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Physical modelling of 4-winged anchor piles

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ABSTRACT: The use of winged piles can significantly enhance the uplift resistance of anchor piles, but their behaviour, and hence design, remains uncertain. Centrifuge tests were conducted at 100*g* on 4-winged anchor piles, designed to represent floating offshore wind turbine anchors. The radial wings were configured to enhance the soil-pile contact area while maintaining the same steel volume as a reference smooth pile. The results show that the addition of wings significantly enhances uplift capacity, but alters the load-displacement response. Results support the efficiency of winged piles as anchors, particularly for tension-leg platforms, and lay the groundwork for further work to produce guidelines and understanding on the use of winged anchor piles for efficient mooring and deployment of floating offshore wind farms.

1 INTRODUCTION

As floating offshore wind expands into deeper waters, winged piles have emerged as a potential anchoring solution to improve load transfer of conventional piles from the tendons to the soil, in particular for Tension Leg Platforms (TLPs, Figure 1a). The uplift resistance of conventional tubular piles is primarily governed by shaft friction, which can be strongly enhanced through careful design of wings on the side of the piles.

This study investigates a 4-winged pile anchor, carefully designed to increase soil-pile interface area without increasing steel volume.

2 EXPERIMENTAL PROGRAMME

2.1 Model Piles

Two model piles were used: a reference tubular pile (RP) and a 4-winged pile (4WP), with wings directly

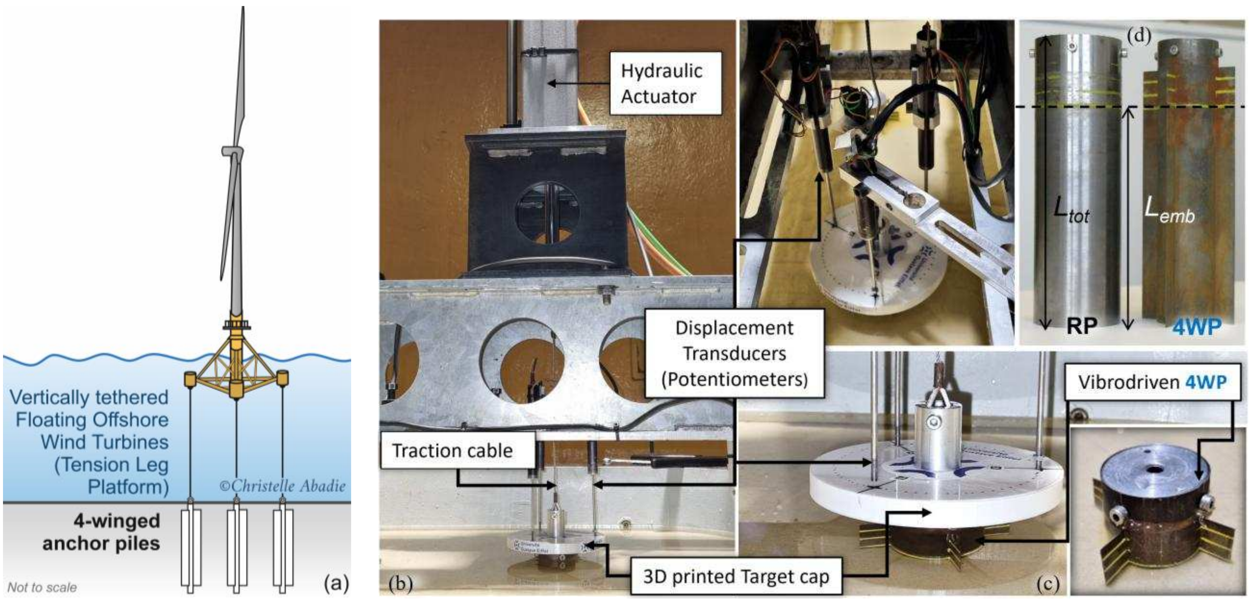

*Figure 1. (a) Conceptual representation of 4-winged pile anchors for FOWT; (b) Bespoke experimental test setup for vertical pull-out of anchors loaded on centrifuge beam;(c) Detailed view of the instrumented 4-winged pile. (d) Reference pile (**RP**) and 4-winged pile (**4WP**)*

Table 1. Pile properties

	Shaft				Wings			
	L_{tot} (m)	L_{emb} (m)	D (m)	t (m)	L_{tot} (m)	L_{emb} (m)	w (m)	t (m)
RP	21	16	6.5	0.04	-	-	-	0.04
4WP	21	16	4.6	0.04	19	16	1.5	0.04

Table 2. Properties of the Fontainebleau NE34 sand (Dano et al., 2024).

Parameter	D_{50} (mm)	C_u	G_s	e_{min}	e_{max}
Value	0.210	1.466	2.65	0.53	0.87

cut into the steel to avoid welding, and integrated into a reduced-diameter shaft (Figure 1d, Table 1).

To maintain equal steel volume, 4WP shaft diameter is reduced by 30%, increasing the lateral surface from 429 to 555 m² at prototype scale (i.e., 23%). Both piles were machined from smooth steel using electrical discharge machining (EDM).

2.2 Soil preparation and pile installation

Centrifuge tests were performed at 100*g* in water-saturated dense Fontainebleau sand (Dr = 80 %, Table 2), using the 5.5 m-radius UGE beam centrifuge at the University Gustave Eiffel. The sand was prepared by air pluviation in a 1200 x 800 x 360 mm strongbox and saturated to 390 mm water level. Piles were installed at 1*g* using an FPLF-12-XS pneumatic vibrator, used here as a vibro-driver, to a prototype embedded length of L_{emb} = 16 m.

2.3 Centrifuge setup and loading procedure

The load-displacement was measured using three potentiometers mounted 120° apart to verify the verticality of the pull-out test (Figure 1c). The pile was pulled using a hydraulic actuator in displacement control, at 0.01 mm/s up to the peak load to promote drained conditions and 0.02 mm/s thereafter. The corresponding load was monitored using a load cell.

3 RESULTS AND DISCUSSION

Two repeat pull-out tests per pile confirmed repeatability of the testing procedure, with peak capacities differing by 3.02% for RP and 7.30% for 4WP. Figure 2 shows the representative load-displacement responses for each pile.

Both piles display a stiff initial response, a clear peak, and post-peak softening. Using peak load as a failure criterion, uplift capacity increased from 8.5 MN (RP) to 19.8 MN (4WP), demonstrating that, for the same steel tonnage, the uplift capacity of the anchor is increased by 133% through the use of carefully designed wings. The displacements at peak load were

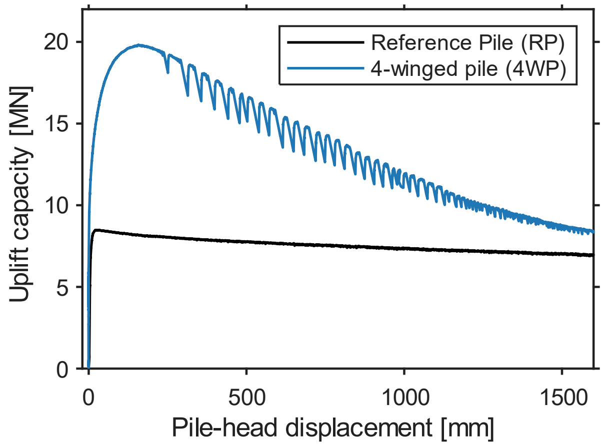

Figure 2. Uplift load-displacement response at prototype scale

observed at 38 mm and 183 mm, for RP and 4WP, respectively.

4 CONCLUSION

Centrifuge tests in water-saturated dense Fontainebleau sand show that a 4-winged pile with the same steel volume as a tubular open-ended reference pile achieves more than twice the uplift capacity of the reference pile. The response appears predominantly shaft-controlled, with the wings increasing the mobilised surface area and therefore the frictional resistance of the anchor. These findings support the potential of winged piles as efficient anchoring systems for floating offshore wind turbines (FOWTs), especially for TLPs. Ongoing work includes parametric testing on different winged geometries, in-flight vibro-installation using a small-scale vibrodriver, and 3D Coupled Eulerian-Lagrangian numerical modelling.

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