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The use of fibre optic and image analysis to investigate the performance of piles in sand under multi-directional horizontal loading

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ABSTRACT: This paper presents some recent modelling developments undertaken to investigate the behaviour of anchor piles subjected to multi-directional loading. This loading regime is relevant to arrays of floating renewable energy devices (waves or wind) when multiple devices are anchored to a single anchor to generate economies of scale. These developments consist in (i) a 6D image tracking system to capture pile displacement and rotation in six degrees of freedom and (ii) a fibre optic system to measure bending deformation (and subsequently establish p-y curves) in any loading direction. Preliminary results on tests featuring alternate loading at 0 and 30 degrees are presented, demonstrating the performance of the two systems, notably a significant improvement in the measurements of the initial stiffness from the image tracking system and the possibility to fully characterise the 6D response of the pile from the fibre optic system.

Keywords: anchor pile, multi-directional loading, 6D image tracking, fibre optic.

1 INTRODUCTION

Piles are practical anchor solution for offshore renewables because of the accumulated knowledge about their performance in various soil conditions. The foundation engineering of any offshore renewable development represents up to 35% of the CAPEX overall cost (Paredes et al., 2013) influencing significantly the economic viability of a project.

To reduce cost, several innovative approaches have been proposed including notably anchor sharing. Anchor sharing consists in using a single device to anchor multiple floating structures organised in an array, rather than designing a separate set of anchors for each renewable energy device (see Herduin et al., 2018).

While significant cost savings might be expected from a reduction of the number of anchors, the loading regime on the individual pile becomes more complex due to cyclic loading applied to the pile from multiple directions (typically two or three) from separate devices. This multi-directional cyclic load case is not well understood, as the main offshore design methods have been developed for floating oil and gas facilities with multiple anchor lines, each of which are subjected to unidirectional loading.

Capturing the pile response under lateral loading in the three-dimensional space presents significant challenges in particular when modelled in a geotechnical centrifuge. Conventional measurement techniques, such as string potentiometers, LDTs, lasers, strain gauges, used in similar studies (e.g. Richards et al., 2021, Herduin et al., 2018) generally result in expensive and/or complex experimental setups that also have some limitations, notably associated the measurement of initial stiffness, pile motion in the six degrees of freedom, and pile bending strains in multiple loading directions. This shortcoming requires the consideration of novel measurement techniques that are not commonly found in traditional geotechnical centrifuge model testing.

This paper presents geotechnical centrifuge model tests on a monopile anchor showcasing two novel measurement techniques that fully characterise the 6D response of the pile using (i) a 6D image tracking system to capture pile displacement and rotation in the 6 degrees of freedom and (ii) a fibre optic system to measure bending deformation in any loading direction. The test results offer insight on the foundation response when subject to loading from multiple directions, and hence their efficiency in supporting renewable energy devices organised in an array.

2 CENTRIFUGE TESTING PROGRAMME

The pile tests presented in this paper were conducted at the National Geotechnical Centrifuge Facility (NGCF) at The University of Western Australia using the 5-m radius beam centrifuge at 80*g* (Gaudin et al, 2018).

2.1 Sample preparation

UWA superfine silica sand obtained from Sibelco, Perth, Australia was used for these tests, with properties as summarised in Table 1. A dense sample was prepared by air pluviation into a square strongbox with base dimensions of 1000 × 1000 mm to a sample height of

300 mm at an average unit weight γ'_{dry} = 16.4 kN/m^3 (i.e. D_r = 70%). The sample was prepared dry to ensure a fully drained response during pile loading. The piles were installed wished-in-place during the sand raining process to avoid installation effects and allow consistency between tests. Sand was first rained to the depth of the pile tip before hanging the piles in position and raining around them. The sand surface was then vacuumed to achieve a pile embedment of 140 mm. A total of nine piles were installed, with a minimum center-to-center spacing of 14*D* and wall-to-center spacing of 9*D*. This layout was chosen to avoid boundary effects while maximizing the number of tests.

Cone penetration tests were conducted using a 5 mm diameter cone to characterise the soil sample before and after testing. The CPT profiles measured showed good consistency across the region of interest.

Table 1. Sand properties after Liu and Lehane (2012).

Description	Notation	Value
Specific gravity	G_s	2.67
Index of uniformity	U	1.9
Median particle size	d_{50}	0.18 mm
Dry unit weight $^{(1)}$	γ'_{dry}	16.4 kN/m^3
Critical sate friction angle	ϕ'_{cv}	31 deg

(1) Based on a relative density of 70%.

2.2 Experimental setup and testing procedure

The centrifuge tests were performed using aluminum pile models shown in Fig. 1 with its properties given in Table 2. As shown in Fig 1(a), the pile surface was coated with a sand resulting in a roughness of R_a/D_{50} = 0.66, resulting in a rough interface. The pile wall thickness (t = 3 mm) was selected to ensure enough flexibility to measure the bending strains along the pile using the fibre optic system. The pile has a closed end, given the wished-in-place installation method.

Fig. 2 shows the novel testing setup comprising marker tracking and optical-fibre measurements. Pile motion was recorded using a marker-based tracking solution provided by Photron (Photron, 2021). A 5-megapixel camera (Allied Vision Technologies Prosilica GC2450C) recorded images of an 'Aruco'-type marker. The marker was glued to a lightweight holder to avoid any secondary moments due to the marker setup and was positioned 44 mm above the load application point of the pile (see Fig. 1 and 3). Commercial software '6D Marker' by Photron resolved the marker position for all three directions (*x*, *y*, *z)* and angles (*roll*, *pitch* and *yaw*) with a precision of 0.01 mm and 0.01 deg, respectively. Furthermore, fibre optic sensors were installed along the pile capable of providing measurement of strain every 3.3 mm along the pile (see Beemer et al., 2018 for more details). A total of 6 fibre strands 30 deg radially apart (see Fig. 1b) were directly bonded to the pile wall. The instrumented piles were calibrated using a cantilever deflection test similar to Beemer et al., 2018 allowing determination of the exact location of the grating points. All data was simultaneous recorded at a sampling frequency of 10 Hz.

As shown in Fig. 3, two actuators (instrumented with in-line load cells) sat perpendicular on two platforms and were connected to the pile via Dyneema ropes which travel around pulleys. The actuators were positioned 450 mm away from the pile at different locations allowing different loading directions. Pile load was measured using 5 kN in-line load cells attached between actuator and the rope.

Table 2. Model pile properties.

Property	Notation	Value
Outside diameter	D_{model} (D_{proto})	22 mm (1.76 m)
Total length	L_{model} (L_{proto})	160 mm (12.8 m)
Embedded length	L_{emb}	140 mm
Eccentricity	e	20 mm
Wall thickness	t	3 mm
Surface roughness	R_a (or R_a/d_{50})	120 µm (or 0.66)

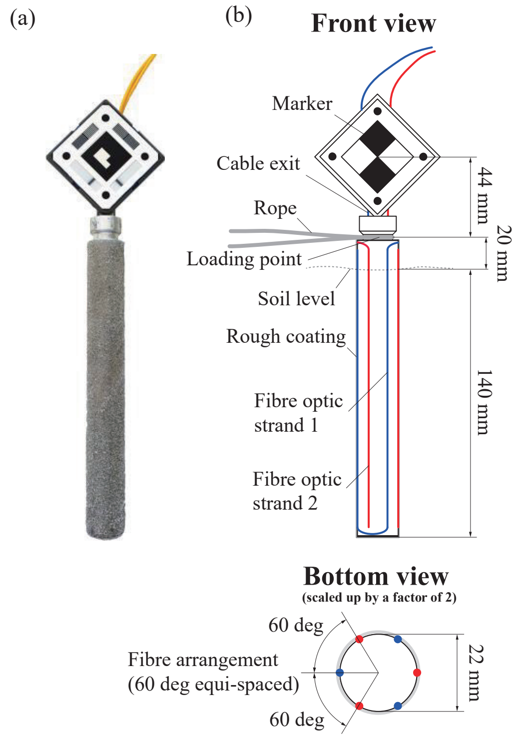

Fig. 1. Instrumented pile (a) photograph and (b) schematic.

Fig. 2. Photo of experimental setup.

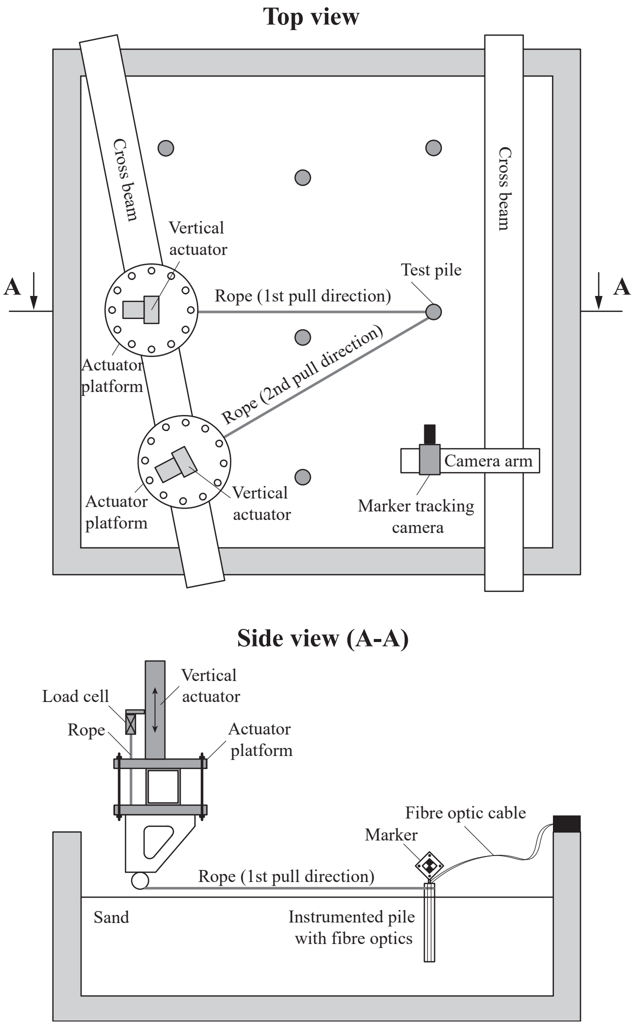

Fig. 3. Schematic of experimental setup.

All tests were performed using a constant actuator velocity of 0.1 mm/s. For uni-directional loading, only one actuator was used. For two-directional loading, the initial pull in the primary direction was continued until 2/3 of the monotonic peak capacity was mobilised while keeping the second line slack. Before pulling in the secondary direction, load on the primary line was released and the pile was subsequently pulled in the secondary direction to complete failure (up to 5*D*).

3 INITIAL RESULTS AND DISCUSSION

The experimental programme comprised a total of 9 tests with 2 monotonic test and 7 tests featuring bi-directional loading, whereas the pile was first loaded to 2/3 of its monotonic capacity before being reloaded to failure at angles of 30, 60, 75, 90, 120 and 180 degrees. However, only the bi-directional test at 30 degrees is presented herein to demonstrate the features of the experimental setup.

3.1 Pile trajectory obtained by marker tracking system

Fig. 4 shows the spatial recording of the marker for a bi-directional test. The projections in the x-z and x-y planes indicate the three-dimensional path of the marker. Not shown in the figure are the axes of rotation (i.e. the rotation matrix) which are also extracted by the marker software allowing the use of linear transformations to define the pile in different coordinate frames.

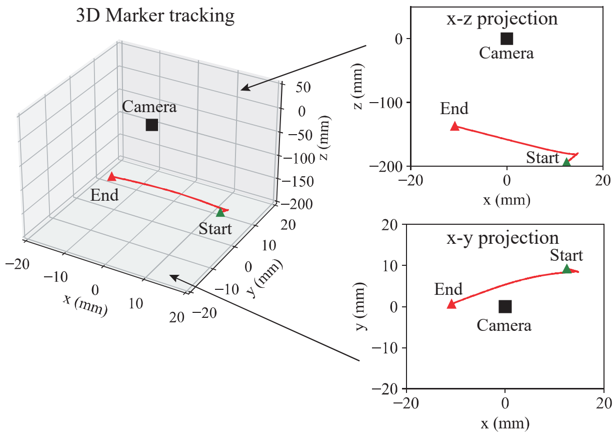

Fig. 4. Results of 6D tracking system showing a bi-directional test.

3.2 Lateral capacities and stiffnesses based on marker data

Fig. 5 presents the pile load-displacement response with displacement captured by the marker tracking system. Fig. 5(a) shows the lateral pile resistance (recorded using the load cell) against the normalised displacement for the monotonic and a 30 deg bi-directional test. The ultimate peak capacity for both test cases appear to be similar. Fig. 5(b) shows the secant stiffness-displacement response in the unidirectional test and in each of the two loading phases of the multidirectional test. During the initial loading of the two tests differences in stiffness occur with the monotonic test exhibiting a slightly stiffer response which may be due to sample heterogeneity. The reloading in the secondary direction shows a significantly stiffer response as a consequence of the previously applied loading. Noteworthy here is the quality of the stiffness measurements inferred from the 6D tracking system.

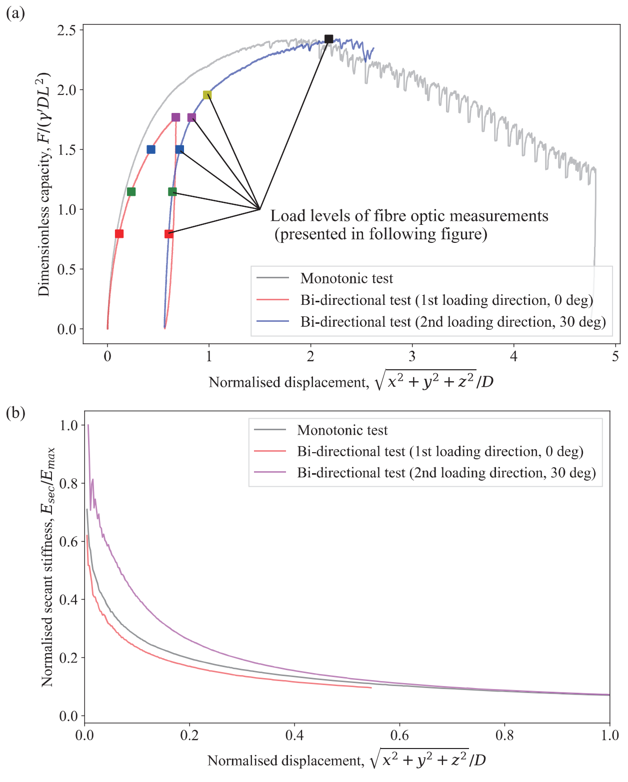

Fig. 5. Bi-directional test: (a) Capacity and (b) secant stiffness.

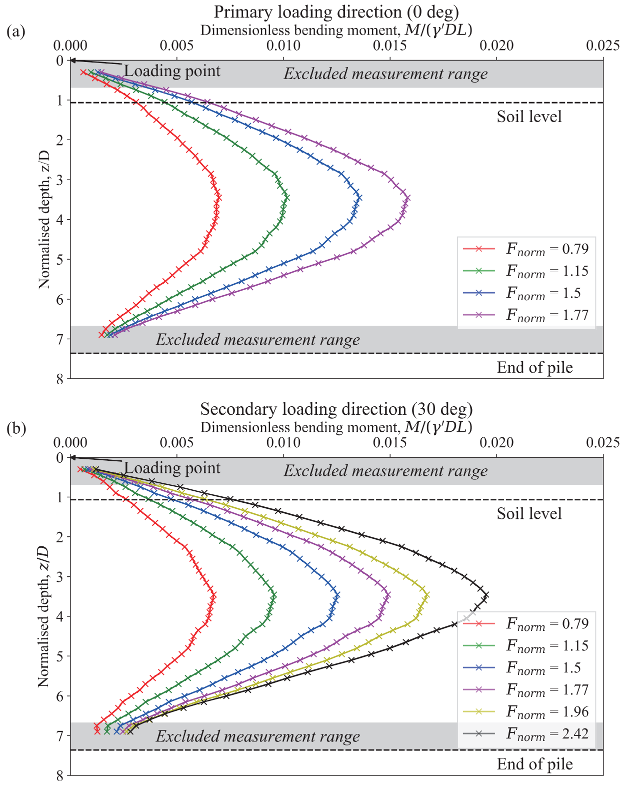

Fig. 6. Bending moment of bi-directional test case for (a) primary loading direction and (b) secondary loading direction.

3.3 Bending moments based on fibre optic data

Fig. 6 shows the bending moment along the pile in the dominant loading direction for the bi-directional test which is calculated based on the averaged bending strains from all 6 fibre optic strands. Fig. 6(a) shows the bending moment distribution in the primary loading direction whereas Fig. 6(b) shows the bending moment in the secondary loading direction (plotted for loads indicated in Fig. 5(a)). The bending moments in the secondary direction during the secondary loading event are lower than during the primary loading indicating a changing load transfer mechanism.

4 CONCLUSIONS

Centrifuge model tests were performed to investigate the performance of piles under multi-directional loading. A new experimental setup was developed to monitor pile movements in three-dimensional space using a 6D-marker tracking system and monitor three-dimensional bending strains along the pile using a fibre optic system.

The experimental setup demonstrates spatial measurements of the pile with high precision. One bi-directional test is presented showing the capability of the setup to apply loads in multiple directions and resolve pile response. Even-though only monotonic (multi-directional) loading is presented for simplicity, additional testing showed that the system is also capable of performing cyclic loading as well as loading in more than two directions.

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