Revisiting the role and outlook of geotechnical mini-centrifuges for offshore geotechnical applications

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ABSTRACT: Accelerated offshore wind development demands scalable and cost-effective design strategies that can adapt to evolving project requirements, compressed timelines, and significant uncertainty in ground conditions and environmental loading. Traditionally, large beam centrifuges with diameters exceeding 3 m have been favoured in offshore oil and gas applications. Such facilities, however, often require lengthy preparation times, customised experimental setups, and large volumes of reconstituted soil, limiting their suitability for rapid exploratory studies. This paper revisits the role of geotechnical mini-centrifuges, defined on a capacity and size basis as facilities with characteristic diameters up to approximately 2.5 m, including both mini-beam and drum centrifuges. While mini-centrifuges are subject to well-known limitations—such as boundary effects, stress gradients, particle size constraints, and restricted instrumentation payloads—they offer clear advantages in terms of fast test turnaround, modular configurations, and cost-effective experimentation. These attributes make them particularly attractive for early-stage concept validation and methodological development within accelerated offshore wind projects. Mini- and large-scale centrifuges are therefore viewed as complementary tools, jointly addressing the evolving demands of offshore renewable energy development. Within the framework of Norway's first offshore foundation research infrastructure, ProWind, this paper summarises key limitations and similitude considerations relevant to mini-centrifuge modelling and reviews selected international facilities to illustrate how targeted accessory and system development has broadened offshore applications. Examples include monopiles, spudcan foundations, suction caissons, anchoring systems, and submarine landslides. The paper concludes with an outlook on how mini-centrifuges can function as scalable, adaptive platforms that complement larger facilities in next-generation offshore geotechnical research.

1 INTRODUCTION

The rapid expansion of offshore wind energy has introduced new geotechnical challenges associated with larger structures, deeper waters, more complex loading conditions, and increasingly compressed project timelines. Offshore foundation design must accommodate substantial uncertainty in soil conditions, cyclic and multidirectional environmental loads, and evolving foundation concepts, while maintaining cost efficiency and design robustness. Physical modelling continues to play an important role in addressing these challenges by providing insight into soil–structure interaction mechanisms under stress conditions that are difficult to replicate at 1g. Large geotechnical centrifuges have traditionally been the primary experimental tool for offshore oil and gas applications, offering high payload capacity, large model space and the ability to simulate full foundation systems with reduced boundary influence. However, their use is often associated with long preparation times, customised experimental setups, and limited flexibility for rapid iteration. These constraints are increasingly misaligned with the needs of offshore renewable energy development, where early-stage concept screening, parametric studies, and method validation must be conducted efficiently. In this context, geotechnical mini-centrifuges have regained prominence and evolved from primarily teaching tools to platforms supporting early-stage research and targeted experimental development. Despite their smaller size and lower payload capacity, mini centrifuges offer several practical advantages, including short test turnaround times, modular experimental configurations, reduced soil preparation requirements, and lower operational costs. However, the design of experimental accessories often requires careful optimisation due to strict limitations on space, payload mass, and sometimes higher g-levels. Mini-centrifuges are not intended to replace large facilities, but rather to complement them by enabling rapid capability development, focused experimentation, broader coverage of development stages, and optimized geotechnical design. When their inherent limitations are explicitly recognised and managed, mini-centrifuges can provide high-value experimental data that inform numerical modelling, guide larger-scale testing programmes, and support accelerated decision-making in offshore geotechnical engineering. This paper does not present new experimental results but instead synthesises existing developments and applications of mini-centrifuges relevant to offshore geotechnical research.

2 LIMITATIONS AND SIMILITUDE CONSTRAINTS

Despite their practical advantages, mini centrifuges are subject to a number of inherent limitations that must be explicitly acknowledged to ensure robust interpretation of experimental results. These constraints arise primarily from reduced model dimensions, lower payload capacity, and increased sensitivity to scaling effects, and they influence both experimental design and the scope of applicable problems. One of the most significant challenges in mini-centrifuge testing is the increased influence of boundary effects. The reduced container size relative to model dimensions may lead to closer proximity of sidewalls and base boundaries, which can affect stress distribution, deformation patterns, and failure mechanisms. As a result, boundary ratios on the order of 3–5 (defined as the distance from the model to the container boundary normalised by a characteristic model dimension) that are acceptable in larger centrifuges may become restrictive in mini-scale facilities, particularly for problems involving large deformation zones or extended soil–structure interaction (Beijer-Lundberg, 2015). Stress gradient effects also become more pronounced in mini centrifuges. The acceleration field varies more rapidly with radius, increasing sensitivity to the choice of equivalent radius and amplifying non-uniform stress conditions along the model depth. This effect is particularly relevant for tall or slender models, where deviations from ideal similitude may influence measured response (Beijer Lundberg, Dijkstra and Van Tol, 2012). Material scaling presents a further constraint. The limited model size imposes stricter requirements on particle size and grain number, especially for coarse-grained soils. Inadequate separation between particle scale and model dimensions may lead to non-representative behaviour, affecting strength mobilisation and dilation mechanisms. Similar challenges arise in scaling interface roughness and membrane thickness for soil–structure interaction problems. Finally, instrumentation and actuation limitations are more pronounced in mini centrifuges. Restrictions on actuator mass, stroke, and force capacity can constrain installation realism and loading complexity, while sensor size and stiffness may influence local measurements (Zhang, Bienen and Cassidy, 2013; Black, 2014). These factors require careful experimental planning and, in many cases, tailored accessory development (e.g. lightweight actuators, loading frames, installation devices, and instrumentation systems). Recognising these limitations is essential. When appropriately managed through problem-specific design, mini-centrifuges can provide reliable and insightful results, particularly for focused parametric studies and early-stage concept evaluation. These considerations form the basis for the facility classification and application-oriented discussion presented in the following sections.

3 CENTRIFUGE LANDSCAPE AND MINI-CENTRIFUGE DEFINITION

Geotechnical centrifuge facilities worldwide span a wide range of sizes, configurations, and capacities, reflecting different historical developments, research priorities, and application domains. Large beam centrifuges have traditionally formed the backbone of national and international research infrastructures. Alongside these facilities, a diverse group of smaller centrifuges—including both beam-type and drum-type systems—has emerged to address more focused experimental needs. Figure 1(a) presents an overview of selected geotechnical centrifuge facilities, illustrating the relationship between centrifuge diameter and rated capacity (g-ton). Based on this overview, centrifuges are classified into mini, medium, and large categories using diameter thresholds of less than 2.5 m, 2.5–8 m, and greater than 8 m, respectively. This diameter-based classification is adopted as a pragmatic framework for discussing experimental capability rather than as a strict indicator of performance. Distinct trends can be observed across these categories. For mini-centrifuges, two characteristic behaviours emerge. Mini-beam centrifuges typically exhibit capacities on the order of 6–10 g-t, with capacity increasing only marginally with diameter. At this scale, achievable capacity is primarily constrained by allowable payload mass, strongbox dimensions, and actuator integration rather than by arm length alone. In contrast, drum centrifuges display a much wider capacity range, from approximately 100 to 900 g-t, despite similar diameters. For medium-sized beam centrifuges, a clearer relationship between diameter and capacity is evident, consistent with conventional scaling of arm length and payload. For large centrifuges, however, no systematic correlation between diameter and capacity can be identified, as design choices are increasingly governed by structural limits, motor power, and facility-specific objectives rather than geometric scaling alone.

Figure 1(b) provides a zoomed-in view of the mini-centrifuge domain, highlighting facilities that have made sustained or rapidly developing contributions and that form the primary focus of this literature review. These include drum centrifuges at the University of Cambridge, the University of Western Australia (UWA), the Hong Kong University of Science and Technology (HKUST), and ETH Zurich, as well as mini-beam centrifuges at the Federal University of Rio de Janeiro (UFRJ), Delft University of Technology (TU Delft), the University of Natural Resources and Life Sciences Vienna (BOKU), and the University of Sheffield. It is emphasised that this overview does not constitute a holistic survey of all global centrifuge facilities. Instead, it highlights a set of representative and influential mini centrifuges that demonstrate how meaningful offshore geotechnical research can be conducted within the limitations discussed in Section 2. These facilities provide the foundation for the application- and capability-focused synthesis presented in the following sections.

4 APPLICATIONS

Within the limitations discussed in Section 2, mini-centrifuge applications in offshore geotechnics have progressed through targeted strategies and lightweight, minimised system design that explicitly accommodate space, payload, and boundary constraints. The following synthesis highlights not only which problems have been studied, but also how mini-centrifuge limitations have been managed in practice.

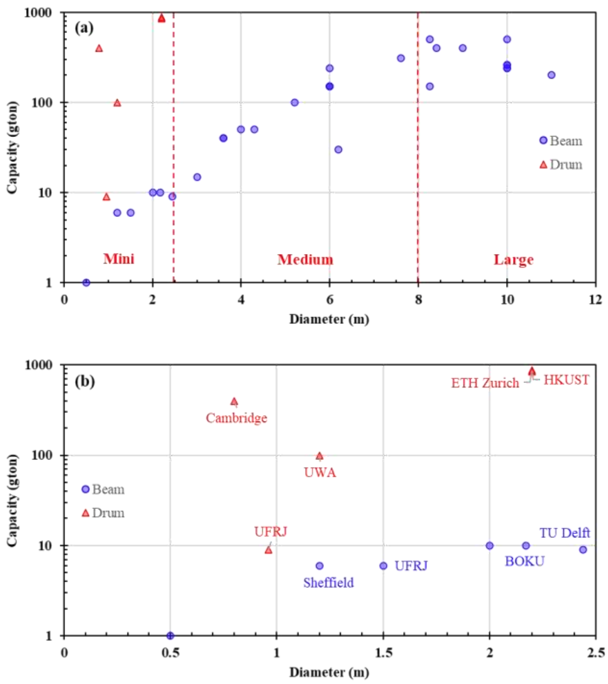

Figure 1. (a) Relationship between centrifuge diameter and rated capacity (g-ton); (b) zoom-in view of the mini-centrifuge domain highlighting representative and influential facilities reviewed in this study.

4.1 Offshore Foundation Design

For offshore foundation problems, mini-beam centrifuges have enabled efficient parametric exploration by (1) simplifying model geometry, (2) decoupling installation and loading stages, and (3) prioritising governing mechanisms rather than full-system replication. For monopiles, lateral response and scour–pile interaction have been investigated using reduced-height models combined with carefully selected equivalent radii, allowing stress-dependent behaviour to be captured while maintaining acceptable boundary ratios (e.g. Chortis *et al.*, 2020; Orakci *et al.*, 2024). Installation effects are commonly idealised within actuator mass and stroke limitations. Approaches include controlled driving or jacking conducted either at 1-g or in-flight during separate stages, as well as wish-in-place conditions where installation effects are represented indirectly (Beijer Lundberg, Dijkstra and Van Tol, 2012; Beijer-Lundberg, 2015). Despite these constraints, mini-beam centrifuge tests have demonstrated good consistency with results from medium and large centrifuges in coordinated comparison and round-robin studies, supporting their validity for selected offshore foundation problems (Almeida *et al.*, 2024; Klinkvort *et al.*, 2025).

For spudcan and shallow foundation problems, centrifuge modelling has focused on penetration resistance, punch-through, and combined loading behaviour using axisymmetric or simplified footing geometries (Cassidy, 2007; Hossain and Randolph, 2010; Gaudin *et al.*, 2011). Mini-centrifuges benefit from reduced soil volume requirements and rapid reconstitution, while installation loads are applied incrementally to remain within actuator capacity limits. Combined vertical–horizontal–moment (VHM) loading has been achieved through compact loading frames or drum-based apparatus, avoiding large external reaction systems. Anchoring systems represent another application well suited to mini-centrifuges. Drag anchors, bi-wing anchors, and torpedo anchors have been modelled using simplified installation trajectories and lightweight attachment systems, enabling systematic investigation of load inclination, cyclic degradation, and group effects (Fanning *et al.*, 2023; Freitas *et al.*, 2024; de Freitas *et al.*, 2025). These studies demonstrate how mini-centrifuges can prioritise installation mechanism and load path rather than absolute geometry.

4.2 Large-Deformation Problems

Drum centrifuges have been widely used to investigate submarine landslides, debris flows, and hydroplaning phenomena, where conventional beam centrifuge strongboxes would impose prohibitive boundary constraints. By employing annular soil configurations and continuous domains, mini-drum centrifuges enable long run-out behaviour and pore pressure evolution to be observed with minimal sidewall interference (Gue *et al.*, 2010; Hotta *et al.*, 2019). These studies illustrate how drum centrifuges, despite their small diameter, can achieve relatively high effective capacity and provide useful experimental capability for large-deformation problems. To accommodate payload and space limits, these studies often rely on minimal external actuation, allowing gravity-driven or stress-controlled triggering of instability. Measurement strategies emphasise global kinematics and pore pressure response rather than dense local instrumentation, reducing sensor mass and wiring complexity. The wide range of effective capacities observed for drum and mini-beam centrifuges reflects this operational philosophy, where soil mass distribution and rotation speed are optimised for specific flow problems rather than general-purpose testing (Zhang and Askarinejad, 2019).

4.3 Accessory Development

A defining characteristic of mini-centrifuge evolution is the development of lightweight, integrated accessories designed explicitly to operate within strict mass and space constraints. Several strategies are consistently observed across facilities. Compact combined VHM and multi-axis loading devices have been developed for drum centrifuges using mechanically efficient linkages and short load paths, allowing complex loading states to be imposed without large actuators (Zhang, Bienen and Cassidy, 2013). In beam centrifuges, installation and loading systems are frequently separated temporally, thereby reducing peak mass requirements during flight (Beijer-Lundberg, 2015; van Zeben, 2017). Similar lightweight in-flight installation systems have been developed for piles and caissons (van Zeben, 2017; Zhang, Sudhakaran and Askarinejad, 2020). Instrumentation strategies have evolved in parallel. Wireless and high-speed data acquisition systems significantly reduce cabling mass and signal routing complexity, enabling higher sensor density within mini-centrifuge payload limits (Gaudin *et al.*, 2009). Optical measurement techniques, including digital image correlation and PIV, have been widely adopted to obtain full-field deformation data while minimising intrusive sensors, particularly in mini-beam centrifuges. Recent studies also demonstrate increasing use of additive manufacturing (e.g 3D printing) to fabricate lightweight, geometry-controlled model components, facilitating rapid iteration and customised interfaces without excessive mass penalty. Beyond offshore wind foundations, selected studies indicate broader applicability of mini-centrifuges. Examples include rainfall-induced slope failure modelling using the BOKU mini-beam centrifuge (Wang and Idinger, 2021), multi-axis pile foundation testing in the ETH Zurich drum centrifuge (Sakellariadis *et al.*, 2023), and the integration of multi-axis loading and wave-generation systems in the HKUST drum centrifuge (Zhang *et al.*, 2022).

These developments highlight the role of mini-centrifuges as complementary platforms for targeted offshore geotechnical investigations under increasingly constrained development timelines.

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REFERENCES

Almeida, M. de S.S. de, Freitas, A.C., Almeida, M.C.F. and others (2024). Centrifuge modelling of monotonic and cyclic lateral responses of monopiles in quartz and carbonate sands. *E3S Web of Conferences*, 07002. http://doi.org/10.1051/e3sconf/202446907002

Beijer-Lundberg, A., Dijkstra, J. and Van Tol, A.F. (2012). On the modelling of piles in sand in the small geotechnical centrifuge. *Proceedings of Eurofuge 2012*, Delft University of Technology.

Beijer-Lundberg, A. (2015). *Displacement pile installation effects in sand*. PhD dissertation, Delft University of Technology.

Black, J.A. (2014). Development of a small scale teaching centrifuge. In: *Physical Modelling in Geotechnics – Proceedings of the 8th International Conference on Physical Modelling in Geotechnics (ICPMG 2014)*, Perth, Australia, pp. 187–192.

Cassidy, M.J. (2007). Experimental observations of the combined loading behaviour of circular footings on loose silica sand. *Géotechnique*, 57(4), pp. 397–401. http://doi.org/10.1680/geot.2007.57.4.397

Chortis, G., Achmus, M. and others (2020). Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. *Ocean Engineering*, 197, 106838. http://doi.org/10.1016/j.oceaneng.2019.106838

Fanning, J., Lehane, B. and others (2023). Pullout capacity of single and biwing anchors in a soft clay deposit: model investigation in a centrifuge and FEM predictions. *Journal of Geotechnical and Geoenvironmental Engineering*, 149(7), 04023050. http://doi.org/10.1061/JGGEFK.GTENG-11103

Freitas, A.C. de, Almeida, M. de S.S. de and others (2024). Pullout behavior of single and clustered torpedo anchors. *Ocean Engineering*, 311, 118858. http://doi.org/10.1016/j.oceaneng.2024.118858

de Freitas, A.C., Almeida, M. de S.S. de and others (2025). Pullout angle influence on the behavior of a single T-120 torpedo anchor. *Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025)*, Nantes, France.

Gaudin, C., White, D.J. and others (2009). A wireless high-speed data acquisition system for geotechnical centrifuge model testing. *Measurement Science and Technology*, 20(9), 095709. http://doi.org/10.1088/0957-0233/20/9/095709

Gaudin, C., Cassidy, M.J. and others (2011). Recent contributions of geotechnical centrifuge modelling to the understanding of jack-up spudcan behaviour. *Ocean Engineering*, 38(7), pp. 900–914. http://doi.org/10.1016/j.oceaneng.2011.02.011

Gue, C.S., Gaudin, C. and others (2010). Centrifuge modelling of submarine landslide flows. *Proceedings of the 7th International Conference on Physical Modelling in Geotechnics*, Zurich, Switzerland.

Hossain, M.S. and Randolph, M.F. (2010). Deep-penetrating spudcan foundations on layered clays: centrifuge tests. *Géotechnique*, 60(3), pp. 157–170. http://doi.org/10.1680/geot.8.P.089

Hotta, M.M., Gaudin, C. and others (2019). Centrifuge tests for evaluation of submarine-mudflow hydroplaning and turbidity currents. *International Journal of Physical Modelling in Geotechnics*, 20(4), pp. 239–253. http://doi.org/10.1680/jphmg.18.00027

Klinkvort, R.T., Achmus, M. and others (2025). Centrifuge modelling considerations of laterally loaded monopiles in sand. *International Journal of Physical Modelling in Geotechnics*. http://doi.org/10.1680/jphmg.24.00036

Orakci, O., Achmus, M. and others (2024). Monopile under lateral loading: centrifuge testing and numerical investigation. *Proceedings of the 5th European Conference on Physical Modelling in Geotechnics (ECPMG 2024)*.

Sakellariadis, L., Askarinejad, A. and others (2023). Testing pile foundations at the ETH Zurich drum centrifuge: recent developments. *International Journal of Physical Modelling in Geotechnics*, 23(5), pp. 219–247. http://doi.org/10.1680/jphmg.22.00016

Wang, S. and Idinger, G. (2021). A device for rainfall simulation in geotechnical centrifuges. *Acta Geotechnica*, 16(9), pp. 2887–2898. http://doi.org/10.1007/s11440-020-01092-4

van Zeben, J.C.B. (2017). *Physical modelling of pore pressure development during impact pile driving using a geotechnical centrifuge*. MSc thesis, Delft University of Technology.

Zhang, L., Ng, C.W.W. and others (2022). The 850 g-ton modular drum centrifuge facility at HKUST. In: *Proceedings of the 10th International Conference on Physical Modelling in Geotechnics (ICPMG 2022)*.

Zhang, W. and Askarinejad, A. (2019). Centrifuge modelling of submarine landslides due to static liquefaction. *Landslides*, 16(10), pp. 1921–1938. http://doi.org/10.1007/s10346-019-01203-7

Zhang, Y., Bienen, B. and Cassidy, M.J. (2013). Development of a combined VHM loading apparatus for a geotechnical drum centrifuge. *International Journal of Physical Modelling in Geotechnics*, 13(1), pp. 13–30. http://doi.org/10.1680/ijpmg.12.00012

Zhang, Y., Sudhakaran, K. and Askarinejad, A. (2020). Centrifuge modelling of suction caissons subjected to cyclic loading in tension. *Proceedings of the 4th European Conference on Physical Modelling in Geotechnics*, pp. 263–268.