.

9. Figures

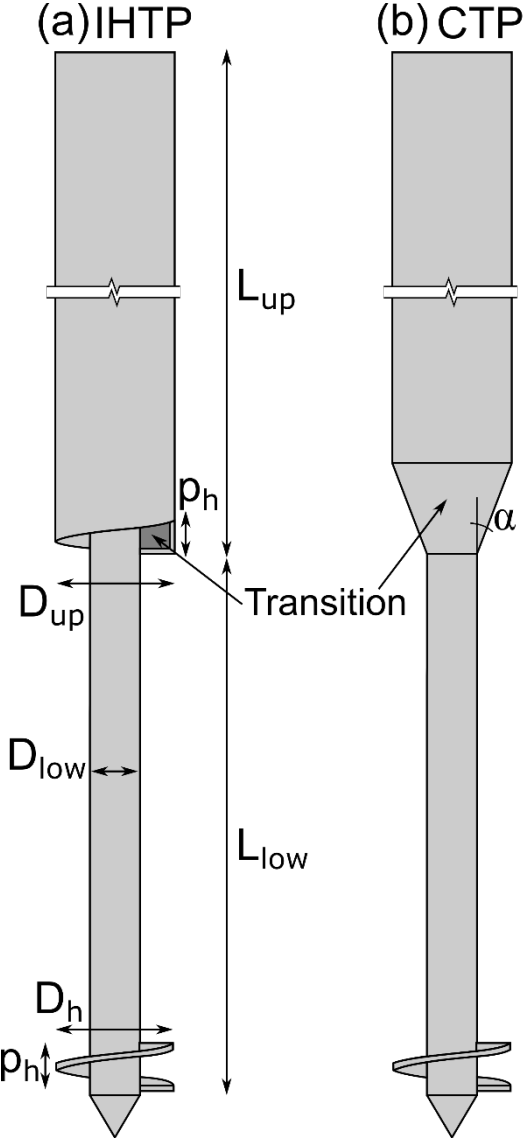


Figure 1 Screw pile models used in the centrifuge and main geometric parameters. (a) Internal helix transition piece (IHTP); (b) Conical transition piece (CTP).

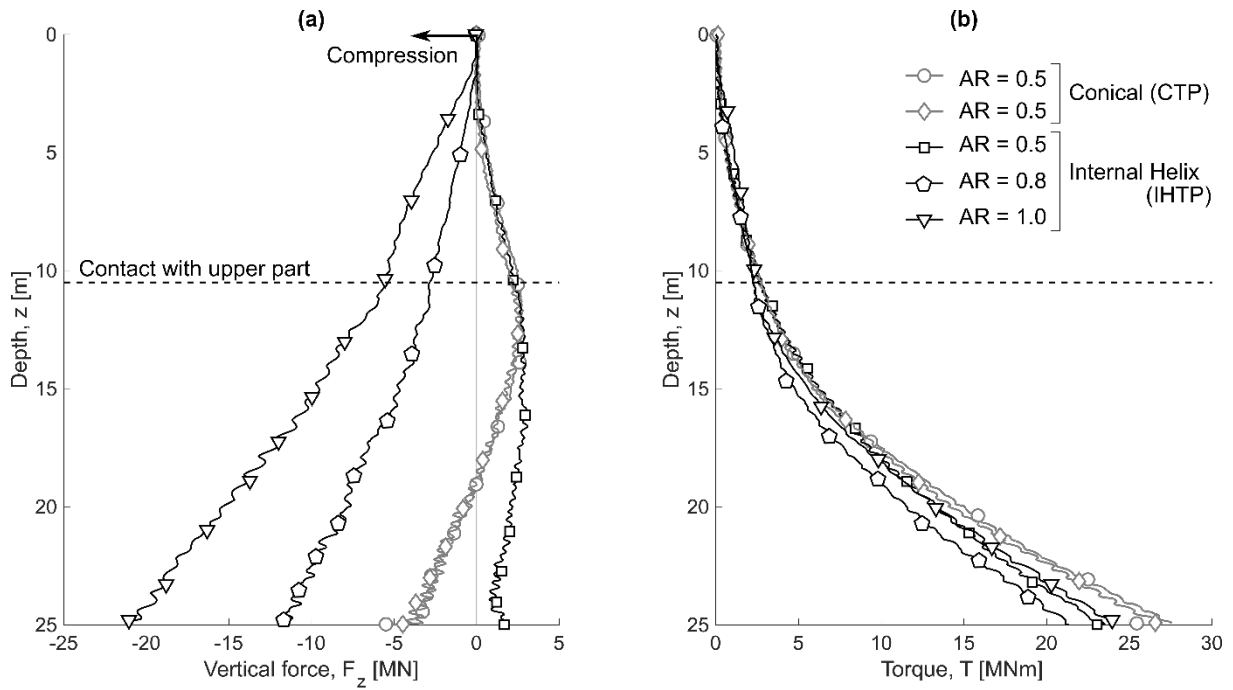


Figure 2 Representative installation (a) Vertical force ( $F_y$ ) and (b) Torque, as a function of depth, of the imposed AR and of the pile geometry (conical transition piece CTP or internal helix transition piece IHTP). Test IDs: 1-3, 7, 10.

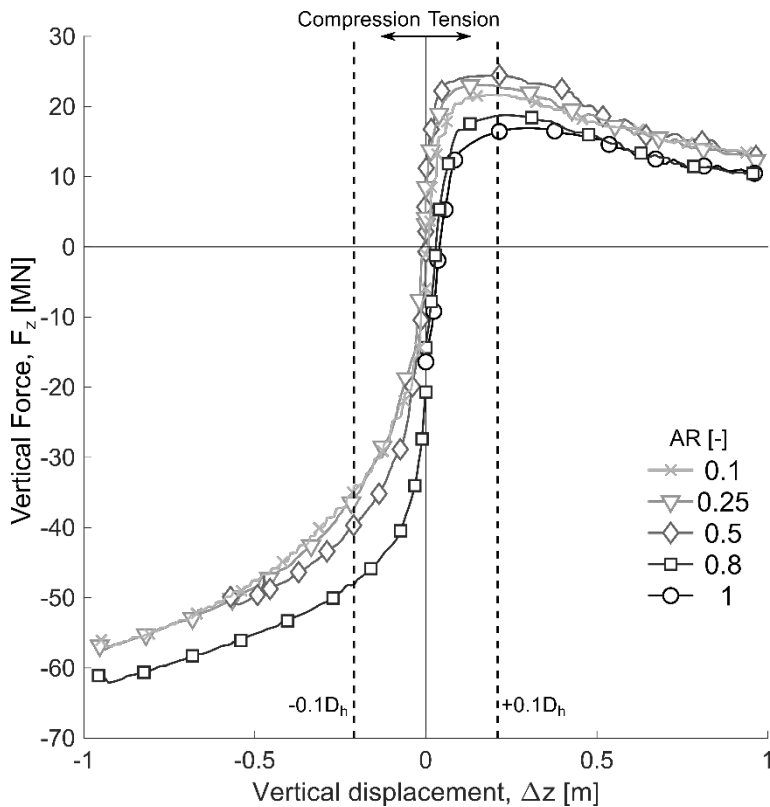


Figure 3 Load-displacement relationship in tension or compression for piles embedded at 25m depth, as a function of the advancement ratio (AR). Test IDs: 2, 4-7, 9-12.



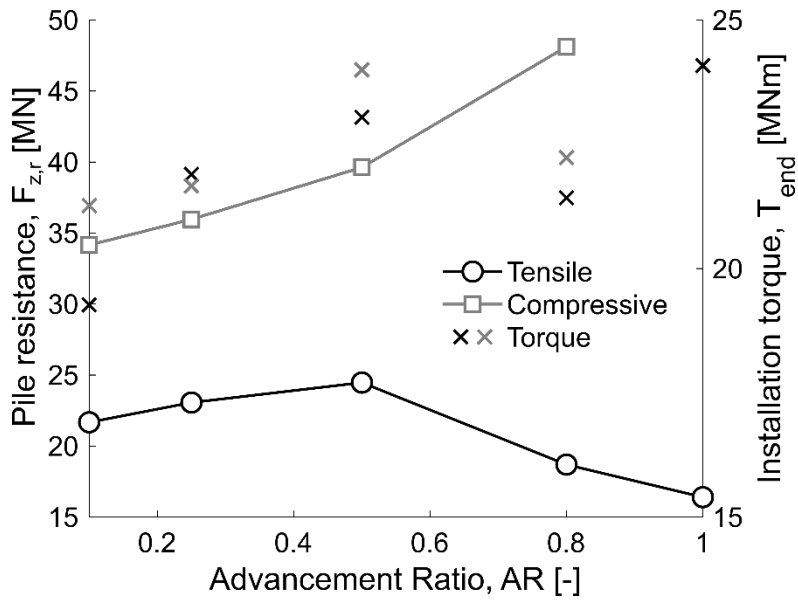


Figure 4 Change in pile tensile or compressive capacity and change of torque at the end of installation as a function of the advancement ratio (cross markers, one for compressive – grey – and one for tensile – black – tests). Pile capacity is calculated as the maximum value within  $0.1D_h$  displacement from the end of installation (25m depth at prototype scale). Test IDs 2, 4-7, 9-12.

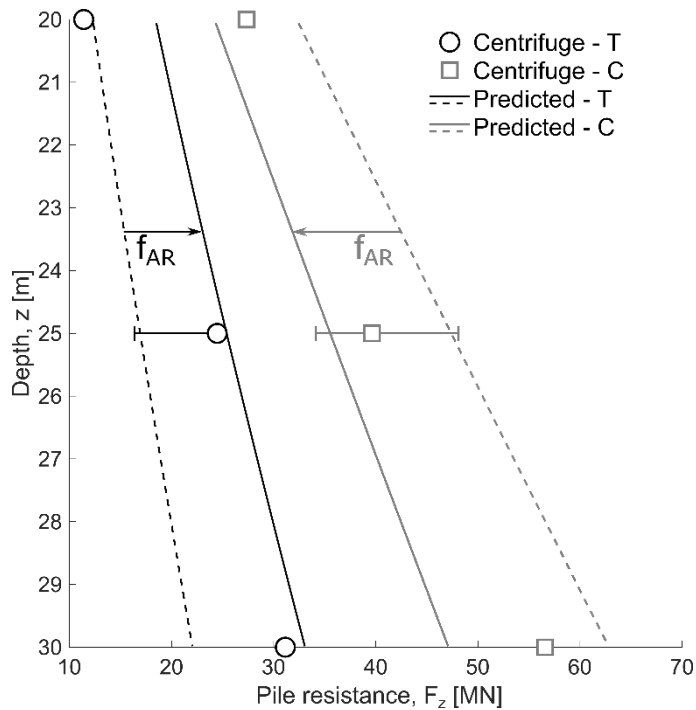


Figure 5 Evolution of the pile capacity in tension (T) or compression (C) as a function of embedment depth for AR = 0.5 and prediction via a simplified approach. Correction factors  $f_{AR} = 0.75$  in compression and  $f_{AR} = 1.5$  in tension are applied from pitch-matched (AR = 1.0, solid lines) to overflighted (AR=0.5, dashed lines) predictions. The horizontal lines indicate the range of variation of measured pile resistance as a function of the AR. Test IDs: 2, 5, 8, 13-15.

## 10. Caption list: tables

Table 1 Properties of the HST95 sand, after (Lauder, 2010; Al-Defae *et al.*, 2013), peak friction angle given at 53% relative density

Table 2 Parameters of the pile at prototype scale

Table 3 List of centrifuge tests undertaken, average relative density of the sand bed ( $D_r$ ), Imposed Advancement Ratio (AR), Target installation depth at prototype scale and loading test type (tensile T or compressive C)

## 11. Tables

Table 1 Parameters of the pile at prototype scale

Parameter	Symbol	Unit	Value
Upper section length	$L_{up}$	[m]	27.5
Lower section length	$L_{low}$	[m]	10.5
Upper section diameter	$D_{up}$	[m]	2.1
Upper section inner diameter	$D_{up,in}$	[m]	1.9
Lower section diameter	$D_{low}$	[m]	0.87
Helix diameter	$D_h$	[m]	2.1
Helix pitch	$p_h$	[m]	0.75
Helix plate thickness	$t_p$	[m]	0.1
Conical transition angle	$\alpha$	[°]	40

Table 2 Properties of the HST95 sand, after (Lauder, 2010; Al-Defae *et al.*, 2013), peak friction and dilatancy angles given at 53% relative density (triaxial test). Interface friction was determined by direct shear test.

Parameter	Symbol	Unit	Value
Effective particle size	$D_{10}$	[mm]	0.09
Average particle size	$D_{50}$	[mm]	0.14
Particle specific gravity	$G_s$	[-]	2.63
Minimum void ratio	$e_{min}$	[-]	0.467
Maximum void ratio	$e_{max}$	[-]	0.769
Minimum dry density	$\rho_{min}$	[kg/m <sup>3</sup> ]	1486
Maximum dry density	$\rho_{max}$	[kg/m <sup>3</sup> ]	1793
Critical state friction angle	$\phi_{crit}$	[°]	32
Peak friction angle	$\phi_p$	[°]	39.6
Peak dilatancy angle	$\psi_p$	[°]	9.2
Sand-steel interface friction angle	$\delta_{crit}$	[°]	24

Table 3 List of centrifuge tests undertaken, average relative density of the sand bed ( $D_r$ ), Imposed Advancement Ratio (AR), Target installation depth of the tip at prototype scale and loading test type (tensile T or compressive C)

<b>ID</b>	<b>Transition Piece</b>	<b><math>D_r</math> [%]</b>	<b>AR [-]</b>	<b>Depth [m]</b>	<b>ULS</b>
1	Conical	57	0.5	25	T
2	Internal Helix	57	0.5	25	T
3	Conical	52	0.5	25	T
4	Internal Helix	53	0.25	25	T
5	Internal Helix	52	0.5	25	C
6	Internal Helix	52	0.25	25	C
7	Internal Helix	52	1.0	25	T
8	Internal Helix	52	0.5	20	T
9	Internal Helix	52	0.1	25	T
10	Internal Helix	52	0.8	25	T
11	Internal Helix	54	0.1	25	C
12	Internal Helix	54	0.8	25	C
13	Internal Helix	54	0.5	20	C
14	Internal Helix	54	0.5	30	C
15	Internal Helix	52	0.5	30	T