The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
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Overflighting screw piles in sand, a detrimental effect?

Sur-rotation des pieux vissés dans les sables, un effet néfaste?

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ABSTRACT: Screw piles are an alternative to offshore driven piles due to their significant uplift capacity and installation without underwater noise. Current design guidance recommends that the pile advancement rate during installation must be of one helix pitch per rotation, to minimise soil disturbance. However, such an advancement rate may require the application of significant crowd force that can exceed the reaction force available from the installation vessel. This paper summarises geotechnical centrifuge tests in sand, in which model single helix screw piles were installed at installation rates lower than the recommended values (pile overflighting). Results show that such an installation procedure has beneficial effects, in that it reduces the vertical force necessary for installation and enhances the uplift capacity. Therefore, it can be concluded that screw piles are particularly suitable to be used as offshore anchors.

RÉSUMÉ : Les pieux vissés sont une alternative aux pieux foncés offshore, grâce à leur importante résistance en tension et leur installation sans émission de bruit sous-marin. Les normes actuelles recommandent que l'avancement du pieu durant l'installation soit égal au pas de l'hélice pour chaque rotation, afin de minimiser la perturbation du sol. Cependant, assurer ce taux d'avancement nécessite une force verticale qui peut excéder la réaction maximale applicable par un navire. Cet article résume des résultats de tests en centrifugeuse géotechnique, pour lesquels des modèles de pieux ont été installés dans un sable à des taux d'avancement inférieur aux valeurs recommandées (sur-rotation). Les résultats montrent qu'une telle installation a un effet doublement positif, elle réduit la force nécessaire durant l'installation and augmente la capacité portante en tension du pieu. On peut donc conclure que les pieux vissés sont particulièrement adaptés à un usage comme ancrage offshore.

KEYWORDS: helical piles; screw piles; floating wind; offshore geotechnics

1 INTRODUCTION

Screw (or helical) piles are widely used onshore as foundations for relatively light structures, such as telecommunication towers (Schiavon et al. 2016). Screw piles are composed of a steel shaft which is connected to one or several helices (Perko 2009; Lutenegger 2015). These piles are installed by applying a torque and force at their head, which rotates (screws) the pile into the ground. Fast and silent (no vibrations) installation is one of the main advantages of screw piles. Their installation also does not generate any spoil that requires excavation and disposal. Screw piles are particularly used for their uplift (or tensile) capacity (Spagnoli and Tsuha 2020), provided by the helix, which acts like an embedded plate anchor.

Their tensile capacity and ability to be installed without underwater noise make screw piles an excellent foundation for offshore applications (Byrne and Houlsby 2015; Spagnoli and Tsuha 2020), either for jacket structures (Davidson et al. 2020) or as anchors for floating offshore renewable energy structures (Cerfontaine et al. 2020b). Guidance for screw pile installation recommends that they must penetrate at one a helix pitch (p_h , height of the helix) per rotation to avoid excessive disturbance of the soil around the helix (BS8004:2015 2015). A vertical compressive (crowd) force may need to be applied during installation to ensure this condition is respected which tends to increase with depth. However, it was shown that the crowd force necessary to install large pile geometries necessary for offshore applications tends towards the maximum reaction force that could practically be achieved by installation vessels (Davidson et al. 2020).

The advancement ratio (AR) is defined as the ratio of the pile displacement per rotation (Δz_h), divided by the helix pitch (p_h), (Bradshaw et al. 2018).

$$AR = \frac{\Delta z_h}{p_h} \tag{1}$$

A pitch-matched installation corresponds to an AR equal to 1. It was numerically shown that installing single helix screw piles at an advancement ratio lower than one has the potential to reduce the crowd force necessary for installation (Sharif et al. 2020). Alternatively, it was shown by small scale 1-g experiments that the AR decreases with depth if a constant load is applied during screw pile installation (Bradshaw et al. 2018).

The objective of this work is to investigate how the uplift capacity of screw piles is affected by the advancement ratio applied during their installation. The screw pile installation will be physically modelled in a geotechnical beam-centrifuge for various pile geometries. The uplift capacity will be systematically measured after the installation.

2 METHODOLOGY

2.1 *Centrifuge testing*

The centrifuge tests were performed using the Actidyn C67-2 3-meter radius geotechnical beam centrifuge located at the University of Dundee (UK). Centrifuge testing reproduces at small scale the stress field existing at prototype scale, enabling the scaling of both soil strength and stiffness. A rig was developed at the University of Dundee which is capable of installing and testing single helix screw piles in one continuous centrifuge flight (Davidson et al. 2018; 2020). The testing equipment enabled precise control of the rotational and vertical displacement of the model piles, powered by two servo-motors. A load cell measured the torque from – 30 Nm to +30 Nm and the axial force from -20 kN to +20 kN at the top of the pile model. The axial displacement was measured by a draw wire transducer. Further details can be found in (Davidson et al. 2020).

2.2 *Sand bed preparation*

Medium-dense and dense sand beds (425 mm deep) were created by dry pluviation of HST95 sand in a strong box (500 mm x 800 mm x 550 mm). It has been extensively used and characterised at the University of Dundee for laboratory testing (Lauder 2010; Al-Defae et al. 2013; Robinson et al. 2019) and used in previous screw pile investigations. A linear pluviator was mounted on rails running above the container at a constant velocity. The sand was pluviated to just above the target height, and the sand surface was levelled. Medium-dense (sand bed average relative density D_r 52-53%) and dense (D_r 72-78%) sand beds were prepared. All tests were undertaken in dry conditions. Additional information on sample preparation and in-flight CPT profiles can be found in (Davidson et al. 2020).

Table 1 List of centrifuge tests

ID	Pile	AR [-]	D_s [m]	D_s/D_h [-]	Base shape	D_r [%]
1	P1	0.10	0.55	0.52	Flat	74
2	P1	0.25	0.55	0.52	Flat	73
3	P1	0.50	0.55	0.52	Flat	75
4	P1	0.80	0.55	0.52	Flat	73
5	P1	1.00	0.55	0.52	Flat	73
6	P1	1.10	0.55	0.52	Flat	73
7	P1	0.10	0.55	0.52	Flat	52
8	P1	0.25	0.55	0.52	Flat	53
9	P1	0.50	0.55	0.52	Flat	52
10	P1	0.80	0.55	0.52	Flat	53
11	P1	1.00	0.55	0.52	Flat	52
12	P2	0.50	0.55	0.52	Asym.	78
13	P2	1.00	0.55	0.52	Asym.	78
14	P4	0.50	0.70	0.66	Asym.	73
15	P4	1.00	0.70	0.66	Asym.	73
16	P3	0.50	0.40	0.38	Asym.	73
17	P3	1.00	0.40	0.38	Asym.	73

2.3 *Tests undertaken*

A total of 17 centrifuge tests are used in this study, varying pile geometry, sand density and advancement ratio. All piles, whose dimensions are given in Figure 1 have the same helix diameter (D_h = 1.06m, prototype scale), but their shaft diameter and tip shape (flat or asymmetrically cut at 45°) vary. All piles were installed so that the relative embedment of the single helix is the same (z/D_h = 7.5). The helix pitch (p_h) is also identical for all piles and equal to 0.35m at prototype scale. A summary of all tests used in this paper is given in Table 1 and further details can be found in Cerfontaine et al. (2021a).

3 RESULTS

3.1 *Installation requirements*

Figure 2(a) depicts the vertical (crowd)force that must be applied to a single helix screw pile, as a function of a normalized depth (z/D_h), to ensure the pile installation at a constant advancement ratio (AR). These results are for a flat base screw pile (P1 in Figure 1) installed in medium-dense sand (Dr ≈ 52%). This figure shows that the vertical force varies from compressive to tensile as the AR is reduced. A tensile force means that the pile effectively pulls itself into the ground at low AR. The force is almost equal to zero for AR = 0.5. This shows that if only a low reaction force is available (field conditions) to install a large pile in a homogeneous sand layer, installation is possible providing the pile is overflighted (AR <1).

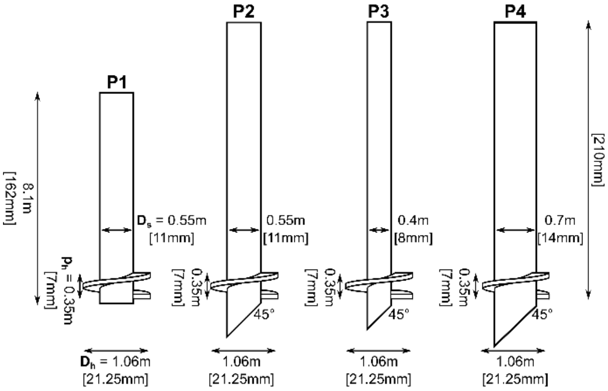

Figure 1 Model single helix screw pile description shown with prototype dimensions, model scale dimensions shown in brackets

Figure 2(b) represents how the torque requirement increases with depth. There seems to be a clear difference between tests leading to a compressive vertical force (F_z <0 for AR = 0.8 and

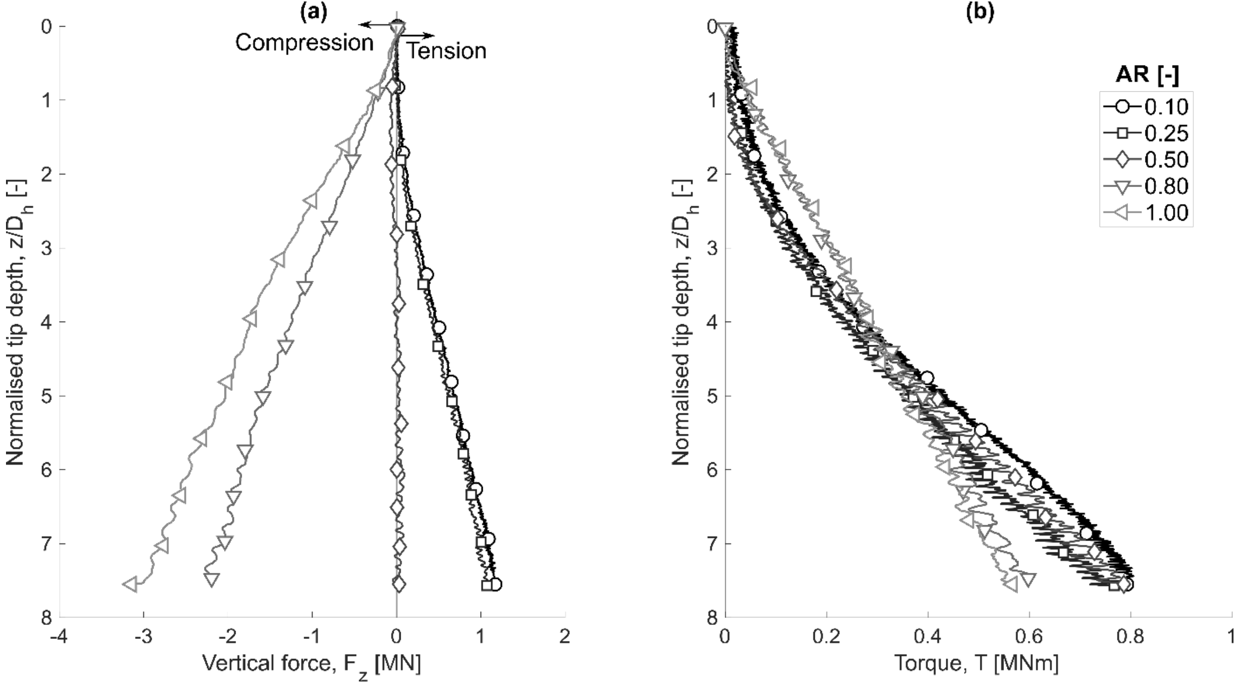

Figure 2 Installation requirements for the pile as a function of the imposed advancement ratio (AR): (a) Vertical force; (b) Torque. Medium-dense sand, flat tip pile (P1).

1.0) and the other tests (AR = 0.1, 0.25 or 0.5). In the former case, the torque increases almost linearly with depth, whilst a clearly non-linear trend can be observed for the latter. This results in approximately 33% torque increase at the final depth investigated (z/D_h = 7.5). However, this variation in torque is much less dramatic than the change in vertical force.

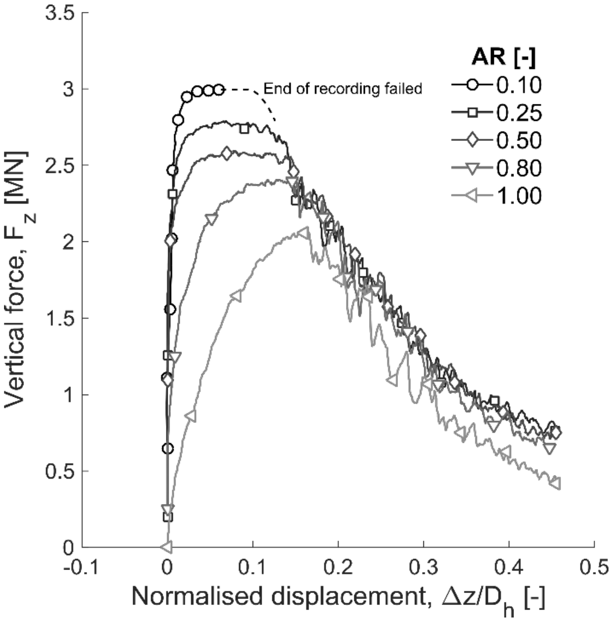

Figure 4 Load-displacement relationship in tension for piles installed at different advancement ratios (AR), medium-dense sand, flat tip pile.

Similar effects are also observed in a denser sand (Dr ≈ 73%) for different pile geometries (shaft diameter or tip shape).

3.2 *Uplift capacity*

The pile load displacement relationship in tension is illustrated in Figure 3 for the same pile and sand relative density. The figure shows that the pile capacity (peak or plateau) increases as the AR is reduced, as well as its initial stiffness. The pile-soil "ductility" also increases as low AR loading exhibits a plateau at the maximum load followed by some softening, whilst the highest AR (=1) reaches a peak before a sudden "brittle" softening. A similar trend was observed in all tests, with overflighted piles exhibiting a greater stiffness and capacity than pitch-matched installation.

3.3 Relationship *between installation force and uplift capacity*

For each test undertaken, the uplift capacity (F_u) was identified as the maximum vertical tensile force, irrespective of the necessary displacement to mobilise it. Vertical installation force (crowd) was calculated as the average vertical force applied over the last 0.5m of the pile installation. For each pile geometry, the pile uplift capacity and installation force for a given AR were normalised by the uplift capacity and installation force measured for a pitch-matched installation ($F_{u,AR=1.0}$ and $F_{z,\ AR=1.0}$ respectively). These data are plotted together in Figure 4a for all tests described in Table 1. The normalised uplift capacity is also depicted as a function of the advancement ratio in Figure 4b.

Results in Figure 4 show that reduction in installation force and increase in capacity are correlated, although a trend as a function of AR can only be identified for flat tip piles (P1 in Figure 1) for which the AR was varied over a broad range of values. In medium dense sand (square markers), there is an almost linear relationship between the installation force reduction, the uplift capacity increase and the AR. The trend seems more non-linear in dense sand (circular markers), with a capacity firstly increasing then decreasing as the AR is reduced. The maximum capacity is obtained for AR = 0.5. The other pile geometries (P2 to P4, with axisymmetric tip and varying shaft diameter) exhibit different levels of vertical force reduction and capacity enhancement.

4 DISCUSSION

4.1 *Overflighting mechanism*

Both installation and uplift behaviours can be explained by the overflighting process, taking place when AR < 1. To idealise the problem, it is possible to write the equation of the vertical displacement (Δz, positive upwards) of a particle that would be

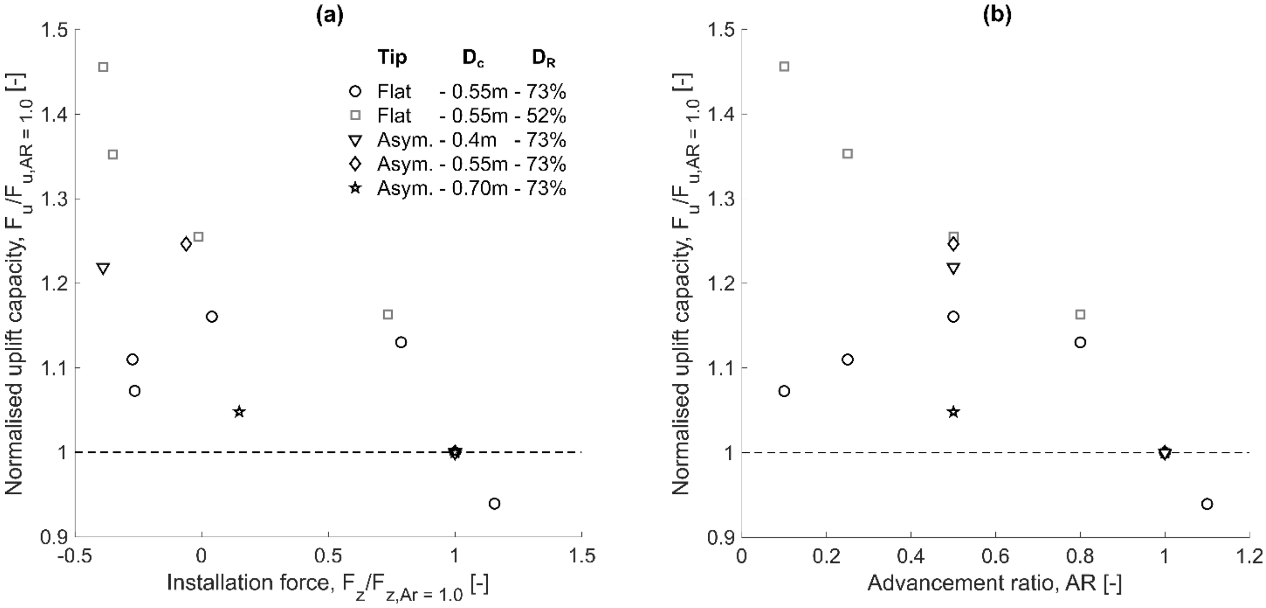

Figure 3 (a) Normalised uplift capacity (F_u) with respect the uplift capacity for pitch-matched conditions ($F_{u,AR=1.0}$), as a function of the normalised vertical force (F_z) necessary for installation over the last 0.5m of installation; (b) Normalised uplift capacity as a function of the imposed advancement ratio (AR).

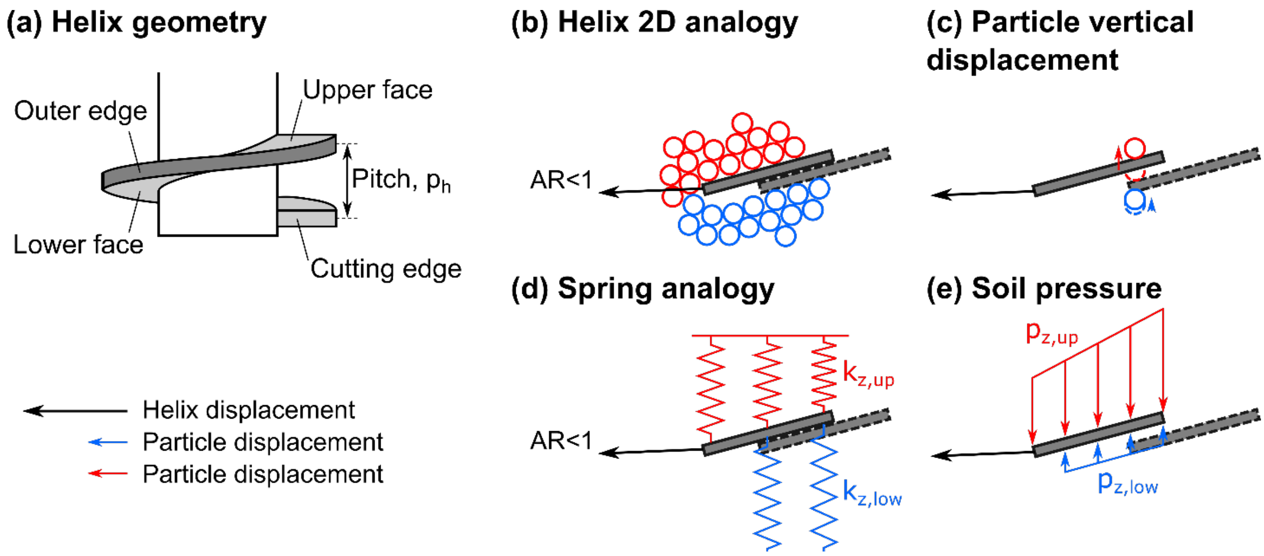

Figure 5 2D analogy of the helix and particle displacement during a small rotation, as a function of the advancement ratio (AR).

initially in contact with the upper part of the cutting edge of the helix, whose horizontal movement would be prohibited and which must remain continuously in contact with the helix. Eq. (2) describes this vertical movement as a function of the AR, the helix pitch (p_h) and the rotation angle (θ), during one rotation of the helix.

$$\Delta z = (1 - AR) \cdot p_h \cdot \frac{\theta}{2\pi}, \theta \in [0°, 360°] \qquad (2)$$

This equation shows that if AR = 1 (pitch-matched), a particle initially in contact with the helix would not be displaced by the helix movement ($\Delta z = 0$). On the contrary, if AR < 1 (overflighted pile), any sand particle in contact with the upper face of the helix will be displaced vertically upwards ($\Delta z > 0$) during one rotation, even if the pile is moving downwards. The non-idealised particle displacement is obviously more complicated. For example, particles are not limited to a vertical displacement during the pile installation and can move in plane. Secondly, even for a pitch-matched installation, the penetration of the helix cutting edge will induce some soil displacement. Finally, the pile shaft penetration will displace a volume of soil laterally and interact with the helix movement.

DEM simulations were undertaken by Cerfontaine et al. (2021b) to further understand the overflighting process. This numerical technique models the soil by spherical incompressible particles whose interaction is controlled by a contact law (O'Sullivan 2011). The behaviour of the soil mass depends on the relative density of the sand bed, similarly to a real soil. This technique naturally enables the modelling of large deformation and penetration of objects, but also the investigation of micro-mechanical mechanisms. The size of modelled particles in this example is ten times the size of real particles to maintain a reasonable simulation time, but the overall behaviour of the soil mass is identical to the modelled soil (Zhang and Evans 2019).

The vertical displacement induced by one pile rotation is depicted in Figure 5a for a pile installed at AR = 0.5 in a medium-dense sand. Figure 5a depicts that the volume of soil affected by one rotation is relatively limited and is mostly located 1 helix pitch above the helix. However, the successive rotations of the helix to reach a given depth will affect the entire volume of soil located above the helix. Figure 5b shows contact forces between particles or between particles and the helix. Each contact force is described by a line, whose thickness and colour depend on the contact force magnitude. A thicker and darker line indicates a greater force magnitude. Figure 5b shows that the contact force magnitudes are greater on the helix cutting edge and upper face, than on the lower face.

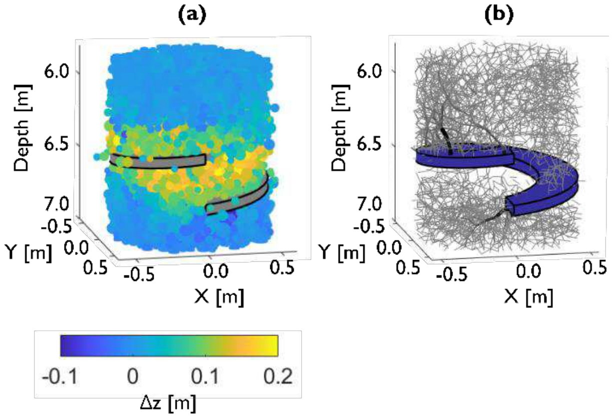

Figure 6 Results of DEM simulation during screw pile installation (AR = 0.5): (a) Vertical displacement (Δz) and (b) contact forces. The shaft was not represented in this figure for clarity, but was modelled.

The overflighting process can be summarised as follows and is illustrated by a 2D analogy in Figure 6. During the helix rotation, the cutting edge cuts through the material and the helix picks up some sand particles that end up in contact with the helix upper face (Figure 6b). As rotation continues, those particles are forced to move upwards because of the overflighting movement (as per Eq. 2 and Figure 6c). This movement has two main consequences. Firstly, it reduces the stress acting on the pile tip and under the helix. This is due to the helix movement relative to the soil, but also on the soil upwards displacement. This effect reduces the penetration resistance of the pile. Secondly, the surrounding soil opposes the upwards displacement imposed by the helix movement, i.e. the soil acts like a spring that would be compressed by an imposed displacement (Figure 6Figure 6d). This creates some compressive forces on the helix upper face (oriented downwards, Figure 6e). These forces create the pull-in behaviour that was observed during the centrifuge tests.

The torque non-linear behaviour for overflighted piles can also be explained by this theoretical model. The helix vertical movement does not only enhance the vertical stress above the helix, it also directly increases the radial stress acting on the shaft close to the helix. This increased radial stress in turn increases the torque necessary with respect to a pitch-matched installation.

The force reduction or creation of some pull-in depends on the pile shaft diameter, pile tip and sand density. All these factors affect the pile behaviour in different ways, as demonstrated by experimental results in (Cerfontaine et al. 2021a). A more thorough description of all micro-mechanical phenomena can be found in (Cerfontaine et al. 2021b).

4.2 *Impact of overflighting installation on pile behaviour*

The overflighting process explains the reduction in force requirement during installation, but also the increase in pile stiffness and capacity. The continuous upwards movement of sand particles creates a pre-loading of the soil, which increases in magnitude as the AR is reduced. Consequently, the soil above the helix is likely to be densified and the stress field magnitude is increased, with respect to a pitch-matched installation. Schiavon (2016) showed that pitch-matched installation generated some loosening of the soil above the helix, therefore the overflighting effect can reduce this effect. The importance of the stress field on the uplift capacity of shallow plates was investigated by Cerfontaine et al. (2020). These authors showed by FE modelling that screw pile capacity and stiffness were increased with respect to wished in place simulations, by mimicking the stress field created by a pitch-matched installation.

The enhanced stiffness could be beneficial for cyclic loading. Schiavon et al. (2017) showed that cyclic tensile loading of screw piles can lead to ratcheting. They linked this ratcheting to the potential gapping created under the helix when the pile moves upwards, which could be progressively filled up with particles coming from the sides. Consequently, the increased stiffness created by the pile overflighting, will reduce the upwards movement necessary to mobilise a given imposed force, hence will also reduce the potential for ratcheting.

The compressive capacity of the pile was not investigated in this study, but it was shown by Sharif et al. (2020), who undertook DEM simulations, that pile overflighting reduces the compressive stiffness and capacity.

4.3 *Limitations*

This paper demonstrates that some experimental conditions exist in which the uplift capacity is not degraded, but enhanced, by single helix screw pile overflighting. This demonstrates that it is erroneous to assume pile overflighting will always be detrimental, but does not demonstrate that pile oveflighting will always be beneficial.

Firstly, the tests were undertaken in clean sand and the conclusions cannot be extrapolated to silty or clayey materials. In fact, it was reported in the literature that overflighting of screw piles can lead to degradation of the pile capacity due to clay remoulding and undrained shear strength reduction (Lutenegger 2019). Secondly, all tests were undertaken at the same relative embdement ratio (z/D_h = 7.5), which should be close to the transition between shallow and deep failure mechanisms for plate anchors (Meyerhof and Adams 1968). At shallower depth, the imposed displacement of the helix may lead to a full failure of the soil during installation in a shallow mode. At deeper depth, the effect can be reduced as the uplift bearing pressure induced by the helix will become smaller with respect to the initial stress state. Thirdly, results presented in this paper clearly show different trends as a function of sand density, with a non-linear AR effect in dense sand. Finally, only more tests on different geometries (shaft to diameter ratios) are necessary to fully characterise the AR effect over a broader range of ARs.

The effect of overflighting a pile with a greater number of helices is unknown. Some preliminary results showed that the pull-in force of sufficiently spaced overflighted helices could add up to increase the overall pull-in effect. However, the effect on the tensile resistance was not investigated. On one hand, the overflighting mechanism will be the same for each helix, forcing soil particles to move upwards, which should have the same enhancing effect as per a single helix. On the other hand, it could be argued that the successive penetration of different helices into the soil could reduce the beneficial effect of overflighting or even degrades the soil strength properties as stated by Tsuha et al. (2012) for pitch-matched installation. A systematic investigation of the overflighting effect on multi-helix pile during installation and tensile loading is necessary, as many screw piles currently used onshore are made of several helices.

4.4 *Importance for field installation*

In the field, screw piles are usually installed by excavators able to apply torque and force at the pile head (Gavin et al. 2014; Wey et al. 2018). The monitoring of the pile displacement is limited and the advancement ratio probably fluctuates during the installation to accommodate the imposed force and soil conditions, as was shown during screw pile field tests (Richards et al. 2018). It is almost impossible to maintain actual pitch-matched conditions without accurate monitoring of the advancement and rotation rates. Therefore, it is likely that many installed screw piles in the field are subjected to some overflighting. Accurate monitoring of screw piles during installation should be generalised to ensure the assumed installation parameters are those actually applied.

In the context of offshore engineering, the available reaction force will be very limited, whether the pile is installed by an underwater remotely operated vehicle (deep water) or by a vessel (relatively shallow water). Results presented in this paper show that it is possible to install a pile even with a very low vertical force, providing pile overflighting is allowed. Consequently, screw piles can be considered as a viable technology for offshore applications if enough torque can be applied by a device to undertake their installation.

5 CONCLUSIONS

In this work, geotechnical beam-centrifuge tests were undertaken to evaluate how the advancement ratio (normalised displacement per rotation of the pile) influences single helix screw pile uplift behaviour and installation requirements for large prototype geometries. Results show that reducing the AR during installation strongly reduces the vertical installation force requirements and even creates some pull-in at the lowest AR (more than 100% change in force magnitude), while the torque only changed by 33%. The uplift stiffness and capacity were enhanced by an AR reduction. This can be explained by the overflighting movement of the pile, which moves sand particles upwards and pre-load the soil during installation.

More tests are necessary to validate and quantify these results at different relative embedment ratios, in more sand relative densities and for different pile geometries and number of helices. However, it can be concluded that the reaction force requirements should not be considered as a hurdle for screw pile installation offshore.

6 ACKNOWLEDGEMENTS

This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 753156. The authors would like to acknowledge the support of the Engineering and Physical Science Research Council (EPSRC) (Grant no. EP/N006054/1: Supergen Wind Hub Grand Challenges Project: Screw piles for wind energy foundations) and the EPSRC NPIF funded studentship with industrial support from Roger Bullivant Limited.

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