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# DEM analysis of helix number effects on offshore screw pile installation and in-service performance

W. Wang[1], M.J. Brown[1], M.O. Ciantia[1], Y.U. Sharif[1], B. Cerfontaine[2]
[1]*School of Science and Engineering, University of Dundee, Dundee, UK*
[2]*Department of Civil, Maritime and Environmental Engineering, University of Southampton, UK*

**ABSTRACT:** Screw piles are potentially silent and efficient foundation and anchoring system for offshore renewable energy applications, although upscaling of screw piles for offshore use may require vertical force applied at pile head, which can be impractical or costly. Recent studies show that it is possible to over-flight a single-helix screw pile to reduce and even eliminate the requirement for vertical force whilst enhancing post-installation uplift performance. Screw piles can have more than one helix to improve in-service performance at the price of increased installation vertical force and torque, but how this affects over-flighting installation and the performance after over-flighting installation has not been determined. In this study, DEM simulations are undertaken on a single-helix and a two-helix screw pile installed using pitch-matched and over-flighting approaches. The results show over-flighting of the two-helix screw pile can also reduce the installation requirements but may not improve the in-service uplift performance. In addition, for pitch-matched screw piles, increasing helix number can improve both compressive and tensile performance post-installation. For over-flighted screw pile, however, adding helices can result in loss of uplift capacity.

**Keywords:** Discrete Element Method; Screw Pile; Offshore geotechnics; Installation effects; Sand

## 1 INTRODUCTION

Screw piles are typically installed by applying torque on pile head with an additional vertical (crowd) force. Because the rotational installation generates less noise and vibration, which is detrimental to marine animals, and there is the potential for decommissioning by reverse rotation, screw piles have been suggested for upscaling from typical onshore sizes as an alternative silent foundation/anchoring solution for future offshore renewable energy e.g. wind turbines supported by screw piles or as anchors for floating systems in deeper water (Al-Baghdadi, 2018, Spagnoli and Tsuha, 2020).

However, if the screw piles are installed using the conventional pitch-matched manner (Advancement Ratio, AR = 1.0, see Equation (1) (British Standards Institution, 2015), increasing the size may lead to prohibitive vertical forces for installation (Davidson et al., 2022).

$$AR = \Delta z / p_h \tag{1}$$

where $\Delta z$ is the vertical displacement per rotation and $p_h$ is the pitch of the helix i.e. the vertical distance between the top and the bottom of a single helix.

Fortunately, recent studies have shown that the over-flighting approach (AR < 1.0) for installation can significantly reduce the required crowd force and can improve the post-installation monotonic and cyclic () uplift performance of single helix piles because soil is displaced upward through the helix opening (see Figure. 1) and therefore creates tension (downward) force on the helix (Cerfontaine et al., 2021a, Sharif et al., 2021, Cerfontaine et al., 2023, Wang et al., 2021).

The design of a screw pile can also involve multiple helices, which are expected to improve axial performance of the pile (Al-Baghdadi, 2018, Davidson et al., 2022). However, the effects of installation advancement ratio on multiple helix screw piles has not received significant attention. In this study, discrete element method (DEM) simulations are used to compare installation requirements and in-service performance of a single-helix screw pile and a two-helices screw pile, installed using pitch-match and over-flighting approaches.

## 2 DEM MODEL SETUP

The computing platform adopted was based upon a desk top PC with an Intel® Core CPU i9-10940X @4.1GHz 14 cores, 32GB RAM. Commercial software package PFC3D 7.0 (Itasca, 2021) was used to simulate screw pile installation and testing in a medium dense soil bed. A similar approach has been adopted and is described in more detail by Sharif et al. (2021).

## 2.1 Pile model

Figure 1 shows the two pile models, here simulated using rigid wall elements. Both the single and two helix pile models were designed and tested in previous studies (Davidson et al. 2022, Cerfontaine et al., 2021a), but the latter was never used for over-flighting installation. The two-helix pile has a similar geometry as the single-helix pile except with an additional helix of the same diameter at a vertical space $S = 2D_h$.

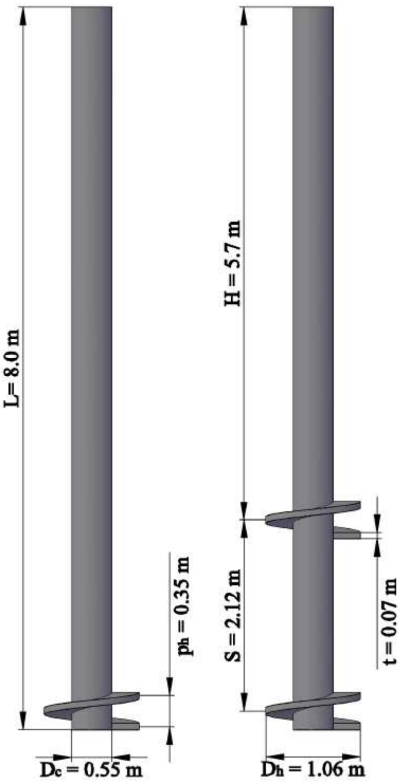


*Figure 1. Screw piles simulated (prototype dimensions shown, after Davidson et al. ,2022)*

## 2.2 Soil bed preparation

The generation of the cylindrical soil bed followed the procedure proposed by Sharif et al. (2019a). The soil particle size distribution (PSD) and properties of the real sand HST95 sand (Lauder, 2010) were used as the starting point for the simulation. Table 1 lists the physical properties of the sand and the numerical parameters adopted based upon previous element test calibration (Sharif et al., 2019a). As shown in Figure 2, the particle refinement method (PRM) (McDowell et al., 2012)), in which particle size scaling factor (SF) increased radially in each subzone by 1.4, was employed to decrease the particle number (and computational cost). The particle size SF in the central zone was 20 leading to $D_s/d_{50}$ (where $d_{50}$ is the mean particle diameter) being equal to 3.9 and the effective helix width ($w_h = (D_h - D_s)/d_{50}$) (Schiavon et al., 2019) being equal to 1.8. Sharif et al. (2021) and Cerfontaine et al. (2021b) suggested similar particle scaling as it is capable of representing the interaction between HST95 sand (Sharif et al., 2019a) and the adopted screw pile models (Sharif, Y., et al., 2019b).. This has been demonstrated to be appropriate by comparison with installation and monotonic loading using centrifuge testing in HST95 sand. The further adoption of smaller particles would lead to unmanageable particle numbers and prohibitive computational demands for the current study and this has been shown to be unnecessary. The width or diameter of the central scaled zone was $3D_h$ (3.5 m for simplification) to allow a sufficient space for the penetrating object and the transfer of force from the pile through the various scaled zones. The radius and depth of the soil bed was $12D_h$ (12.5 m) and $2.5L$ (20 m) to avoid boundary effects.

For better soil bed homogeneity and less soil bed generation time, the periodic cell replication method (PCRM) (Ciantia et al., 2018) was used to create the whole soil bed from a representative elementary volume (REV). The initial REV was also a cylinder with the same radius as the final soil bed but with height of 4.25 m (3.5 times of diameter of the largest particle), which was replicated seven times to build the final soil bed.

The global porosity of the final soil bed was 0.38, which corresponds to medium-dense (relative density $D_r$ = 55%) HST95 sand.

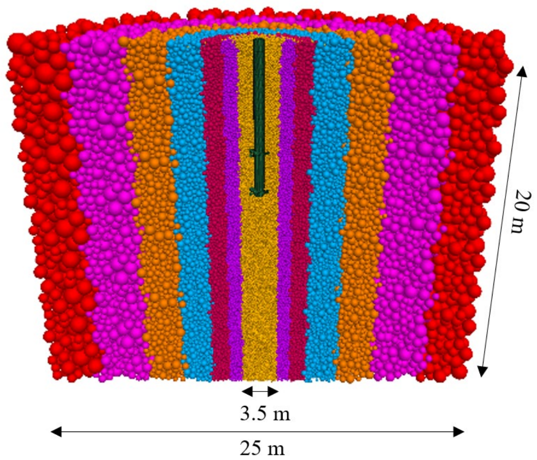


*Figure 2. Half soil bed with the two-helix screw pile installed (colour of particles indicates the regions of different particle scale)*

## 2.3 Contact model

Both particle-particle and pile-particle contacts were modelled using modified Hertz-Mindlin model (Itasca, 2021). Table 1 lists the contact parameters used. Particle-particle contact parameters were calibrated against element tests on HST95 sand. Rotation of the spherical particles was inhibited to capture the rolling resistance of granular sand grains. The particle-pile friction coefficient was assumed to be identical to steel-soil friction coefficient.

## 2.4 Pile installation

Pile installation was undertaken in line with the guidance of previous studies (Cerfontaine et al., 2021b, Ciantia et al., 2019). To limit computational demands, installation speed of the screw piles should be upscaled with inertial effects being checked.

Sharif et al. (2021) assumed widths of the plastic deformation zone for vertical and rotational velocities to be $3D_s$ and $4D_h$, and introduced Equation 2 to estimate allowable maximum vertical velocity for quasi-static installation.

$$v_{z,max} = \min(4p_h AR, 3D_s)\frac{I_{max}}{d_{50}}\sqrt{\frac{p_0^{'}}{\rho_s}} \quad (2)$$

where $p_h$ is the helix pitch, $D_s$ the shaft diameter, $I_{max}$ is the maximum inertial number and assumed to be 0.01 since further reduction of the limit has been shown to have little effect on the results  but would significantly increase computational demands (da Cruz et al., 2005, Cerfontaine et al., 2021b, Sharif et al., 2021), $d_{50}$ the mean particle diameter, $\rho_s$ the particle density and $p_0^{'}$ average confining stress which increases with depth. As $p_0^{'}$ increases with depth, $v_{z,max}$ can also increase with depth.

## 2.5 Loading tests

Monotonic constant rate penetration/uplift tests on the screw pile, vertically displacing to 0.2 $D_h$ at a constant velocity of 0.1 m/s, were undertaken to determine the axial tensile and compressive response after the installation.

*Table 1. Properties of the HST95 sand (after Lauder, K., 2010) and DEM parameters (after Sharif et al., 2021)*

| Sand properties [unit] | Symbol | Value |
|---|---|---|
| **Minimum void ratio [-]** | $e_{min}$ | 0.467 |
| **Maximum void ratio [-]** | $e_{max}$ | 0.769 |
| **Critical state friction angle [°]** | $\phi_{cs}$ | 32 |
| **Sand-steel friction coefficient [°]** | $\mu_{pile}$ | 0.445 |
| **Particle dimension [mm]** | $d_{50}$ | 0.141 |
| **Particle dimension [mm]** | $d_{100}$ | 0.213 |
| **Particle density [kg/m³]** | $\rho_s$ | 2650 |
| **DEM properties [unit]** | | |
| **Particle shear modulus [GPa]** | G | 3 |
| **Particle Poison's ratio [-]** | $\nu$ | 0.3 |
| **Particle friction coefficient [-]** | $\mu$ | 0.264 |
| **Wall friction coefficient [-]** | $\mu_{pile}$ | 0. 445 |

# 3 RESULTS

## 3.1 Installation requirements

Figure 3 and Figure 4 show the installation requirements on the pile head simulated in the DEM. For comparison, results of centrifuge experiments of the single-helix pile conducted by Cerfontaine et al. (2021a) are also presented.

### 3.1.1 Vertical force

It is shown in Figure 3 that, despite the DEM overestimates the vertical force of the single-helix pile installed at the both ARs, generally good approximation of the behaviour due to over-flighting can be seen, which significantly reduces the required vertical force during installation and even changes the force from compression to tension.

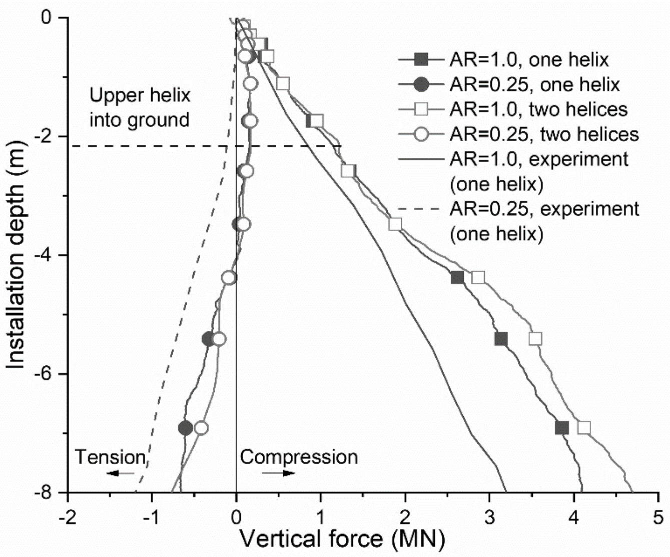


*Figure 3. Installation vertical force required at the pile head for single-helix and two-helix screw piles installed at various advancement ratios*

The results suggest that the additional upper helix increases vertical compressive force for both pitch-matched and over-flighting installation. During pitch-matched installation, the two-helix pile starts to require a higher (16% at the end of installation) vertical force than the single-helix pile at a depth of 3.5 m (embedment depth of upper helix is 2.4 m or 2.3 $D_h$). When AR reduces to 0.25, the difference of required installation crowd force is less obvious. After the upper helix penetrates into ground to a depth more than 4.5 m (4.2 $D_h$), the single-helix pile shows a slightly larger tensile installation force than the two-helix one.

### 3.1.2 Torque

Figure 4 presents required installation torque on the pile head. In terms of the single-helix pile, the torque predicted by DEM matches well with the centrifuge results for AR=1.0. For AR = 0.25, the DEM underestimates the torque but the non-linear depth dependence, which is in contrast with the linear depth dependence for AR = 1.0, is well captured.

Similar to the vertical force, the additional upper helix leads to a visible increase in torque for AR = 1.0 (38% at the end of installation), which occurs earlier than that of vertical force (3.5 m) at a depth of 3.0 m. Also consistent with the vertical force, the installation torque difference for AR = 0.25 is less obvious and occurs later (at a depth of 4.5 m) than that for AR = 1.0 (3.0 m).

However, the two-helix screw pile requires a lower torque than the single-helix one, which is in contrast with vertical force where the two-helix pile requires a higher value.

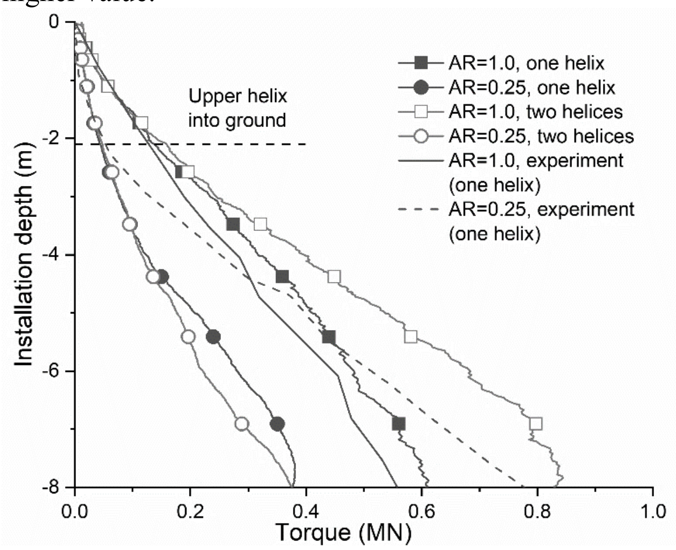


*Figure 4. Installation torque required at the pile head for single-helix and two-helix screw piles installed at various advancement ratios*

### 3.1.3 Summary

No matter what the helix number, over-flighting during installation can significantly reduce the requirements of vertical force and torque. But the helix number effects vary with AR.

For pitch-matched installation, the additional upper helix results in higher requirements of both vertical force and torque for installation. However, for AR = 0.25 (over-flighting), the additional helix slightly reduces torque required and the tensile force generated on the pile (or more likely need compressive force for installation)

In addition, the effects of the additional helix on installation requirements are more pronounced with increasing AR and the effects of helix number on torque is more significant than the effects on vertical force.

## 3.2 In-service performance

It has been reported that over-flighting can also improve uplift capacity/stiffness of screw piles at expense of compressive capacity for a single-helix screw pile (Sharif et al., 2021). This section explores monotonic uplift and compression behaviour of the two-helix screw pile, compared to the single-helix one.

### 3.2.1 Monotonic uplift performance

Figure 5 presents monotonic uplift performance of the piles. Defining capacity as resistance at pile vertical displacement of $0.1D_h$, the additional helix increases uplift capacity of the pitch-matched pile by 8.4% (from 3.33 to 3.61 MN). This is consistent with the centrifuge test by Davidson et al. (2022), where an increase of uplift capacity of 4% is seen. However, in terms of the over-flighted piles, the two-helix screw pile shows a 12.8% (4.31 to 3.76 MN) lower uplift capacity than the single-helix screw pile.

In addition, as opposed to the significant increase of uplift capacity of the single-helix screw pile due to reducing AR from 1.0 to 0.25, Figure 5 shows similar resistance-displacement relationships between AR = 1.0 two-helix and AR = 0.25 two-helix. This suggests geometry dependence of over-flighting improvements on uplift capacity of screw piles.

### 3.2.2 Monotonic compression performance

Figure 6 shows that, for AR = 1.0, the additional helix improves compressive capacity of the screw pile (by 25%, from 8.7 to 11.0 MN), which is much more significant than the improvements of uplift capacity (8.4%, Figure 5). This observation can be also seen in centrifuge tests by Davidson et al. (2022).

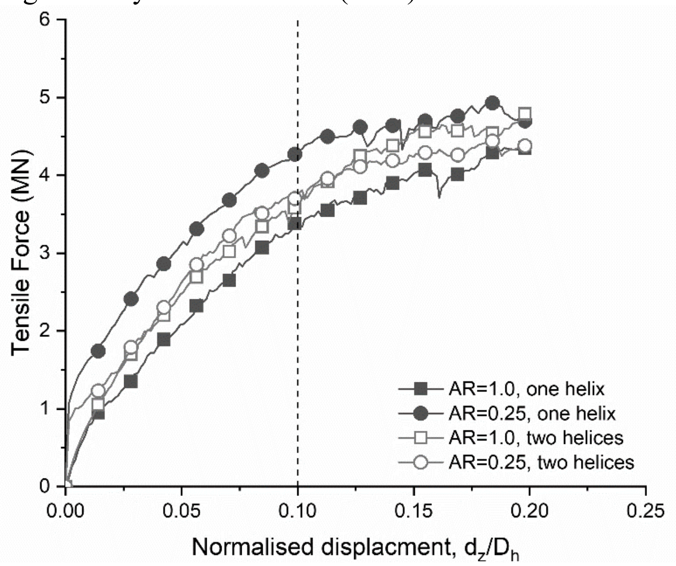


*Figure 5. Monotonic uplift test results for single-helix and two-helix screw piles installed at various advancement ratios*

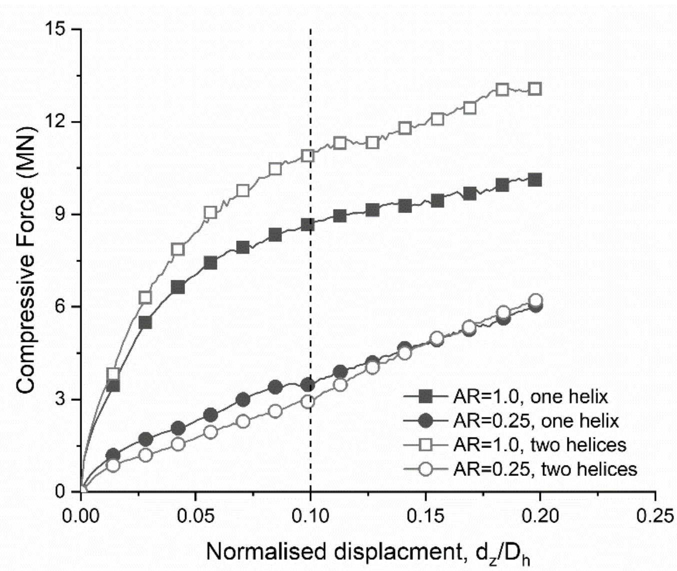


*Figure 6. Monotonic compression test results for single-helix and two-helix screw piles installed at various advancement ratios*

In terms of compressive performance of the over-flighted screw piles, Figure 6 shows no significant difference induced by helix number.

#### *3.2.3 Summary*

It is possible to increase uplift capacity/stiffness of the single-helix screw pile at expense of compressive capacity/stiffness by reducing installation AR. However, for the two-helix screw pile, reducing AR can worsen compressive performance with no improvement of tensile performance seen.

The effects of helix number also vary with installation AR. When AR = 1.0, tensile capacity slightly increases due to the additional helix. The compressive capacity increasing by a greater proportion. For AR = 0.25, the additional helix, makes no significant difference to compressive performance and can worsen tensile performance of the screw pile.

In summary, increasing the helix number at the investigated spacing may not improve the pile in-service performance and over-flighting a single-helix pile appears to be a potentially optimal solution for improved uplift performance. Increasing helix number could be effective to improve compressive performance of a pitch-matched screw pile, although the installation requirements may be a concern.

### *3.3 Post-installation stress field*

Installation requirements and post-installation in-service performance can be related to variation of stress field around the piles.

Consistent with Sharif et al. (2021), Figures 7(a) and 7(b) show that, for the single-helix screw pile, reducing installation AR can decrease vertical stress beneath the helix and pile tip, which results in less compressive resistance and consequent reduction of installation vertical force (Figure 3) and in-service compressive stiffness/capacity (Figure 6). However, the higher vertical stress locked above the helix due to over-flighting improves the uplift performance of the pile (Figure 5).

For AR = 1.0, when assessing the vertical stress field around the two-helix pile (Figure 7c), no visible difference is seen around the lower helix from the single-helix case (Figure 7c). This leads to no loss in both tensile and compressive resistance of the lower helix. As a result, combined with the additional resistance on upper helix, the two-helix pile has better tensile and compressive performance than the single-helix pile.

Comparing two-helix, AR = 0.25 to single-helix (Figure 7d), AR = 0.25 (Figure 7b), it suggests that adding an additional helix at this spacing ratio can significantly decrease the vertical stress between the two helices and the high stress that is locked-in above the lower helix for the single-helix case partially shifts to above the upper helix. However, the increase in normal stress on the upper helix is lower than the reduction of normal stress on the lower helix. Therefore, less tensile force is generated on the two-helix pile during installation (Figure 3), and this pile has worse uplift performance (Figure 5). Like AR = 1.0, increasing helix number for AR = 0.25 does not change the vertical stress below the lower helix (or pile base). Combined with zero stress below upper helix, which means no compressive resistance at a limited displacement, similar compressive performance between single-helix and two-helix piles installed at AR = 0.25 is seen. Finally, the reduction of total vertical force (stress) on the helix decreases shear resistance of helix when the helix penetrates during installation, which consequently reduces installation torque as shown in Figure 4 (Cerfontaine et al., 2021b).

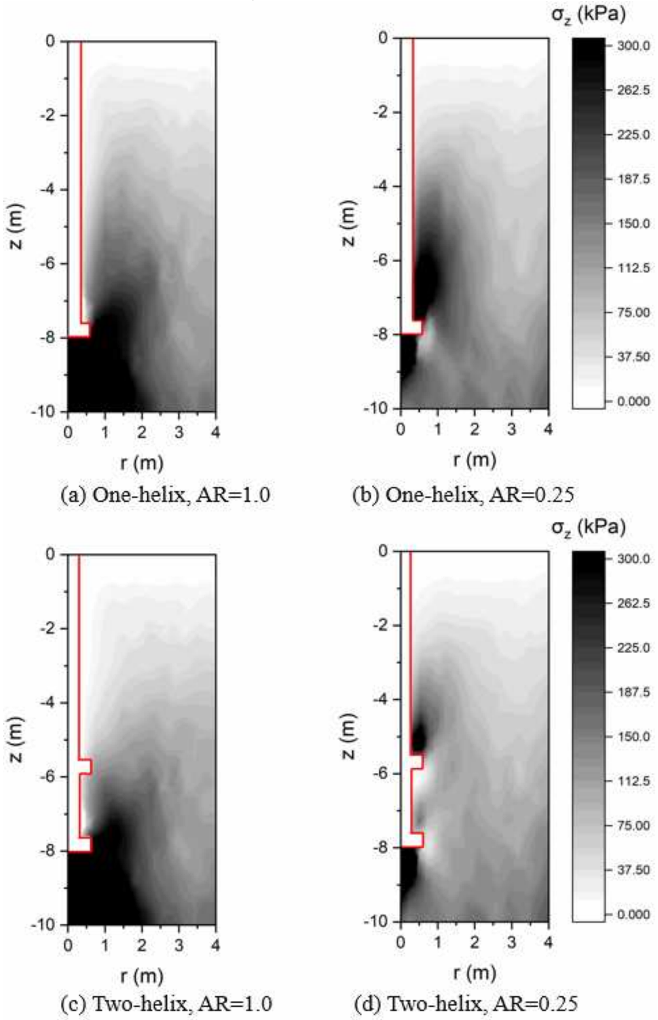


*Figure 7. Vertical stress contour post-installation: (a) one-helix, AR=1.0; (b) one-helix, AR=0.25; (c) two-helix, AR=1.0; (b) two-helix, AR=0.25*

## 4 CONCLUSIONS

By using DEM simulation, this paper compares installation requirements and in-service performance of a single-helix screw pile and a two-helix screw pile installed using pitch-matched and over-flighting approaches. It is shown that the effects of an additional helix on installation requirements and in-service behaviour of screw pile varies with installation advancement ratio (AR).

For the pitch-matched installation (AR = 1.0), no significant difference is seen between the post-installation vertical stress fields around the one-helix and two-helix screw piles. Therefore the additional resistance on the upper helix of the two-helix pile results in greater vertical force and torque required for installation and better in-service performance than the single-helix pile.

When reducing AR to 0.25 i.e. adopting over-flighting, the introduction of the upper helix can significantly decrease the vertical stress between the two helices, although the vertical stress above the upper helix moderately increases. This leads to less tensile vertical force and torque for installation and worse post-installation uplift performance. Therefore, over-flighting during installation may need to be carefully considered for multi-helix screw piles.

Based upon this limited investigation, over-flighted single-helix offshore screw piles appear to be the best design for objects carrying tensile loads (e.g. anchoring for floating wind) due to the low installation requirements and optimised uplift performance. However, this conclusion is only for the geometry tested and may not be indicative when the geometries are changed.

## 5 ACKNOWLEDGEMENTS

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