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Centrifuge investigation of impact-driven laterally loaded monopiles in uncemented carbonate sand

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ABSTRACT: Monopile foundations in Australian waters will likely be installed in seabed conditions dominated by carbonate sediments. Unlike siliceous sands, carbonate sands are highly crushable and compressible, which can lead to significant changes in grain size distribution due to particle breakage occurring during installation and potentially under cyclic loading. These characteristics affect strength, stiffness, and long-term displacement behaviour, presenting challenges for reliable foundation design. This study presents results of centrifuge tests comparing impact-driven (ID) and wished-in-place (WIP) monopiles subjected to lateral loading, carried out without stopping the centrifuge. The monopiles were installed in reconstituted uncemented carbonate sand samples. Preliminary results indicate generally similar trends compared with laterally loaded monopiles in siliceous sands, including clear differences in stiffness and capacity due to the installation process. Future work will expand the parametric space through numerical studies to further improve predictive tools for monopile performance in carbonate sediments.

1 INTRODUCTION

Monopile behaviour in siliceous sand is well studied, but much less is known about the response of such large cylindrical piles in carbonate sands with angular particles, where high compressibility and particle crushability can alter soil properties during installation and affect lateral performance. This study uses centrifuge tests on impact-driven (ID) and wished-in-place (WIP) monopiles to examine how installation affects lateral stiffness and displacement behaviour in uncemented carbonate sand.

2 EXPERIMENTAL ARRANGEMENT AND PROCEDURES

Centrifuge testing was carried out in the C72 10 m diameter beam centrifuge at the National Geotechnical Centrifuge Facility at UWA at 80 g. The soil is a reconstituted offshore sample representative of uncemented carbonate sands common along the coast of Western Australia. Figure 1 (left) presents a µCT image of the carbonate sand, characterised by angular, irregular particles, and the corresponding cone tip resistance profile. The sample was prepared by pluviating the sand through a water column, minimising the risk of particle breakage. During the raining process, 8 WIP piles were installed. The model piles were 0.5 m long open-ended stainless steel tubes (V2A-steel), with a Young‘s modulus of 207 GPa and a yield stress of 205 MPa. The external diameter was D = 50 mm with a wall thickness of t = 0.5 mm (D/t = 100). The WIP piles were suspended from wires during pluviation to achieve an embedment depth of 200 mm (4D). The final sample height was 350 mm, comprising a 100 mm silica-sand drainage base layer and 250 mm of carbonate sand above, with a relative density of D_r = 35%. Five conditioning spins to 80 g were performed to minimised densification during subsequent ramp-ups. The cone resistance profiles in Figure 1 (right) show strong similarity at five locations in the strongbox before and after pile testing.

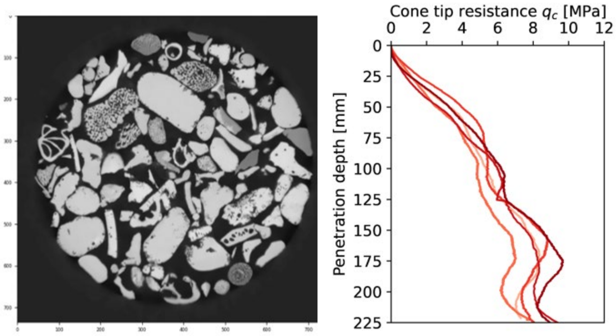

Figure 1. Visualization of carbonate sand captured with µCT (NGI) and cone tip resistance profile q_c

The modified impact hammer (Nietiedt et al., 2026), was connected to the pile head before driving, enabling lateral loading at the target embedment depth without spinning down the centrifuge. The hammer was used to install the ID piles, which were pre-embedded at 1g under self-weight to 1D, and to laterally load both WIP and ID piles. WIP pile locations were spaced at least 200 mm (4D) centre-to-centre and 125 mm (2.5D) from the strongbox boundary. The minimum spacing between WIP and ID locations was 300 mm (6D).

The discussion focuses on the initial and post-cyclic monotonic push-over responses for WIP (dark grey) and ID (light grey) piles, alongside the cyclic responses for WIP (blue) and ID (red). The cyclic tests involved two-way loading over 1,000 cycles from - 0.1 to 0.3 of the monotonic capacity at 0.1D mudline displacement, followed by a post-cyclic monotonic push-over with an unload-reload loop.

3 EXPERIMENTAL RESULTS

Test results are presented in model scale as load versus mudline displacement in Figure 2 and secant rotation stiffness versus mudline rotation in Figure 3. In both tests, the impact-driven piles exhibit a higher initial secant stiffness than the wished-in-place piles, a distinction that persists throughout lateral loading. As displacement and rotation increase, stiffness progressively decreases while the relative difference between WIP and ID remains similar across the loading range, a trend also observed in silica sand e.g. by Fan et al. (2021). In the figures, the dashed lines represent the initial monotonic response, while the solid lines show the post-cyclic behaviour.

Accumulation of permanent displacement is evident under cyclic loading, consistent with typical ratcheting behaviour (LeBlanc et al., 2010). The impact-driven pile shows noticeably less displacement accumulation than the wished-in-place pile under the same load pattern, consistent with densification and increased stresses, particularly around the base of the pile resulting from driving, as also reported by Fan et al. (2021). The post-cyclic monotonic response reveals reduced stiffness for the ID pile, whereas the WIP pile exhibits a stiffening effect, likely due to assimilation of the state of the surrounding sand during lateral cycling.

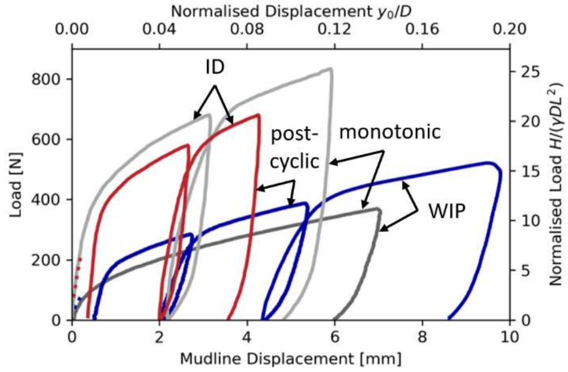

Figure 2. Initial and post-cyclic push-over response of WIP and ID piles

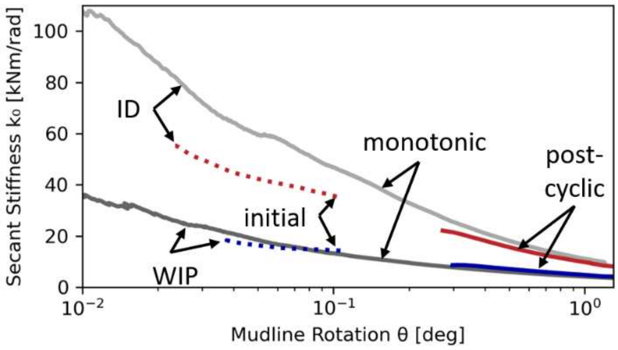

Figure 3. Secant rotational stiffness of WIP and ID piles

4 CONCLUSIONS

The test results highlight differing responses between installation methods and loading patterns in the loose, uncemented carbonate sand tested here:

- Impact driven piles showed significantly higher initial stiffness compared to wished-in-place piles.
- Cyclic lateral loading resulted in displacement accumulation which was less pronounced for impact driven piles.
- Lateral response differences between installation methods, such that the initial lateral stiffness and the ultimate capacity are influenced.

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