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Locked-In Stresses Matter: the Effect of Centrifuge Spin-Down on Helical Anchor Performance in Sand

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ABSTRACT: Geotechnical centrifuge modelling offers a cost-effective, high-fidelity means of investigating geotechnical processes, from foundation installation through to in-service loading. Foundation installation alters the stress state in the soil, and while preserving installation-induced stress history is crucial for reliable interpretation, the technical challenges of performing both installation and loading within a single centrifuge flight often leads to modelling compromises, with the centrifuge stopped between installation and loading. This study investigates how a centrifuge spin down/up cycle between installation and loading influences the behaviour of helical anchors in dense saturated sand, aiming to clarify whether continuous in-flight modelling is essential to accurately represent the performance of helical anchors. Two anchor tests were performed under different conditions: (i) in-flight anchor installation under constant weight followed by anchor extraction (ii) in-flight constant weight anchor installation followed by a spin down/up cycle before anchor extraction. The anchor installed and loaded in-flight without stopping the centrifuge gave a higher capacity (by more than 30%) and a markedly stiffer load–displacement response compared to the test involving a spin down/up cycle, suggesting that post-installation stress relaxation has a sufficient influence on anchor behaviour to warrant maintaining in-flight conditions throughout installation and loading. Any interruption may release locked-in stresses and lead to significant underestimation of anchor strength and stiffness.

1 INTRODUCTION AND BACKGROUD

Helical anchors are gaining momentum as a potential offshore anchoring technology for floating renewable energy devices. This anchor type comprises a steel shaft with one (or more) helical plates, as shown in Figure 1. Interest in the use of helical anchors for offshore renewable energy developments is due to their advantages compared to other anchor types, including: speed and ease of installation (Al-Baghdad et al., 2017; Perko, 2009), avoidance of acoustic emissions associated with pile driving, high capacity to weight ratio, certainty on the as-installed embedment depth and location (less uncertainty on capacity), and simple end-of-life decommissioning. The tensile capacity of helical anchors in sand is known to be significantly affected by the installation method and advancement ratio, *AR* defined as the ratio of the vertical pile displacement for one helix revolution to the helix pitch, *p*. Anchors installed with AR ~ 1, known as 'pitch matched', tend to exhibit similar tensile capacity to wished-in-place (WIP) anchors (Giampa et al., 2017, Hao et al., 2019) while anchors installed with lower AR tend to exhibit higher tensile capacity (Cerfontaine et al., 2023). For practical reasons, anchors in the field are installed by imposing a constant weight (anchor + rig weight) such that AR is measured rather than controlled. In such cases AR decreases with depth until it reaches an asymptotic value which is commonly lower than 1, resulting in higher tensile capacities than those predicted for WIP or AR = 1 conditions (Giampa et al., 2017), as demonstrated through field tests (Bittar et al., 2023), and centrifuge experiments (Nietiedt et al., 2025). Numerical investigations of installation suggests that the higher capacity of installed anchors is linked to a combination of soil densification and locked-in stresses around the helix (Sharif et al., 2021, Davidson, 2025), although no study has explicitly decoupled the two. Furthermore, technical difficulties in conducting both anchor installation and loading in a single centrifuge spin has made WIP and 1g installations common practice, possibly to the detriment of capturing the true anchor capacity. The effect of in-flight installation in the centrifuge followed by a spin-down/up cycle before uplift loading has not been explicitly modelled.

This study investigates how a centrifuge spin down/up cycle between installation and loading influences the behaviour of helical anchors in dense saturated sand, aiming to clarify: (i) whether continuous in-flight modelling is necessary to accurately represent the performance of helical anchors; and (ii) whether the locked-in stress changes during installation is the main contributor of the higher capacity of installed anchors.

2 CENTRIFUGE MODELLING AND SOIL SAMPLE

The helical anchor tests were carried out using the 10 m diameter beam centrifuge (Gaudin et al., 2018) at the National Geotechnical Centrifuge Facility at University of Western Australia at centrifuge acceleration of 30g. The experiments were conducted in fine to medium poorly graded sub-angular silica sand (referred to as 'UWA silica sand') prepared by dry pluviation into a rectangular 'strongbox' (1000 mm × 1000 mm × 500 mm) with properties as listed in TABLE 1. Several centrifuge 'conditioning ramps' — cycling from 1g up to the testing acceleration of 30g — were performed to bring the sample to an equilibrium density state before testing. Measurements of mass and volume following these conditioning ramps indicated a relative density of approximately 80%. The tests reported in this paper were conducted in a sample that was originally prepared to investigate the behaviour or helical anchors in sand under partially drained conditions, and so was saturated using cellulose methocel ether (METHOCEL™) as the pore fluid, prepared at a concentration to achieve a kinematic viscosity, μ = 500 mPas. For the tests reported in this paper, both installation and extraction were performed at sufficiently low rates to ensure fully drained conditions.

Table 1. Index properties of UWA silica sand

Parameter	Value
Specific gravity, G_s	2.67
Particle size, d_{10}, d_{50}, d_{60}	0.12, 0.18, 0.19 mm
Dry density, ρ_d	1712 kg/m^3
Minimum dry density, ρ_{min}	1497 kg/m^3
Maximum dry density, ρ_{max}	1774 kg/m^3
Constant volume friction angle, φ_{cv}	31.9° (triaxial)

3 TEST SET-UP AND PROCEDURE

The geometry of the model helical anchor used in this study is shown in Figure 1. The anchor was manufactured from stainless steel and consists of a single helix with a diameter of D_h = 25 mm, a pitch, p = 8 mm and thickness, t_h = 2 mm. The helix was located 21 mm above the conical tip on a stainless-steel hollow shaft with a diameter, D_s = 10 mm.

The model helical anchor was attached to the base of a rotary actuator (Duverneuil, 2024) that was connected to the vertical axis of a two-dimensional electromechanical actuator. The rotary actuator is capable of delivering up to 35 Nm of torque at rotational speeds up to 13 RPM, while the vertical actuator can apply axial loads up to 6 kN with a maximum travel rate of 3 mm/s. Throughout installation and extraction, torque and axial force were measured using a bi-axial load cell positioned above the pile, and axial displacements were measured using an optical encoder located on the motor driving the vertical axis of the actuator. Load cell signals were transmitted through a 14-channel electrical slip ring to allow continuous data acquisition during rotation.

3.1 Installation procedure

Two tests are reported in this paper, with both following the same in-flight installation procedure. This involved applying a constant rotational speed, ω = 6°/s and a constant thrust force, F = 50 N from the sample surface (tip penetration depth, z_t = 0 mm) until the anchor tip reached the final embedment depth, z_t = 125 mm (z_t/D_h = 5). This represents a mid-helix embedment depth, z_h = 104 mm (z_h/D_h = 4.16) such that a shallow failure mechanism is expected. With this procedure, vertical velocity is not controlled, and advancement ratio, *AR*, is measured rather than imposed.

3.2 Extraction procedure

The only difference between the two tests was during the anchor loading phase. In test IF ('In-Flight') anchor loading was carried out after a short wait period at the end of installation, all without stopping the centrifuge. In test RD ('Ramp-Down'), the centrifuge was stopped after anchor installation before being spun back to the 30g testing acceleration. During this spin down/up cycle the actuator position was locked in place, such that no anchor head movement was allowed. The anchor was then loaded at 30g. Both uplift tests were carried out under drained conditions by displacing the actuator at a constant vertical speed, v_v = 0.03 mm/s.

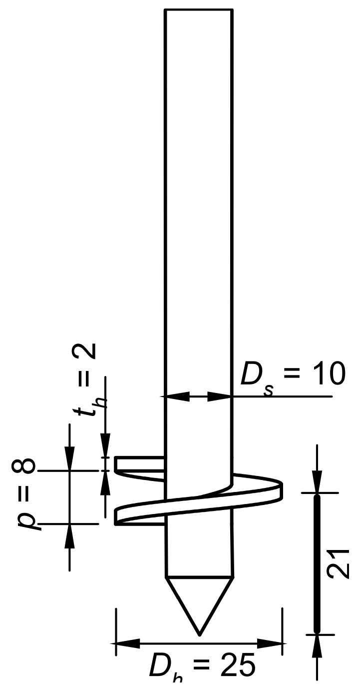

Figure 1. Model helical anchor dimensions (in mm)

4 RESULTS AND DISCUSSIONS

4.1 Time histories

Time histories of axial force and torque are presented for both tests in Figure 2, which also shows the centrifuge acceleration for each test. As noted earlier, both anchors underwent the same installation procedure, but the IF test was loaded directly after installation without stopping the centrifuge, whereas the centrifuge was stopped and then restarted between installation and loading in the RD test. The forces measured by the load cell during the centrifuge spin down/up cycle are a mix of real loads, applied to the anchor as the soil stress state changes during unloading and reloading, and 'fictitious' loads caused by the changing weight acting on the load cell as the centrifuge acceleration level changes. Of more interest is the load measured after the centrifuge returned to 30g in the RD test – with the axial force, F, returning to close to the 50 N that was applied during installation (no load hold was applied). In contrast, while in the IF test some of the installation torque relaxed prior to anchor loading, this torque had almost completely dissipated after the spin down/up cycle in the RD test. A clear reduction in tensile capacity can be seen, which is discussed in section 4.3.

4.2 Installation comparison

Depth profiles of axial force, torque and advancement ratio are presented in Figure 3, which show nearly identical installation behaviour between both tests. The assigned constant force, F = 50 N stabilised after z_t = 15 mm and remained constant through the remaining installation for both tests. Both torque profiles develop similarly, with the IF test displaying a 4% greater torque at the end of installation. The profiles of advancement ratio were similar, stabilising at AR = 0.60 (z_t = 65 mm), very close to the calculated AR_{crit} = 0.63 (Cerfontaine et al., 2023).

4.3 Uplift capacity comparison

Figure 3 shows the capacity mobilisation response of both tests, with evident differences in both the anchor capacity and the capacity mobilisation stiffness. The capacity measured in the in-flight test (IF) was 385 N, mobilised at a displacement, d/D_h = 2.5%. This was 31% higher than the 293 N capacity measured in the ramp-down test (RD) at a much larger displacement, d/D_h = 15%, despite the very similar installation responses. Furthermore, the capacity of the RD anchor was similar to that of a wished-in-place or AR = 1 anchor, as indicated by the Giampa et al. (2017) calculation also shown in Figure 3.

For a shallowly embedded anchor, the failure mechanism for uplift loading is commonly idealised as an inverted conical frustum where the inclination of the shear plane is typically assumed to be equal to the mobilised soil dilation angle, ψ (Giampa et al., 2017). Although numerical work has suggested that helical anchors installed in loose sand with AR = 0.5 may cause a 10% increase in relative density around the shaft (Sharif et al., 2021), the tests in this paper were conducted in dense sand such that it is unlikely that any densification that occurred during installation would have disappeared during a spin down/up cycle – meaning that the 31% higher capacity of the IF test may be attributed to preservation of the installation induced locked-in stresses that were released during ramp down for the RD test.

One factor that warrants consideration (and is the subject of ongoing study), is the effect of the shaft. Increases in radial stresses around the helical anchor shaft have been observed numerically (Sharif et al., 2021, Davidson, 2025). This is significant given the shaft diameter used in model tests is often larger than would be expected in the field – which suggests the increase of 31% may be on the high side, and this should be considered when interpreting centrifuge results.

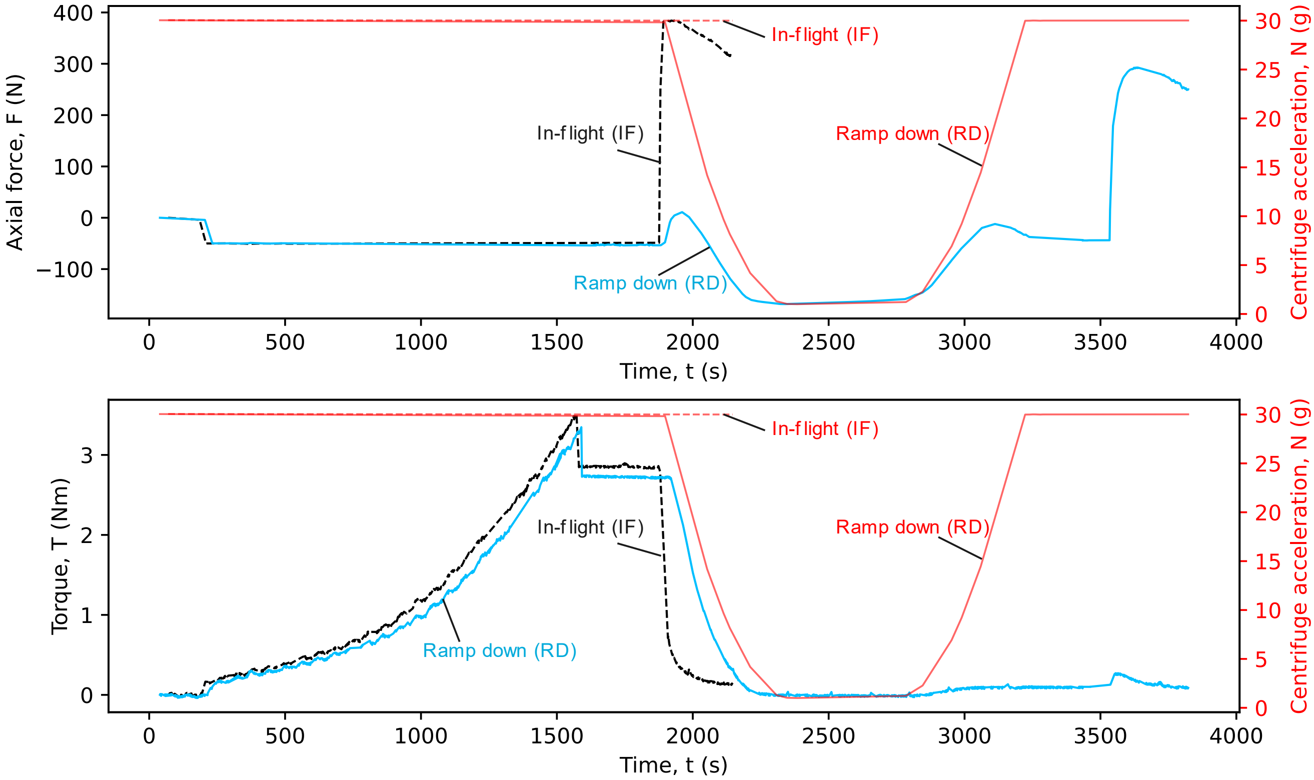

Figure 2. Time histories of axial force and torque.

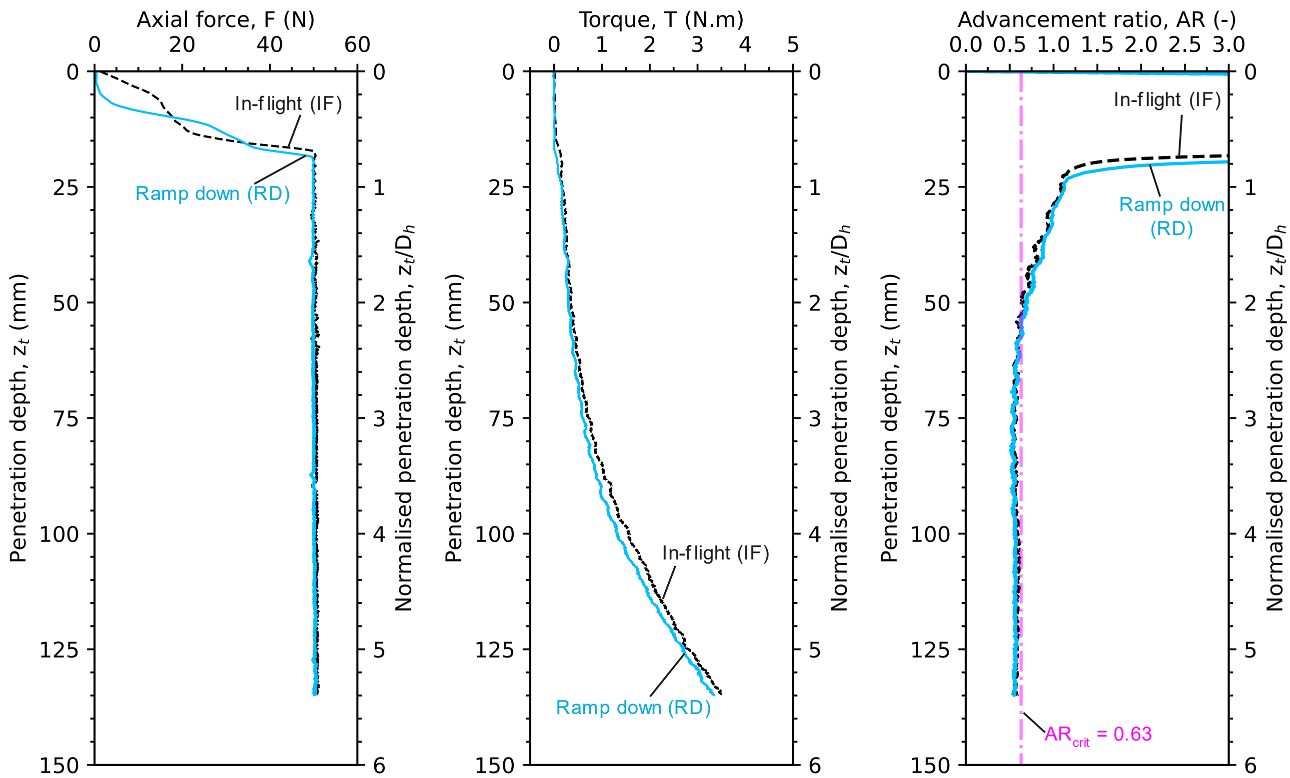

Figure 3. Axial force, torque and advancement ratio profiles during installation.

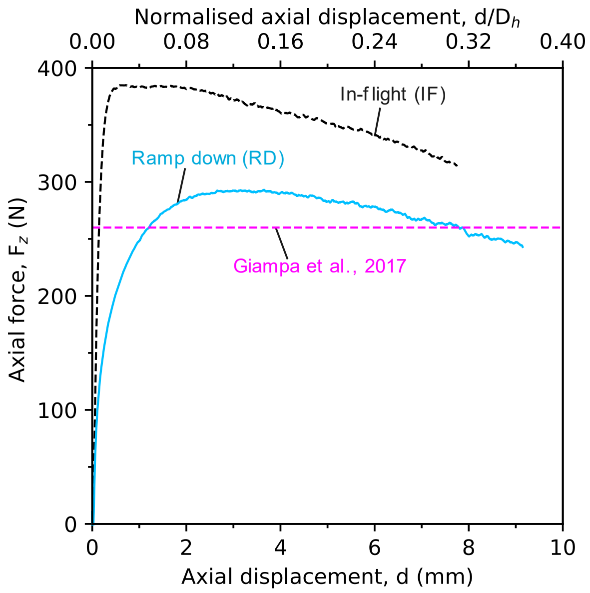

Figure 4. Capacity mobilisation response

5 CONCLUSIONS

This paper presents results from two proof-of-concept helical anchor tests conducted in a geotechnical centrifuge to investigate how stopping the centrifuge between installation and uplift loading affects anchor tensile capacity and stiffness. The results showed that when the anchor was installed and loaded in-flight without stopping the centrifuge, the capacity was 31% higher than when the anchor was installed in-flight, but loaded after a centrifuge spin down/up cycle. The stiffness response in the test without the spin down/up cycle was also much stiffer, with a capacity mobilisation displacement, d/D_h = 2.5% compared with d/D_h = 15 % when there was a spin down/up cycle. Differences in soil density are unlikely to explain this behaviour, and the enhanced capacity and stiffness may be attributed to the preservation of installation-induced locked-in stresses, which would have relaxed and redistributed once the centrifuge was stopped. The results show that the correct behaviour for helical anchors is only achieved when both installation and subsequent loading are conducted in-flight, without stopping the centrifuge. This is not generally a challenge for single anchor tests, but does present challenges when modelling anchor groups due to the need to disconnect and reconnect with each anchor in the group without stopping the centrifuge.

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