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Assessing repeatability, scale effects, and consistency in geotechnical physical modelling: a collaborative benchmark exercise on horizontally loaded piles in dry sand

J. Liaudat, A. Kochnev, H. Zachert
Institute of Geotechnics, Technical University of Darmstadt, Department of Civil and Environmental Engineering, Darmstadt, Germany
joaquin.liaudat@tu-darmstadt.de, alexander.kochnev@tu-darmstadt.de, hauke.zachert@tu-darmstadt.de

W. Ovalle-Villamil, S. Muraro, M.A. Cabrera
Geo-Engineering section, Delft University of Technology, Delft, Netherlands
w.f.ovallevillamil@tudelft.nl, s.muraro@tudelft.nl, m.a.cabrera@tudelft.nl

M. Blanc, L. Thorel
Centrifuges for Geotechnics Lab. GERS-CG, University Gustave Eiffel, Bouguenais, France
matthieu.blanc@univ-eiffel.fr, luc.thorel@univ-eiffel.fr

A. Marin, L. Jones, I. Anastasopoulos
Institute for Geotechnical Engineering (IGT), DBAUG, ETH Zurich, Switzerland
alexandru.marin@igt.baug.ethz.ch, liam.jones@igt.baug.ethz.ch, ioannis.anastasopoulos@igt.baug.ethz.ch

S. Stanier, G. Viggiani, S. Haigh, S. Liu, S.P.G. Madabhushi
University of Cambridge, United Kingdom
sas229@cam.ac.uk, gv278@cam.ac.uk, skh20@cam.ac.uk, *sl2101@cam.ac.uk, mspg1@cam.ac.uk*

S.J.M. van Eekelen, K. Castelein, D. de Lange, C. Cengiz
Geo-engineering Department, Deltares, Netherlands
suzanne.vaneekelen@deltares.nl, koen.castelein@deltares.nl, dirk.delange@deltares.nl, cihan.cengiz@deltares.nl

O. Jenck, C. Dano, R. Chalhoub
3SR, Université Grenoble Alpes, Grenoble INP, CNRS, Grenoble, France
orianne.jenck@univ-grenoble-alpes.fr, christophe.dano@univ-grenoble-alpes.fr, rami.chalhoub@univ-grenoble-alpes.fr

ABSTRACT: This paper outlines an ongoing collaborative benchmark exercise conducted at multiple geotechnical experimental facilities within the GEOLAB community. The exercise involves two prototype large-scale pile tests performed at Technical University of Darmstadt and several small-scale centrifuge tests replicating the large-scale conditions. The prototype pile consisted of a hollow, open-ended steel pile with a diameter of 0.325 m, a wall thickness of 5.25 mm, and a total length of 3.00 m. The prototype piles were embedded 2.00 m into dry, dense sand prepared in a 5.00 m x 5.00 m x 2.85 m pit. The piles were subjected to various lateral load combinations, including monotonic loading until failure and cyclic loading at different load amplitudes and up to 10,000 cycles. The tests monitored the load-displacement response, rotation of the pile, longitudinal strains, and bending behaviour. The small-scale centrifuge tests aim to replicate the prototype geometry and loading conditions and will use identical soil, scaling factors and g-levels, while various centrifuge sizes and instrumentation methods will be employed. The participants will meticulously document each experiment, facilitating a comprehensive analysis and comparison of the results. The outcomes will be open-access data, which will significantly contribute to understanding reproducibility and scale effects in geotechnical physical modelling. The exercise will propose strategies for enhancing consistency and provide a valuable database for validating numerical models.

1 INTRODUCTION

Physical modelling plays a fundamental role in geotechnical engineering, as it provides cost-effective and time-efficient alternatives to field testing or large-scale modelling for studying complex geotechnical structures and loading conditions, such as lateral loading of pile foundations. Reduced-scale models have been essential for a better understanding of soil-pile interaction and the performance of piles under different load patterns (e.g., Abdoun et al. 2003; Zhu et al. 2016; Davidson et al. 2022), leading to significant improvements in design, construction, and maintenance practices (e.g., Arany et al. 2017).

Despite these significant contributions, physical modelling practice faces numerous challenges and uncertainties, primarily due to using reduced-scale models that hardly replicate in-situ stress-dependent soil behaviour and soil-structure interactions. The centrifuge modelling technique is an effective alternative for overcoming some of these limitations (Taylor 1994; Iai et al. 2005). However, additional challenges arise due to the increased gravitational acceleration field and the potential for scaling conflicts. In the case of centrifuge modelling of piles under lateral loading, it is typical to follow conventional scaling laws derived analytically, but experimental validations that allow a better interpretation of centrifuge results are still limited in the literature.

This article presents a benchmark study on the response of a single pile embedded in dry sand under monotonic and cyclic lateral loading using multi-scale physical models. The study involves a prototype single pile tested in a medium- to large-scale experimental setup and several small-scale centrifuge models replicating the larger scale conditions. The main objectives are to assess the accuracy and replicability of centrifuge models using conventional scaling laws and to evaluate the effects of additional parameters on the observed behaviours, including model dimensions, centrifuge facility characteristics, and instrumentation. This research is performed under the framework of the GEOLAB project and aims to assess the predictive capabilities of small-scale centrifuge models in geotechnical applications.

2 THE GEOLAB PROJECT

GEOLAB is an initiative sponsored by the European Union's Horizon 2020 Research and Innovation Programme, which has been operational since 2021 (European Commission 2021). Its primary aim is to address the complex challenges that critical infrastructure across Europe faces, including climate change, extreme weather, ageing, and the ongoing transition to cleaner energy sources. The project's strategy promotes innovative research through interdisciplinary and cross-institutional collaboration, extending the expertise and infrastructure of its partner institutions to other sectors, such as academia, government, and industry. This collaborative approach ensures the engagement of key stakeholders relevant to current engineering practices and decision-making processes. Activities within GEOLAB include the Transnational Access (TA) programme and Joint Research Activities (JRA) that facilitate knowledge sharing across institutions, ultimately benefiting the broader European Union.

This study is ongoing research performed under the JRA programme of the GEOLAB project, with the participation of six partner institutions and their physical modelling facilities. The large-scale prototype experiments were conducted at the Technical University of Darmstadt (TUDa), while the ongoing centrifuge experimental campaign is conducted at Université Gustave Eiffel (Uni Eiffel), Deltares (DELTARES), University of Cambridge (UCAM), ETH Zürich (ETHZ), and the Delft University of Technology (TUD).

3 PROTOTYPE TESTS

The prototype tests were performed at the Geotechnical Test Pit of TU Darmstadt as part of the GEOLAB TA project SAM-WT (Chalhoub et al. 2024). These tests involved sequences of lateral monotonic and cyclic loading on individual, open-ended piles. This section provides a brief description of the setup and experimental procedure. For a detailed description and a complete experimental dataset, please refer to Chalhoub et al. (2024).

3.1 Experimental setup

The setup was the same for the monotonic and cyclic loading tests. Figures 1 and 2 show an overview and the main dimensions of the setup, respectively. The setup involved a hollow, open-ended steel cylinder with a length of 3.00 m, and an embedded length of 2.00 m in dry compacted sand. The lateral force was applied 0.58 m above the sand surface.

Figure 1. The prototype pile experimental setup.

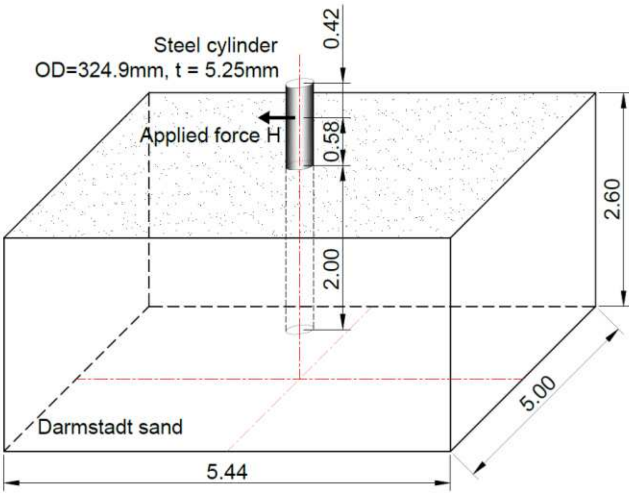

Figure 2. Geometry and main dimensions of the prototype pile test setup.

The sand was placed in the pit in 13 layers, each compacted using a vibratory plate. After compacting the first three layers, the pile was positioned at the centre of the pit and firmly held in place using a supporting structure at the pile head. Following the compaction of the remaining ten layers, the pile was filled with sand poured through the top end. This compaction procedure resulted in an average sand density of 1768 kg/m³.

The mechanical properties of the medium-coarse river sand used (Darmstadt Sand) were thoroughly characterised through geotechnical laboratory tests. These characterisation tests included visual description, particle density, particle size distribution, maximum and minimum density, oedometer tests, undrained and drained monotonic triaxial tests, and cyclic triaxial tests. The resulting dataset has been published by Beroya-Eitner et al. (2024).

Lateral loading of the pile was achieved using a hydraulic actuator pulling the pile laterally at the loading level. This hydraulic actuator was securely attached to a highly rigid horizontal loading frame.

Table 1. Loading sequence for Test 1(Monotonic).

Stage	Mode	Description
1	DC	Monotonic loading at 1 mm/min until the loading point reaches 65mm displacement with respect to the initial pile position.
2	FC	Maintain the force achieved in Stage 1 constant for 20 minutes **or** until the displacement rate drops below 0.02 mm/min, whichever occurs last.
3	DC	Monotonic unloading at 1 mm/min

Table 2. Loading sequence for Test 2 (Cyclic).

Stage	Mode	Description
1	DC	Monotonic loading at 1 mm/min until the force reaches $H = H_{m1} = 0.2H_f$
2	FC	First cyclic loading package $H = H_{m1} + H_{c1}\sin(2\pi f t)$ with $H_{m1} = 0.2H_f$, $H_{c1} = 0.1H_f$, and $f = 0.125$ Hz. Total number of cycles: 10,000
3	DC	Monotonic unloading at 1 mm/min
4	DC	Monotonic loading at 1 mm/min until the force reaches $H = H_{m2} = 0.5H_f$
5	FC	Second cyclic loading package: $H = H_{m2} + H_{c2}\sin(2\pi f t)$ with $H_{m2} = 0.5H_f$, $H_{c2} = 0.2H_f$, and $f = 0.125$ Hz. Total number of cycles: continue until any of the following conditions is reached: • $N > 1000$ and $D_{max} > 33$mm • $N > 3000$ • $D_{max} > 65$mm where N is the cumulative number of cycles in this package, and D_{max} is the peak displacement during the cyclic loading.
6	DC	Monotonic unloading at 1 mm/min

The pile was connected to the actuator by means of a connection rod with spherical joints at both ends. The connection to the pile was established at the centre of gravity of the pile cross-section, facilitated by a small hole in the pile wall and a rigid loading rig inserted into the pile. This rig was firmly connected to the pile and designed to exhibit negligible deformation.

The applied force was measured by a load cell positioned between the hydraulic actuator and the pulling rod. Displacement and rotation of the pile at the loading point were monitored using nine displacement transducers, which sensed at various points and directions on the rigid body formed by the loading rig. Additionally, longitudinal strains developed at specific pile cross-sections during lateral loading were measured using a total of 32 strain gauges attached to the pile below the loading level.

3.2 Loading sequences

Tables 1 and 2 present the loading sequences used for the monotonic and the cyclic tests, respectively. In Test 1, a slow, monotonic, displacement-controlled (DC) loading was applied until a displacement of 65 mm was reached, which is approximately 20% of the pile's outer diameter (OD). This was followed by a force-controlled (FC) creep phase and a DC unloading. Test 2 involved two cyclic loading sequences. Stage 2 consisted of 10,000 small load cycles, while Stage 5 involved up to 3,000 force cycles, reaching up to 70% of H_f. H_f is the force reached in Test 1 for a horizontal displacement of 33 mm (10% of the OD) at the loading point.

4 CENTRIFUGE TESTS

The centrifuge facilities participating in this study used the same scaling strategy and increased gravitational acceleration field, Ng, while other aspects varied, such as the overall size of the model and the instrumentation used. This section presents general details of the centrifuge facilities and the models used.

4.1 Centrifuge facilities

The facilities participating in this study included both small and large beam centrifuges with swinging baskets. Table 3 shows the effective radius to the basket floor, r_0, load capacity, and usable basket space for each centrifuge.

Table 3. General characteristics of centrifuge facilities.

Facility	**Load Capacity** (g-ton)	r_0 (m)	**Basket Size** (L-W-H, m^3)
Uni Eiffel	200	5.5	1.4 - 1.15 - 1.5
DELTARES	260	5.0	1.2 - 1.2 - 1.8
UCAM	150	4.125	0.85 - 0.85 - 1.5
ETHZ	500	4.125	1.25 - 1.25 - 2.0
TUD	9	1.215	0.46 - 0.32 - 0.56

4.2 Experimental setup

The small-scale models and the testing gravitational acceleration field were designed to replicate the stress-dependent response of the soil and the pile, which govern the soil-pile interaction observed in the prototype experiments. Conventional scaling rules were used for the design of the centrifuge models, as shown in Table 4.

Table 4. Scaling factors (model/prototype) for design of centrifuge models with an acceleration of Ng.

Variable	**Dimensions**	**Scaling Factor**
Acceleration	$L\ T^{-2}$	N
Length	L	N^{-1}
Displacement	L	N^{-1}
Time	T	N^{-1}
Velocity	$L\ T^{-1}$	1
Frequency	T^{-1}	N
Stress	$M\ L^{-1}\ T^{-2}$	1
Density	$M\ L^{-3}$	1
Force	$M\ L\ T^{-2}$	N^{-2}
Flexural Rigidity (EI)	$M\ L^{3}\ T^{-2}$	N^{-4}
Bending Moment	$M\ L^{2}\ T^{-2}$	N^{-3}

The same soil type and density as in the prototype were used to achieve soil behaviour similar to that observed in the prototype. The scaling of the prototype pile flexural rigidity, EI, was selected as the governing parameter for the model pile material, its dimensions, and subsequently, the testing g-level. Two pile geometries were selected:

- Model A: an aluminium pile with E = 69 GPa, OD = 19 mm, and t = 1 mm;
- Model B: an aluminium pile with E = 69 GPa, OD = 28 mm, and t = 1.5 mm.

The testing g-level for Models A and B was $17.25g$ and $11.65g$, respectively, based on an equivalent radius of rotation at 1/3 of the embedment depth of the pile. The loading procedures of Tables 1 and 2 were scaled for the centrifuge tests following the scaling factors of Table 4.

Figure 3 shows the typical small-scale model proposed for the centrifuge experiments. A specific sample preparation method was not standardised as part of the project. In contrast, each facility chose its own preparation method and pile installation method to best replicate the prototype, although a wished-in-place condition was recommended, mimicking the prototype installation.

As the overall geometry of the small-scale models was intended to follow the scaling factors in Table 4, relevant dimensions, such as the embedment depth, L_e, and the loading eccentricity, L_{ecc}, were maintained in all tests. Nonetheless, differences in boundary conditions may occur, for example, the distance between the edge of the pile and the closest

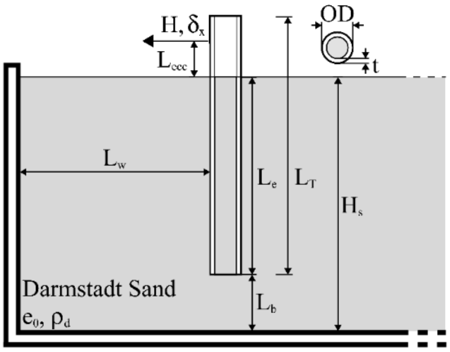

Figure 3. General sketch of the small-scale centrifuge models.

container wall in the loading direction, L_w, or the distance L_b to the bottom of the container. Other differences may occur in the overall model dimensions and shape, which vary depending on the usable basket space and container availability, such as the total length of the pile, L_T.

The instrumentation employed in the centrifuge tests was also chosen independently by each facility, but all aimed to measure the same parameters as in the prototype tests. In general, load cells were used for measuring the applied loads during lateral loading, while displacement transducers, including LVDTs and laser sensors, measured lateral deflections and pile inclinations. Likewise, optical strain gauges or strain gauges positioned for bending strains were used to estimate the bending moments along the small-scale piles.

Figure 3 shows the characteristics of centrifuge models A and B proposed for this study. Since the experimental campaign is still ongoing, the table shows only the information available at the time of this conference, including the normalised geometries based on the pile's outer diameter OD, the average value of soil density ρ_d, and general remarks onmodel preparation. The values at the prototype experiments were included for comparison.

5 METHODOLOGY FOR THE ANALYSIS OF THE RESULTS

As indicated in Table 1, the monotonic tests are intended to analyse three stages: loading, creep, and unloading. The analysis will focus on several parameters during these stages, including the applied force, horizontal displacement, pile rotation, longitudinal bending moment profiles during loading and unloading, and at specific times during the second stage. The same parameters will be studied in the cyclic tests. However, the comparison will be limited to the stages with cyclic loading; Stages 2 and 5, as described in Table 2.

For all the models, the bending moment profiles will be derived from the longitudinal and bending strain readings, assuming the validity of the classic Euler-Bernoulli beam theory. Spline interpolation will be applied to complete the bending moment profile along the entire pile length. Careful analysis of these comparisons will allow for the assessment of the consistency of geotechnical physical modelling results among the centrifuge facilities and their ability to predict the results of the prototype test.

A detailed discussion will follow, considering each facility's different model parameters and procedures. This will allow for the formulation of recommendations for improving consistency in centrifuge physical modelling.

6 SUMMARY

This article introduces a benchmark experimental campaign to evaluate measurements in small-scale centrifuge models of single open-ended piles installed in dry sand under different lateral loading conditions. The experiments are performed in centrifuges with different dimensions and will be documented in separate factual reports and published alongside all the acquired data as open-access datasets. This ensures that the produced data can be revisited in the future. From these comprehensive datasets, selected measurements from the small-scale models will be compared against prototype test results.

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Table 5. General characteristics of the prototype and small-scale, centrifuge models. Linear dimensions are normalised by the pile OD. Only the information available at the time of this conference.

Facility	**Test**	**Nominal S.F.**	**g-level at**			$\frac{L_T}{OD}$	$\frac{L_e}{OD}$	$\frac{L_{ecc}}{OD}$	$\frac{L_b}{OD}$	$\frac{L_w}{OD}$	$\frac{H_s}{OD}$	ρ_d (kg/m^3)	D_r (%)	**Preparation Method**
			Ground surface	**1/3th pile embedment**	**Pile tip**									
TUDa	Mono	1.00	1.00	1.00	1.00	9.23	6.16	1.79	1.85	7.86	9.23	1768	89	Layer compaction with vibratory plate. Wished-in-place pile.
	Cyclic											1773	90	
DELTARES	Mono	17.25	17.10	17.25	17.54	10.16	6.12	1.79	14.74	32.71	20.84	1660	81	Layer compaction by means of tamping. Wished-in-place pile.
		11.65	11.56	11.70	11.99	10.04	6.13	1.79	8.00	22.0	14.14	1660	81	
	Cyclic	17.25	17.10	17.25	17.54	10.16	6.12	1.79	14.74	32.71	20.84	1660	81	
		11.65	11.56	11.70	11.99	10.04	6.13	1.79	8.00	22.0	14.14	1660	81	
UCAM	Mono	17.25	17.07	17.25	17.60	10.16	6.12	1.79	10.16	22.1	20.32	1726	88	Dry pluviation. Pushed-in pile.
		11.65												
	Cyclic	17.25	17.07	17.25	17.60	10.16	6.12	1.79	10.16	22.1	20.32	1726	88	
		11.65												
TUD	Mono	17.25	16.63	17.25	18.48	9.15	6.11	1.77	1.89	6.05	10.0	1751	90	Layer compaction by means of tamping. Pushed-in pile.
		11.65												
	Cyclic	17.25	16.63	17.25	18.48	9.15	6.11	1.77	1.89	6.05	10.0	1753	91	
		11.65												
ETH	Mono	17.25												Dry pluviation. Wished-in-place pile.
		11.65	11.40	11.60	11.99	9.5	6.29	1.68	1.14	12.89	7.43	1692	85	
	Cyclic	17.25												
		11.65	11.40	11.60	11.99	9.5	6.29	1.68	1.14	12.89	7.43	1692	85	
Uni Eiffel	Mono	17.25												
		11.65												
	Cyclic	17.25												
		11.65												

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