Centrifuge Modelling of Laterally Loaded Piles in Sand: Benchmarking against Large-Scale Tests

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ABSTRACT: A collaborative benchmarking exercise within the GEOLAB project involves two large-scale pile tests and 16 centrifuge tests replicating the prototype conditions. The prototypes were 3 m-long, 325 mm-diameter open-ended steel piles embedded 2 m in dense sand. One test applied monotonic lateral loading, and the other involved 13,000 loading cycles. Load–displacement, rotation, and strain responses were recorded. Centrifuge tests reproduced the prototype geometry and loading at 11.65*g* and 17.25*g*, using the same sand but differing in soil model preparation, loading, and instrumentation. The paper evaluates cross-scale consistency, sources of variability, and inter-facility reproducibility, providing experimental evidence to assess the reliability of centrifuge modelling for laterally loaded piles.

1 INTRODUCTION

A collaborative benchmarking exercise was conducted in 2024-2025 across six European geotechnical physical modelling facilities within the framework of the GEOLAB project. The exercise involved two large-scale load tests on instrumented steel piles (prototypes) conducted at the TU Darmstadt, alongside 16 centrifuge tests performed at different facilities to replicate the prototype conditions under scaled gravity, enabling a direct cross-scale and inter-facility assessment of centrifuge modelling performance. Data analysis is currently in progress.

2 METHODS

The prototype piles were hollow open-ended steel piles with an external diameter D=325 mm, wall thickness of δ=5.25 mm, and a total length of 3.0 m. The wished-in-place piles were embedded 2.0 m into dry, medium-coarse sand compacted in layers in the 5.00 m × 5.44 m × 2.85 m (L×W×H) test pit.

In the first test, the pile was subjected to monotonic lateral displacements applied at a constant rate up to approximately 20% of the pile diameter, followed by a constant-force phase maintained until the displacement rate became negligible, and finally an unloading phase at a constant displacement rate. The second test applied 13,000 cycles of lateral loading in two packages with different load ranges.

Throughout testing, lateral load–displacement response, pile head rotation, and longitudinal strains along the pile were continuously recorded.

The centrifuge tests replicated the prototype geometry and loading conditions at g-levels of 11.65*g* and 17.25*g*, and used the same sand as in the prototype. The hollow model piles were made of aluminium with the wall thicknesses calibrated to match the prototype's bending stiffness under scaling laws (δ/D=1.5/28 and δ/D=1/19). Differences arise, however, in the methods used by each facility to place the sand (dry pluviation or tamping) and install the pile (wished-in-place, jacked, or hammered).

Schematic representations of the experimental setups are shown in Figure 1, and Table 1 summarises the model characteristics at each facility. Facility names have been omitted for comparison purposes at this stage. A follow-up publication will address them thoroughly. Preliminary results from the monotonic tests are presented in the following section.

Table 1. General characteristics of the prototype and centrifuge models. Length are normalised by the pile diameter D; n is the scaling factor; R_t is the centrifuge radius of rotation measured to the sand surface. Other abbreviations are defined in Figure 1.

Facility	n	R_t [m]	$\frac{L_e}{D}$	$\frac{L_{ecc}}{D}$	$\frac{L_b}{D}$	$\frac{L_w}{D}$	ρ_d [g/cm^3]
Prototype	1.00	n/a	6.16	1.79	1.85	7.86	1.768
Centrif. 1	11.65	4.57	6.13	1.79	8.00	22.00	1.660
	17.25	4.51	6.12	1.79	14.74	32.71	1.660
Centrif. 2	11.65	3.40	6.27	1.79	1.09	12.89	1.698
	17.25	3.36	6.16	1.79	5.37	19.24	1.692
Centrif. 3	11.65	5.10	6.16	1.74	6.70	10.70	1.710
	17.25	5.08	6.16	1.74	12.80	15.70	1.710
Centrif. 4	17.25	1.04	6.11	1.77	1.89	6.05	1.739
Centrif. 5	17.25	3.77	6.12	1.79	5.66	11.18	1.726

3 PRELIMINARY RESULTS

Figure 2 shows the force–displacement curves obtained at the loading point for all tests and across the three loading stages. Forces and displacements from the centrifuge models have been upscaled to prototype scale. A statistical analysis of the parametrised curves indicates that the lower pile-soil interaction stiffness observed in the centrifuge tests during the loading stage, compared with the prototype, can be mainly attributed to the lower sand density and the greater distance to container walls in the centrifuge setups.

Figure 3 presents the bending moment diagrams for a horizontal reaction force $H = 40$kN, during the loading stage. These diagrams were derived independently by each facility from strain-gauge measurements at several pile cross-sections, using different methods and assumptions. Differences in bending moment between the prototype and centrifuge tests are within approximately $\pm 40\%$. The theoretical bending moment at ground level ($M = L_{ecc} \cdot H$) is well captured by the prototype test and by some of the centrifuge tests, but is significantly underestimated or overestimated in others. Despite some dispersion, the depth of the maximum moment is essentially the same.

4 CONCLUSIONS

The presented benchmarking exercise seeks to assess the consistency of experimental results across different scales and facilities and to identify the main factors contributing to variability among tests. These findings highlight the value of such coordinated efforts for cross-validation within the geotechnical physical modelling community, providing a bridge between large-scale and centrifuge-scale testing practices.

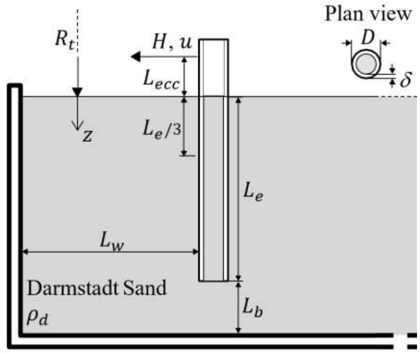

Figure 1. Schematics of the geometry of the models.

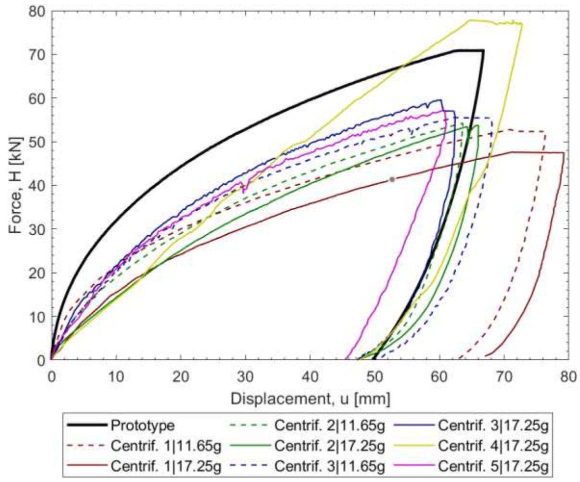

Figure 2. Monotonic loading tests: force versus lateral displacement, evaluated at the loading point.

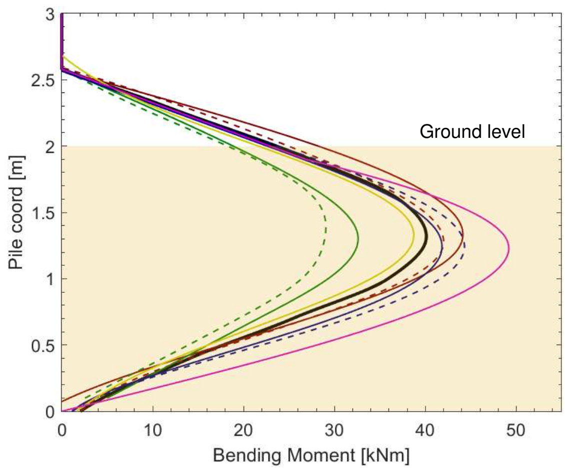

Figure 3. Pile bending moment diagrams for $H = 40kN$

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