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A 4D investigation of model pile installation

Une etude 4D de l'installation de pieux modeles

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ABSTRACT: Offshore wind turbines are typically fixed to the seabed via open-ended (OE) pile foundations. The risk and cost associated with OE pile installation may be reduced by performing field-scale tests to ensure adequate in-service capacity, as well as gain understanding of installation characteristics for equipment specification. However, to do so is often expensive and in most cases, highly impractical. Instead, 1*g* small-scale model tests can be used, in part, to study mechanistic behaviour which can aid in validating numerical methods which are capable of scaling to field conditions. In this paper, 1*g* pile model tests are undertaken in both sand and soft rock and the differing *in-situ* mechanisms are revealed through novel in-test X-ray techniques with time-resolve enabling a 4D study. The tests presented here are facilitated using a new compact multi-axis loading frame which is operable from within a CT bay.

RÉSUMÉ: Les éoliennes offshore sont généralement fixées au fond marin via des fondations sur pieux à extrémité ouverte (OE). Le risque et le coût associés à l'installation de pieux peuvent être réduits en effectuant des tests à l'échelle du terrain pour garantir une capacité en service adéquate, ainsi qu'en comprenant les caractéristiques d'installation pour les spécifications de l'équipement. Cependant, cela s'avère souvent coûteux et ce n'est pas pratique dans la plupart des cas. Au lieu de cela, les tests sur modèle 1*g* à petite échelle peuvent être utilisés, en partie, pour étudier le comportement mécaniste, ce qui peut aider à valider des méthodes numériques capables de s'adapter aux conditions de terrain. Dans cet article, des tests sur modèles de pieux de 1*g* sont entrepris à la fois dans le sable et dans la roche tendre et les différents mécanismes in situ sont révélés en raison de nouvelles techniques de rayons X en cours de test avec résolution temporelle permettant une étude 4D. Les tests présentés ici sont facilités à l'aide d'un nouveau bâti de chargement multi-axes compact qui peut être utilisé depuis une baie CT.

Keywords: Plugging; pile installation effects; MicroCT.

1 INTRODUCTION

Offshore structures are commonly fixed using open-ended (OE) pile foundations. These, which vary in diameter from less than 1 m to more than 8 m (Buckley et al., 2020), are designed to resist large environmental loads and to do so, require sufficient penetration defined by axial and lateral capacity requirements. Actual installation performance on site can vary, and risks such as pile run and conversely pile refusal can occur, leading to uncertain capacity. For small diameter piles, the risk of refusal is often associated with the occurrence of plugging, for which there is a greater tendency in small diameter piles due to ease of arching. This leads to an increased end bearing component as the plug forms (Fan et al., 2021) and can make reaching installation depth required for adequate lateral and axial capacity challenging. With the above in mind, novel small-scale model tests performed at 1*g* and paired with X-ray imaging are used here to investigate the occurrence of plugging on installation performance in sand and soft rock, the latter notorious for uncertainty in pile installation (Lord et al., 2002). These tests demonstrate how a blend of radiography and computed tomography (CT) can be used to track pile installation and fabric changes, offering new valuable insights which build on prior application of pile tracking through static CT (Doreau-Malioche et al., 2018). Carrying out live X-ray tomography during the installation is challenging and, in this instance, has been achieved by utilising a new multi-axis loading frame developed by Riccio et al. (2024) which is operable from within a CT bay, shown in *Figure 1*.

The tests reported in this study are not aimed to replicate real engineering application due to the limitations of the low-stress level and boundary effects. Rather, they focus on mechanistic, grain scale insight thanks to the micro level (µm) resolution of CT which may help ease the validation of new numerical simulation techniques, like those used to study pile installation in complex geomaterials (Ciantia, 2022).

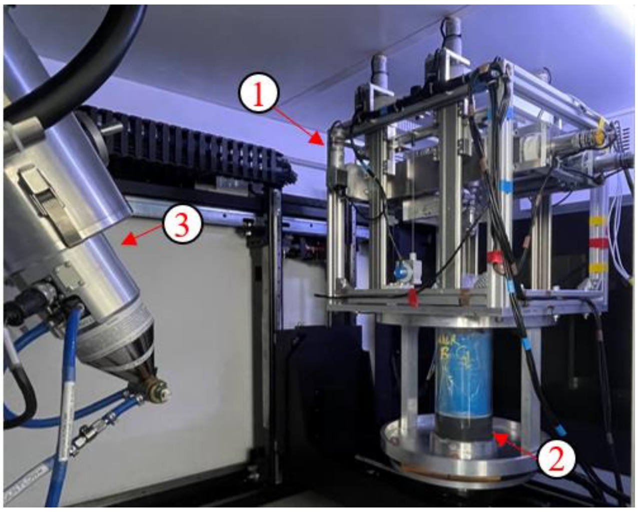

Figure 1. Multi-axis loading frame (1) with sample installed (2) positioned in lab-based X-ray CT scanner (3).

2 MATERIAL AND EXPERIMENT SET UP

2.1 Multi-axis actuator

The model tests were performed using a new multi-axis loading frame (*Figure 1*), which can apply up to 5 kN of vertical load and 400 N laterally. Actuation in the X, Y and Z plane was facilitated by DC motors controlled by a software based PID feedback which enabled both monotonic and cyclic displacement control (Riccio et al., 2024).

2.2 Sample material and preparation

Samples were prepared in a 300 mm tall acrylic chamber with a diameter of 120 mm which was fixed below the multi-axis actuator as shown in *Figure 1*. A well characterised dry sand (HST-95, see e.g., Lauder et al. (2013)) was used and pluviated from an automated hopper into the acrylic tube, achieving a relative density of $D_r = 80\ \%$. The soft rock sample ($\sigma_c < 2\ \text{MPa},\ d_{50} = 86\ \mu\text{m}$) consisted of a highly porous sedimentary calcarenite rock which is widely spread along mediterranean coasts and is present at several offshore wind farms (Ciantia et al., 2015; Palix & Lovera, 2020). The cored soft rock sample, 150 mm tall and with a diameter of 100 mm, was fully saturated, notable as its strength reduces with an increasing degree of saturation (Ciantia et al., 2015).

2.3 Experimental procedure

For the soft rock a model pile of diameter Ø11.65 mm and wall thickness of $t_w = 0.74$ mm was used and for the sand a Ø15.37 mm ($t_w = 0.86$ mm). The installation depth was 100 mm in both cases, with a rate of 0.03 mm/s for the calcarenite, in order to preserve fully-drained conditions; and 0.1 mm/s for the dry sand. Following installation, tension pulls were performed on the pile installed in soft rock. During all of the aforementioned stages, live radiography was used to monitor the installation procedure. The CT scan for the soft rock test was performed following installation to study the material fabric around the pile and consisted of 8 frames per position (3141) acquired with an X-ray beam tension of 220 kV and current of 500 µA. The radiography used the same ray settings and projections were obtained every 500 ms.

3 RESULTS

3.1 Force-displacement response

In Figure 2(a) and (b), the installation force-displacement profiles for the sand (a) and the soft rock (b) are shown.

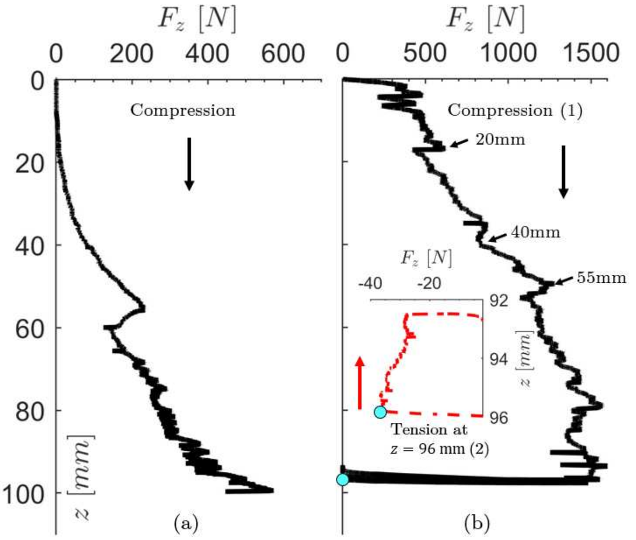

Figure 2. (a) HST-95 sand installation force profile (15.37mm pile) (b) Calcarenite installation (1) tension force profiles (2) (11.65mm pile).

The force-displacement profile of the pile penetrating the sand grew exponentially, indicative of plugging (White et al., 2000). This was likely due to the increasing internal shaft friction caused by dilation, principal stress rotation and soil-arching, sandwiching the lower portion of the plug statically (Liu et al., 2022). Between 50-100 mm the load profile was more volatile with sporadic drops, suggesting a stick-slip mechanism within the pile plug, which may have been favoured by minor variations in the pluviated material. except for the large dip experienced at 50 mm which was a result in a brief pause in the servo actuation.

For the soft rock, the installation force profile (1) was characterised by a linear trend, with a more jagged response caused by local failures of the brittle intact material immediately below the pile toe, see Figure 2(b). The lack of an exponential force increment implies that the pile remained unplugged. However, the profile exhibited discrete step changes at 20, 40 and 55 mm and the jagged profile gradually smoothened with on-going penetration. It is hypothesised that the profile change indicated that the pile no longer experienced internal shaft stick-slip cycles and brittle failure (unplugged state) and instead transitioned to a ductile punch-like behaviour due to the closure of the pile base. This was supported by the low uplift capacity (2) (< 20 N, which was only 2.5% of the peak compressive penetration load at the same depth), a product of the material's low Poisson's ratio and damage generated around the pile during installation. This has been identified as a cause of low axial capacity of pile foundations in soft rock via large deformation simulations of fully installed close-ended model piles (Ciantia, 2022).

3.2 Post-installation visualisation

Figure 3(a) shows a 2D section through the centre of the pile following installation in the soft rock. The reconstructed image, with a resolution of 120 μm, shows the porosity distribution, obtained by calibration of the grey-values (GV) via the approximate linear relationship between GV and density (Alvarez-Borges et al., 2022). This shows that the pile did indeed plug during installation, leading to a highly densified zone of material ahead of the pile, in which the structure of the intact calcarenite rock collapsed. The bulbous failure zone (R) emphasised in Figure 3(b) extended approximately $2-3D$ ahead of the pile tip. The damage extent, previously observed in close-ended piles, is characteristic of a flat structure punching through rock (Alvarez-Borges et al., 2022; Castellanza et al., 2009). Along the pile walls the extent of damage appeared to increase with penetration depth. At ground level this extended radially by approximately the wall thickness of the pile, increasing to 2-3mm as the pile surpassed the plug initiation zone (exemplified at 2D above the pile tip, see Figure 3(c). This was likely due to the effect of the increased pile displacement which causes marked increases in radial stress, inducing failure of the surrounding material (Fan et al., 2021). The plug structure itself varied along its length as shown in Figure 3(a). At the top of the plug a mixture of intact discs and puttified material could be seen, indicative of the stick-slip mechanism. Toward the pile tip, the material progressively degraded into a dense, destructured state, in-line with the sandwiching mechanism highlighted by Liu et al. (2022).

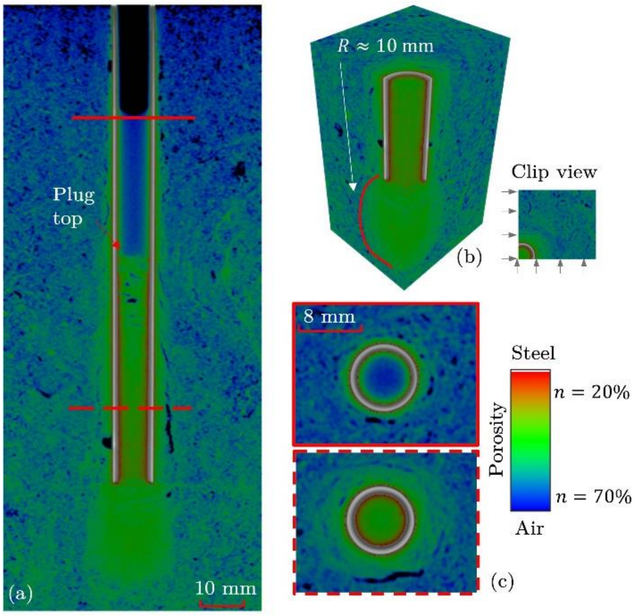

Figure 3. CT image of post installation of OE pile in calcarenite (a) 3D cross-sectional view of pile centre b) damage extent around pile annulus before plugging and after and (c) Damage bulb ahead of tip.

The plugging of this pile was unexpected, opposing a recent study in a similar soft rock (Alvarez-Borges et al., 2022), whereby the OE model pile ($D = 7.94$ mm) penetrated in full coring conditions leaving a small torus damage zone beneath the pile tip. Given that the inner diameter of the pile in this study was greater than that of Alvarez-Borges et al. (2022), a similar coring condition was anticipated. The reasons behind the different penetration mechanism appeared to stem from the variation in average pile roughness (R_a) and material grain size (d_{50}). Alvarez-Borges et al. (2022) used an acrylic pile with an $R_a \approx 0.02$ μm in conjunction with a finer grained chalk sample which had a $d_{50} \approx 5$ μm. In this study, the stainless-steel pile had an $R_a = 1.12$ μm. Combining this with the coarser-grained calcarenite resulted in a three-fold increase in R_a/d_{50}, indicative of a significantly rougher interface. This likely encouraged interlocking of the grains at the pile interface, inducing plugging.

3.3 Live installation visualisation

While it is challenging to use live radiography to assess fabric changes, it enabled real-time visualisation of the plug position for the sand example throughout the installation, revealing real-time behaviour not attainable from the static CT scan. Figure 4(a) shows the live plug evolution during installation which was identified as the sharpest variation in the average grey-scale intensity along the pile length, e.g., Figure 4(b). This indicated that the pile cored initially and then progressively plugged corroborating with the penetration resistance, see Figure 2(a). As the pile plugged, the sand level surrounding the pile exterior rose significantly due to the increased displacement generated by the pile base closure as was evidenced between 40 and 96 mm of penetration. Although summarised briefly, the potential of live X-ray radiography has been evidenced by the ability to constantly track the pile behaviour and soil during installation.

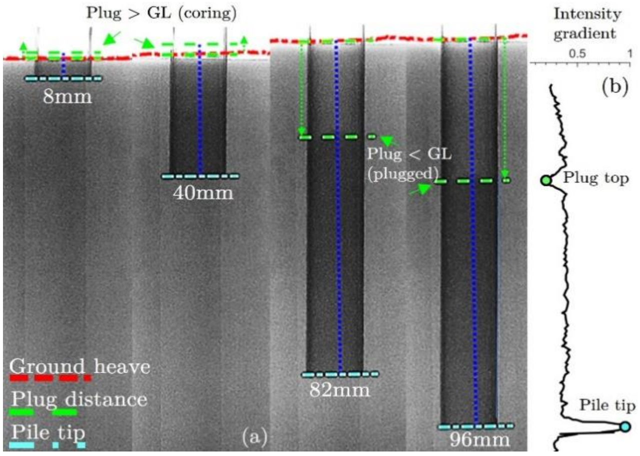

Figure 4. Radiography use in tracking pile and plug displacement during penetration for the sand example.

4 CONCLUSION

This paper has shown how the effect of plugging can alter the soil resistance to jacking. While the focus was on the plugging mechanism exhibited during installation, the CT and radiography techniques employed identified significant other mechanistic behaviour otherwise not revealed during conventional experimental or field scale studies. The new multi-axis loading frame has been highlighted as a valuable tool for researchers wishing to study 3D soil-structure problems in unison with X-ray, offering new insights into in-situ soil/rock-structure interactions.

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