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DEM simulation of cyclic tests on an offshore screw pile for floating wind

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Abstract

Screw piles need to be upscaled for offshore use e.g. being an alternative foundation and anchor form for offshore floating wind turbines, although the high demand of vertical installation forces could prevent its application if conventional pitch-matched installation is used. Recent studies, using numerical and centrifuge physical tests, indicated that the vertical installation force can be reduced by adopting over-flighting which also improved axial uplift capacity of the screw pile. The current study extends the scope to axial cyclic performance with respect to the installation approach. Using quasi-static discrete element method (DEM) simulation it was found that the over-flighted screw pile showed a lower displacement accumulation rate, compared to a pitch-matched installed pile, in terms of load-controlled cyclic tests. Sensitivity analysis of the setup of the cyclic loading servo shows the maximum velocity during the tests should be limited to avoid significant exaggeration of the pile displacement accumulation but this may lead to very high run durations.

1. Introduction

Screw piles, which are usually installed by applying a torque with additional vertical crowed (vertical or push-in) force to the top of the pile, are steel piles that consist of a straight shaft or core with one or more helices welded to the core. The ratio of the vertical penetration per rotation Δ_z to the helix pitch p_h, is referred to as the advancement ratio (AR) (Bradshaw et al., 2019), and is used to describe the installation of screw piles:

$$AR = \frac{\Delta_z}{p_h} \tag{1}$$

BS8004 (British Standards Institution, 2015) recommends that a pitch-matched installation (AR=1) should be employed with a tolerance of ± 0.15 to minimize the ‘disturbance’ of in-situ soil.

Recently this pile form has been considered as an alternative solution for offshore renewable energy development in deeper water due to silent installation. The upscaling of pile geometry which aims to carry significant loading in the offshore environment, however, raises concerns in terms of practical challenges. For example, can current installation vessels provide the very large reaction force required for installation of large diameter offshore screw piles if conventional pitch-matched installation is used (Davidson et al., 2021)?

More recent studies using centrifuge physical modelling (Cerfontaine et al., 2021) and numerical simulation (Sharif et al., 2021) showed that by reducing AR the installation crowd force could be significantly reduced with limited influence on the installation torque. This was because soil particles moved upward through the helix during the over-flighting installation (AR<1.0) and generated downward reaction force on the helix. The particle movement pattern during the over-flighting installation also resulted in a zone above the helix with higher density and residual stress in comparison to the pitch-matched installation, therefore improving pile monotonic axial uplift capacity (Cerfontaine et al., 2021, Sharif et al., 2021).

Although monotonic behaviour has been studied in some detail, cyclic performance has seen less detailed consideration, particularly with respect to the influence of installation approaches. Offshore piles may be exposed to millions of cycles of loading induced by wind and waves during their lifetime, so assessing how the pile stiffness and capacity vary and how the permanent displacement accumulate with cycling could be a key design factor. Some limited insights have been given into cyclic uplift performance of conventional onshore screw piles installed under pitch-matched conditions, but the influence of upscaling of geometries and that of over-flighting installation are still unknown.

The discrete element method (DEM) has been used to investigate installation and monotonic capacity of both conventional straight shafted piles and screw piles. Ciantia (2021) extended application of the DEM to cyclic performance of straight shafted piles. In this study, DEM simulation of cyclic uplift tests of a screw pile installed by pitch-matched and over-flight approaches was carried out. Discussion is also included on the challenges overcome when setting up of the force-controlled servo for cyclic loading.

2. Numerical setup

Commercial software package PFC3D 6.0 (Itasca, 2021) was used in this work to build a virtual centrifuge experiment platform where a screw pile was installed and then tested in a medium dense soil bed (D_r=52%). The pile geometries, listed in Table *1***Error! Reference source not found.**, and the test gravity conditions (50g) were in line with previous centrifuge experiments (Cerfontaine et al., 2021, Davidson et al., 2021).

The soil bed had a 0.25 m radius and was 0.4 m height and the soil particle size distribution (PSD) of HST95 sand (Lauder, 2010) was used. The interactions between individual particles and between the particle and wall representing the pile surface were modelled using a simplified Hertz-Mindlin contact model (Itasca, 2021). Spherical particles were used with the rotation of the particles inhibited to capture the rotational resistance of angular grains. The contact parameters used in this study were calibrated based on triaxial tests and pile penetration tests by Sharif et al. (2019) and are listed in Table 1.

Table 1 Hertz-Mindlin contact model parameters for HST95 sand (Sharif et al., 2019)

Parameter	Units	Value
Shear modulus, G	GPa	3
Friction coefficient, μ	-	0.264
Poisson's ratio, ν	-	0.3
Interface friction coefficient of pile μ_p	-	0.445

To achieve a manageable number of particles in the soil bed and to enhance the efficiency of soil bed generation, a combination of the periodic cell replication method (Ciantia et al., 2018) and the particle refinement method (McDowell et al., 2012) was used following Sharif et al. (2019). A particle size scaling factor (SF) of 20 was used in the central zone with an increase of 1.4 for each subsequent radial zone. A more detailed description of the formation process of the soil bed can be found in Sharif et al. (2019). The number of particles in the final soil bed was 320,000.

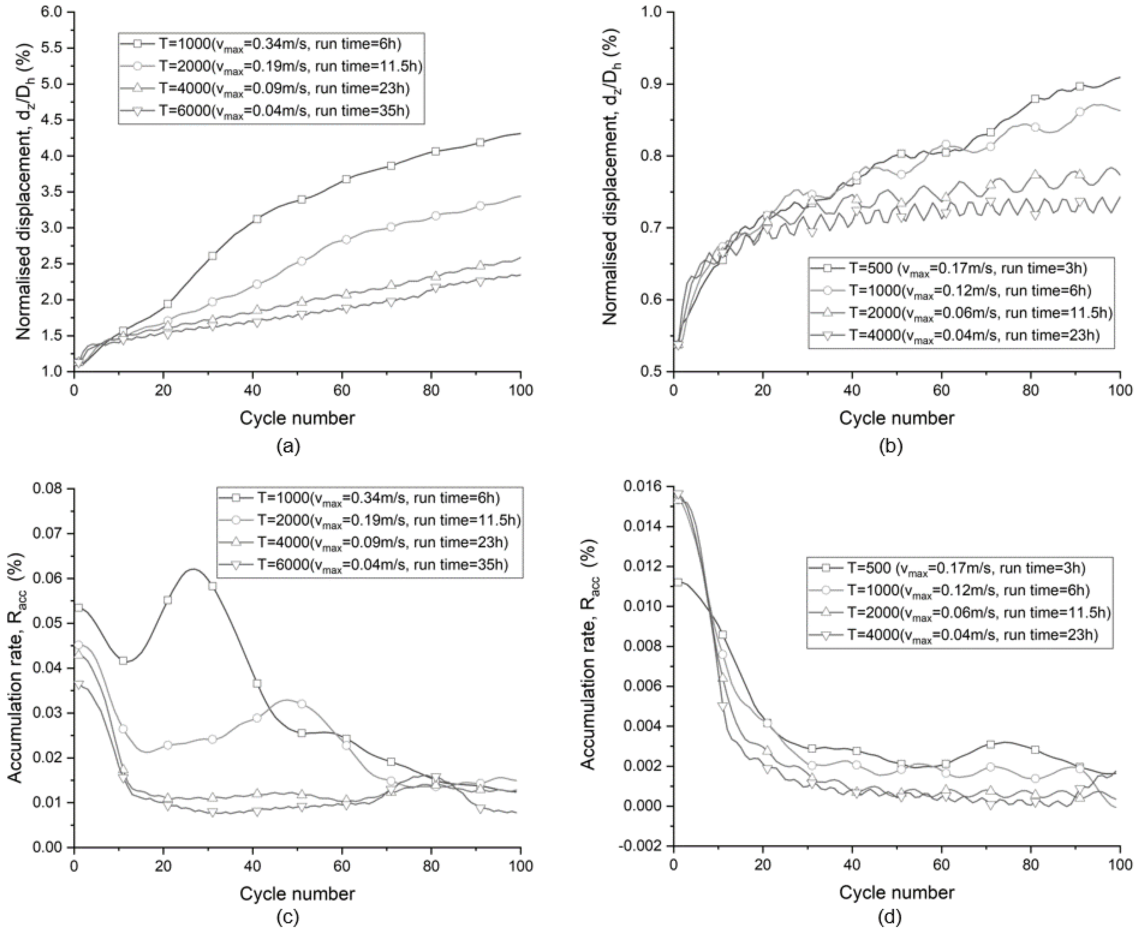
The pile was installed at AR=1.0 and 0.5 under quasi-static conditions (Sharif et al., 2021) before the vertical force on the pile top was unloaded by slowly uplifting the pile. Using a computing platform with Intel® Xeon® CPU i9-10940X @4.1GHz, 32GB RAM and 64-bit operating system, the simulation time for installation at AR=1.0 and 0.5 were 79 hours and 158 hours, respectively. After unloading, force-controlled cyclic tests were performance on the pile. To achieve the force-controlled cyclic loading tests, a servo function proposed by Ciantia (2021) was used:

$$F = F_{mean} + F_{cyclic}(2\pi t/T) \tag{2}$$

where F_{mean} is the mean axial load, F_{cyclic} is the cyclic load amplitude and T is the period of the cyclic load. In this study, period T was the number of PFC calculation steps composing a load cycle. To ensure the quasi-static conditions, sensitivity analysis of T was carried out in association with F_{mean}=F_{cyclic}=375 kN.

3. Results

Figure 1 shows the permanent normalised displacement d_z/D_h and the accumulation rate of d_z/D_h (R_{acc}) versus cycle number. It is clear that the increase of period *T* aggravated the cyclic loading induced permanent axial displacement accumulation. After 100 cycles, the pitch-matched (AR=1.0) pile presented accumulated normalised displacement of 4.3% and 2.3% with *T* = 1000 and 6000, respectively (Figure 1a). In terms of the over-flighted pile, *T* = 500 led to an accumulated displacement of 0.91% at 100th cycle, which is higher than that of *T* = 4000 at 0.74%, as shown in Figure 1b. Figure 1c and 1d shows that the accumulation rate of the normalised displacement R_{acc} generally decreased with cycle number in two phases. The first phase includes the first t 20 cycles where R_{acc} reduced rapidly. In the second phase, R_{acc} was relatively stable although some noise can be seen in AR=1.0 (*T*=1000 and 2000). Although being influenced by *T*, the initial and plateau displacement accumulation rates of the over-flighted pile was much lower than those of the pitch-matched pile. It can be concluded that the over-flighting induced improvement on uplift performance can remain when the pile is subject to cyclic loading.



(a) (b)
(c) (d)

Figure 1: Effect of period *T* on displacement accumulation: (a) permanent normalised displacement (AR=1.0); (b) permanent normalised displacement (AR=0.5); (c) normalised displacement accumulation rate (AR=1.0); (d) normalised displacement accumulation rate (AR=0.5)

The velocity of pile movement was recorded during the cyclic tests. The average maximum velocity (model scale) and the run time (real time) of each test were also noted in legends of Figure 1. The pitch-matched pile had a higher maximum velocity than the over-flighted pile with a same period T because of its lower axial uplift stiffness (Sharif et al., 2021). Decreasing the velocity by increasing T could significantly moderate the displacement accumulation when the maximum velocity v_{max} was beyond 0.1 m/s. From this viewpoint, v_{max} should be limited to lower than 0.1 m/s to avoid exaggeration of displacement accumulation. However, the run time increases linearly with *T*. If adopting $T = 4000$ for AR=1.0 to ensure a v_{max} below 0.1 m/s, 23 hours are needed to complete 100 loading cycles. To determine the cyclic stability of pile, 1000 cycles may be needed as suggested by (Jardine and Standing, 2012), which will lead to a run duration of 230 hours. Thus, a balance between efficiency and accuracy should be considered carefully with respect to adopting period T for the force-controlled servo.

4. Conclusion

In this study, virtual centrifuge cyclic loading tests using DEM with well calibrated contact parameters were performed on an offshore screw pile which was installed using pitch-matched and over-flighting methods. It was shown that over-flighting installation benefited cyclic performance of the screw piles resulting in a lower displacement accumulation rate compared to that of the pitch-matched one. The value of cyclic period used in the loading servo should be considered carefully because limiting the maximum velocity in the test to lower than 0.1 m/s by adopting a large cyclic period can avoid overestimation of displacement accumulation but significantly increases simulation time.

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