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FINITE ELEMENT MODELLING OF THE UPLIFT BEHAVIOUR OF SCREW PILES IN SAND

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SUMMARY: In this paper a simplified procedure to incorporate some installations effects into the numerical finite element modelling of screw pile uplift is presented. The procedure consists of the approximation of the installation phase through 1) the application of a compression loading corresponding to successive embedment depths, 2) the use of modified soil properties over a disturbed zone. Pre-defined failure mechanisms are added to introduce some weakened zones due to either soil disturbance or strain-localisation. The results of numerical simulations are compared to a centrifuge test undertaken at the University of Dundee. The simulation considering an inclined failure mechanism and the simulated installation better captures the uplift capacity and initial stiffness.

INTRODUCTION

Screw piles have three main advantages that make them particularly suitable for offshore anchoring and foundations[1]. The environmental disturbance generated during their installation, that can be damaging for marine mammals (noise, vibrations), is limited as the pile is screwed into the soil during its installation. A significant uplift capacity can be mobilised as the helix acts as an embedded plate. Finally, they can be easily removed from the soil by applying the reverse procedure, restoring the seabed back to its initial conditions.

The uplift capacity is a critical feature for several offshore applications, such as floating wind turbines[2] or jacket foundations[3]. The prediction of the screw pile uplift capacity is largely based on criteria developed for plate anchors[4]. However, these methods do not incorporate any installation effects, while recent studies have shown that the installation can modify the failure mechanism[5,6] and reduce the uplift capacity.

The deployment of offshore screw piles will necessitate a significant upscaling of the onshore typical designs and the applicability of relatively small-scale based methods to large geometries is unknown. Finite element modelling is a relatively simple tool to simulate a large number of configurations but does not allow the modelling of the entire installation process. This would require more advanced numerical methods such as MPM[7] or DEM[8], which are computationally intensive and require specialised expertise, not always available.

The objective of this paper is to develop a simplified methodology to incorporate some installation effects into the finite element modelling of screw piles. The installation effects of two different possible failure mechanisms (cylindrical[9] or conical[3]) are assessed and numerical results are compared with experiments undertaken in the centrifuge at the University of Dundee[3].

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INSTALLATION DISTURBANCE

The installation of piles inherently generates some disturbance, as the piles replace the soil previously in place. The soil disturbance consists of a change of the soil structure (e.g. density, anisotropy) and/or a change of the stress field around the pile. This disturbance results from the combination of several physical phenomena, as reported in Figure 1. Their relative importance and magnitude strongly depend on the installation method (e.g. following a true helical movement -pitch-matched- or not), but also on the geometry of the pile (e.g. helix and shaft diameters).

The crowd force applied to install the pile influences the soil far below the pile tip, generating settlement and increasing the vertical stress, as illustrated in Figure 1(a)(1). When the pile tip reaches a given depth, it creates some cavity expansion[8] and moves the soil laterally, increasing vertical and lateral stress, as shown in Figure 1(a)(2) and demonstrated through DEM simulations11. Afterwards, the soil particles are moved upwards, downwards or remain at the same depth, depending on the helix pitch, as described in Figure 1(a)(3), loosening the soil just above the helix. Finally, some cavity expansion occurs, decreasing the lateral and vertical stress fields after the helix movement. Some relative displacement between the helix and the soil particles holds, due to the soil shearing, as represented in Figure 1(a)(4).

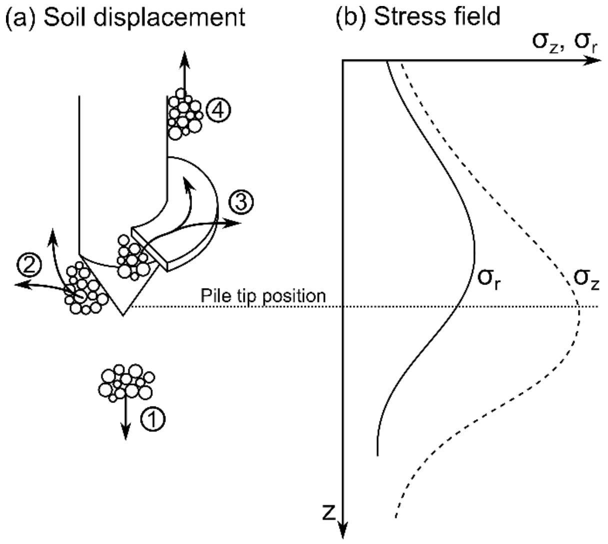

Figure 1: Idealisation of the disturbance induced by the screw pile installation on the (a) soil displacement and (b) vertical σ_v or radial σ_r stress field around the pile

The physical and strength properties of the soil disturbed due to the installation process are likely to affect the behaviour of the pile, while loaded. The tensile capacity of the pile is expected to be the more affected, as all density disturbance is located above the helix. While the tensile failure mechanism is usually assumed to be a conical soil wedge[8], a highly disturbed cylindrical volume of soil located above the helix has been observed by Schiavon et al.[8] and it was assumed failure occurred along a cylindrical failure surface. In the following both failure mechanisms are investigated, and results are compared to a centrifuge test.

NUMERICAL PROCEDURE

A numerical procedure has been recently proposed[11] to incorporate some simplified installation effect into the finite element simulation of screw pile uplift behaviour in sand. It has been compared against centrifuge tests and was shown to provide results consistent with centrifuge test results. The original two-stage procedure is illustrated in Figure 2 and only incorporates a stress field disturbance, i.e. there is no significant modification of porosity or soil strength.

The first stage of the procedure (Figure 2(a)) consists in identifying the failure mechanism of the considered screw pile assumed wished-in-place in an undisturbed soil. The magnitude of the shear strain along the failure mechanism is also inspected. It could be expected that some strain-softening should take place at large shear strain (above a given threshold), although the HSsmall model used does not simulate it.

In the second stage, interface elements are defined along the position of the observed failure mechanism (Figure 2(b)). The constitutive law assigned to these interface elements allows a reduction of the shear strength along a ‘softening zone’, close to the edge of the pile, where the shear strain is beyond a given threshold. The length of this softening zone was set up to two helix diameters D_h. The stress field is modified by considering the crowd force applied during installation (Figure 2(c)). Five successive steps representative of increasing penetration depth H are simulated. The plate elements corresponding to the pile geometry at a given depth are activated and the corresponding crowd force is applied, then reduced to zero.

The procedure can be extended easily to incorporate a cylindrical failure mechanism, as shown in Figure 2(b). In this case, interface elements are defined vertically. The properties of this interface as well as the disturbed volume of soil enclosed are defined to be at critical state, to be consistent with a large soil disturbance.

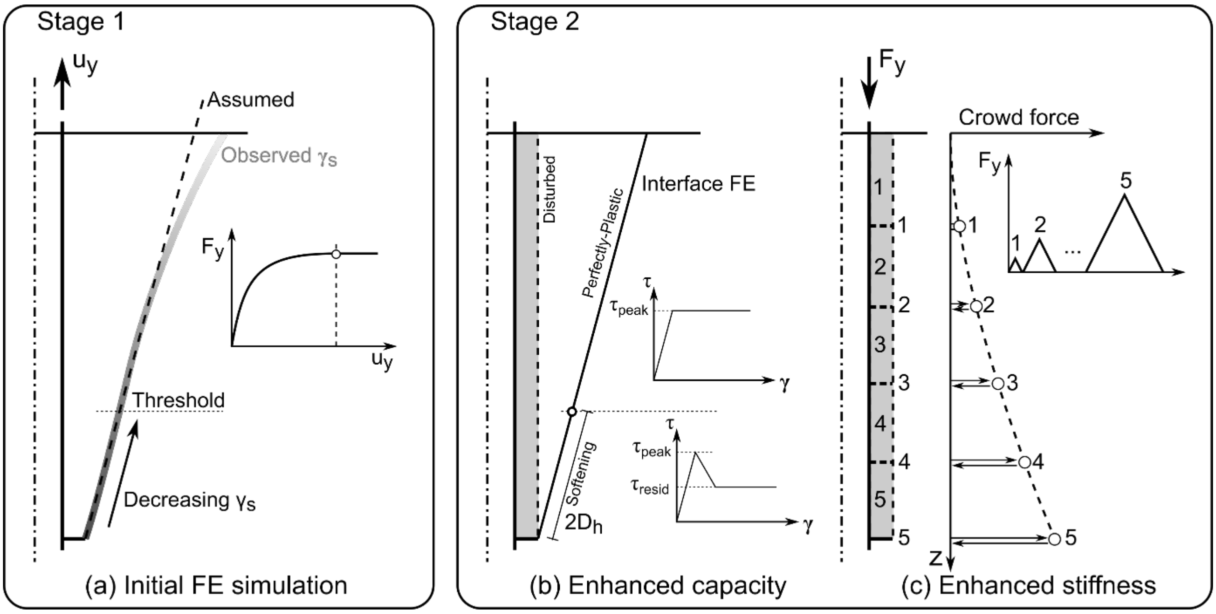

Figure 2: Summary of the two-stage procedure for the simulation of the uplift capacity of screw piles, incorporating a simplified modelling of the installation effects.

RESULTS AND DISCUSSION

The example simulated in the following consists of a screw pile embedded in saturated dense sand ($D_r \approx 84\%$) at the relative embedment ratio H/D_h equal to 5.9. The main soil parameters are given in Table 1 and more detailed information about the tests and simulations can be found in[11,12].

Table 1: HSsmall soil parameters of the HST95 sand, relative density (D_r), peak friction and dilatancy angles (ϕ_p, ψ_p), cohesion (c’), total unit weight (γ_{tot}), secant reference modulus (E^{50}_{ref}) and material parameter m.

Dr [%]	ϕ_p [°]	ψ_p [°]	c’ [kPa]	γ_{tot} [kN/m^3]	E_{50}^{ref} [MPa]	m [-]
84	45.8	17	1	20.3	51.5	0.52

Figure 3(a) compares experimental result (Centrifuge) to the simulation of a wished-in-place pile (No mechanism) or incorporating only a pre-defined failure mechanism (Cylindrical or Conical, stage 2(b)). The vertical uplift load F_y corresponding to the wished-in-place simulation overpredicts the centrifuge capacity, which was also observed for the other geometries considered in[11] at deeper embedment or in a medium-dense sand. Considering a conical pre-defined failure surface leads to a slight underestimation of the capacity, while the cylindrical surface grossly underpredicts the capacity. In all cases, the stiffness is not correctly captured.

Figure 3(b) compares centrifuge and numerical results after the full numerical procedure has been applied, namely a compression load has been applied at several depths. This case shows an improvement of the prediction for both cases (stiffness and capacity). However the conical mechanism is still the best approximation of the experimental results.

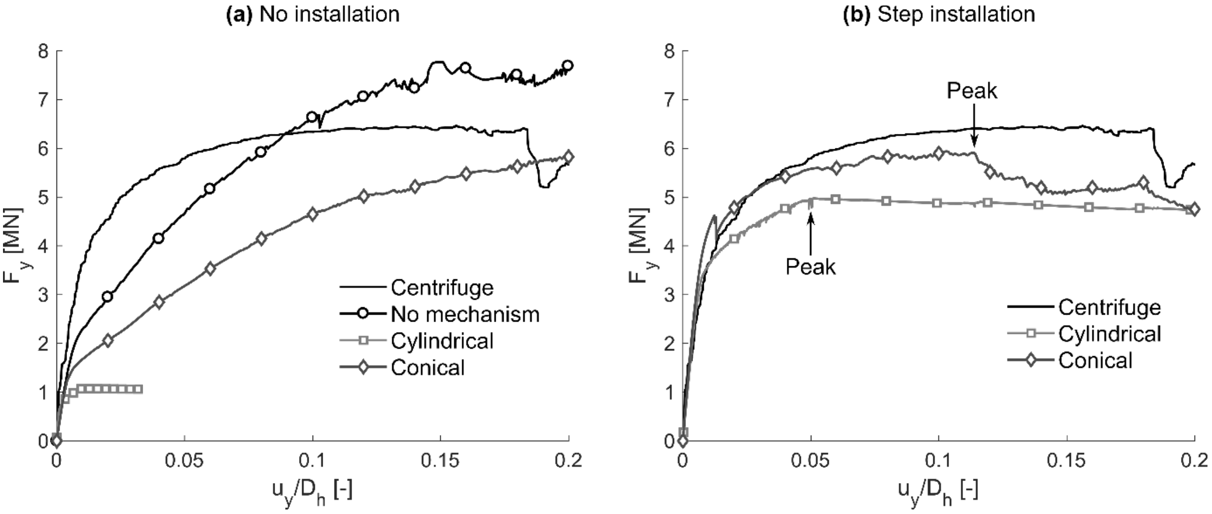

Figure 3: Comparison of centrifuge tests with uplift simulation of a shallow screw pile (H/Dh = 5.9) (a) Considering stage 1 simulation (no mechanism) or a pre-defined mechanism (cylindrical or conical); (b) Considering a pre-defined mechanism (cylindrical or conical) and installation effects

The vertical displacement u_y and plastic points corresponding to the maximum uplift force (peak in Figure 3) are depicted in Figure 4. This figure shows that the failure mechanisms active at the end of the simulation are the ones that were predefined (a wedge and a cylinder respectively), although the conical failure mechanism departs slightly from the linear pre-defined shape while approaching the surface. In addition, the displacement field clearly exhibits that the vertically moving soil is not monolithic, but a gradient of displacement exists due to the soil compressibility. This soil compressibility induces an increase in lateral stress which in turns enhances the maximum shear stress available along the failure mechanism (with respect to the initial stress distribution), as discussed in[13].

The step procedure used to simulate installation applies a compression force of increasing magnitude at different fixed depths. The volume of soil affected by this load is mainly located directly below the helix and extends laterally as a function of the load magnitude, i.e. it is greater at greater depth. The normal stress distribution along the pre-defined failure mechanism in Figure 5 illustrates how the stress distribution is affected after the installation and during uplifting (at peak uplift force).

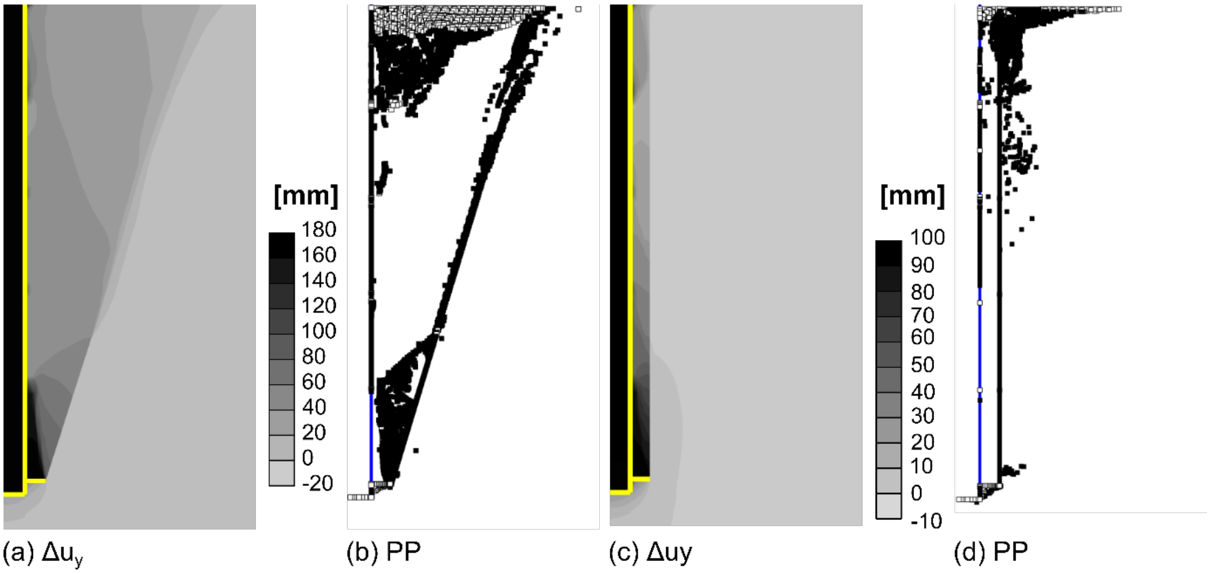

Figure 4: Comparison of vertical displacement Δu_y and plastic points PP for pre-defined (a-b) conical failure mechanism and (c-d) cylindrical failure mechanism. Results are given at peak, depicted by an arrow in Figure 3(b).

In all cases, the installation procedure increases the lateral stress along the location of the failure mechanism (even before the uplift starts), as shown in Figure 5(Initial). The conical failure mechanism continuously moves away from the shaft while approaching the soil surface, i.e. it moves away from the area where the stress magnitude was increased. On the contrary, the cylindrical failure mechanism is continuously located where the stress increase has been the greatest. Subsequently, the maximum shear stress that can be mobilised at failure increases and the enhanced capacity is fivefold the one which does not consider any installation.

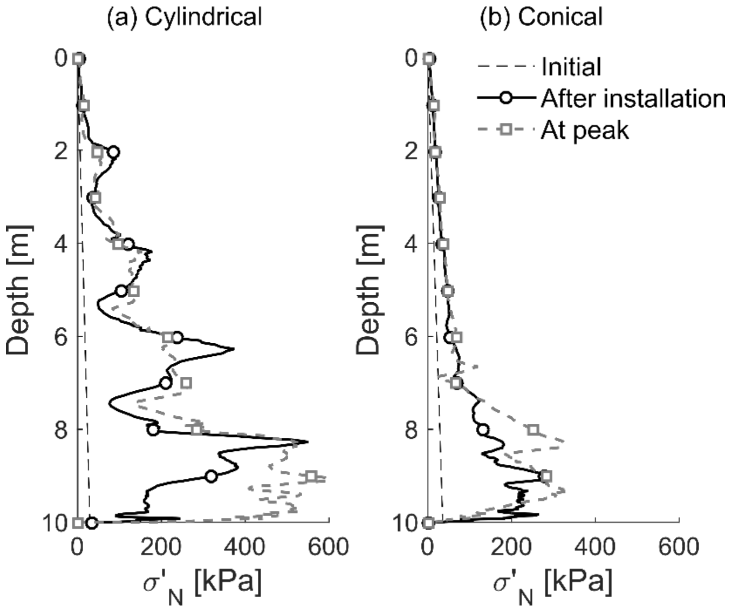

Figure 5: Normal stress distribution along the failure mechanism at different time steps in case along a pre-defined (a) cylindrical or (b) conical failure mechanism

CONCLUSION

Screw piles have been recognised as a promising technology for the foundations and anchoring of offshore and marine renewable energy devices. Experience and design method are available from onshore applications, but a significant upscaling is necessary for offshore applications. However, no standard simulation method is currently able to simulate the installation effects onto screw pile uplift behaviour.

The screw pile installation generates a disturbed zone around the anchor where the soil density is modified due to the penetration of the helix and the shaft. The stress field around the pile is also modified due to the cavity expansion generated by the shaft penetration and the relatively large crowd force applied during installation.

This paper introduces a simplified procedure to take into account some installations effects into the numerical simulation of screw pile uplift. The crowd force is applied in several steps, corresponding to successive screw pile depths. The soil properties corresponding to a disturbed zone are modified to introduce the helix disturbance. A pre-defined failure mechanism is finally added into the mesh to consider a weakened zone due to the helix disturbance (cylindrical mechanism) or strain localisation (conical mechanism).

Simulations considering a conical failure mechanism are shown to better predict the anchor uplift capacity, but also the initial stiffness, when compared to centrifuge tests.

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