The paper was published in the proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG2026) and was edited by Ioannis Anastasopoulos. The conference was held from June 8th to June 12th 2026 in Zurich, Switzerland.

ICPMG 2026

Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Design and Commissioning of a High-Energy Impact Hammer for Large-Diameter Monopile Installation in the Deltares Centrifuge

C. Cengiz, A. R. Piedrabuena, R. Zwaan, K. Castelein
Deltares, Delft, The Netherlands, cihan.cengiz@deltares.nl, alba.rodriguezpiedrabuena@deltares.nl, rob.zwaan@deltares.nl, koen.castelein@deltares.nl

T. Quinten, M. A. Cabrera
TU Delft, Delft, The Netherlands, t.o.quinten@tudelft.nl, m.a.cabrera@tudelft.nl

A. Elkadi
Deltares, Delft, The Netherlands, ahmed.elkadi@deltares.nl

ABSTRACT: This contribution elaborates on the design and commissioning of a large impact hammer developed at Deltares for use in the geotechnical centrifuge. The hammer is intended to enable in-flight installation of monopiles with a model diameter of 0.1 m, corresponding to 10 m in prototype scale, under 100 g conditions. This represents a significant scale-up compared to previous centrifuge impact hammers, both in terms of the blow energy delivered and the pile size that can be installed. The development builds upon earlier efforts such as the cam-driven hammers reported in the literature, but targets higher energy levels, improved controllability, and structural robustness to accommodate the larger model dimensions. The paper outlines the main design considerations including the mechanical energy delivery system, ram and anvil configuration, pile-hammer interface. Instrumentation to monitor impact forces, penetration resistance, and embedment depth will be integrated in the system to capture installation performance at high fidelity. The commissioning phase currently involves off-flight calibration tests. Future endeavours will include in-flight trials, during which challenges associated with scaling energy input and maintaining repeatability under enhanced gravitational fields will be addressed. The hammer is expected to enable systematic research on the influence of installation method and energy on the axial and lateral response of large-diameter monopiles for offshore wind applications.

1 INTRODUCTION

The increasing use of large-diameter monopiles for offshore wind has intensified the need to understand installation effects under realistic stress conditions. Installation method, delivered energy, and penetration rate influence soil disturbance, excess pore pressure generation, and the resulting axial and lateral response of the foundation. While centrifuge modelling offers a means to reproduce prototype stress levels, existing centrifuge impact hammers (Nietiedt et al., 2024; Maatouk et al., 2024; Quinten et al., 2024) are limited in delivered energy and pile size, restricting their applicability to modern monopile geometries. To address this gap, the development of a high-energy impact hammer development was initiated. The hammer is capable of installing model piles of 0.1 m diameter under 100 g conditions. This paper reports on the early phases of this development, focusing on the initial design, system integration, and first commissioning activities.

2 DESIGN CONCEPT

The hammer is based on a drop-weight principle using a cam-driven lifting system that raises and releases a ram onto an anvil connected to the pile head. The concept builds on earlier cam-based centrifuge hammers, but is scaled to deliver substantially higher impact energies. The delivered energy is controlled through adjustable ram mass, drop height, and impact frequency. The hammer frame incorporates linear bearings to guide the ram. A dedicated pile-hammer interface ensures axial alignment during installation while allowing decoupling after driving. A vertical positioning system follows pile penetration in-flight, enabling continuous installation without stopping the centrifuge. At this stage, the system represents a first-generation configuration intended to establish basic functionality and identify design limitations. Figure 1 illustrates a schematic of the system.

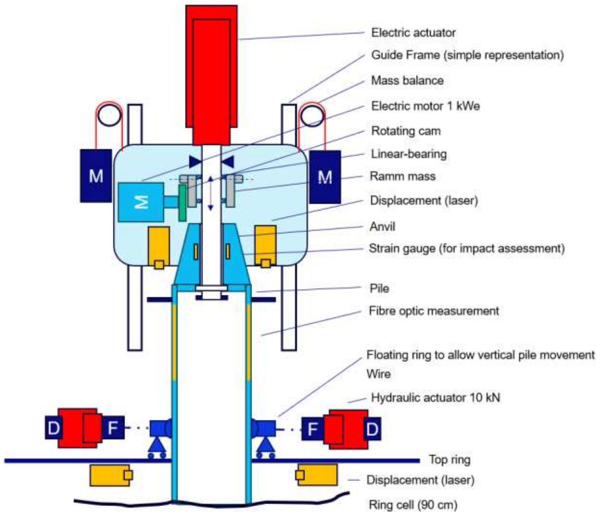

Figure 1. A sketch of the impact hammer, the ring cell is a strongbox which is of cylindrical shape. At Deltares, ring cells can be stacked on top of each other to create strongboxes of up to 1.5m deep.

3 INSTRUMENTATION AND CONTROL

The system is instrumented to capture installation performance at high temporal resolution. Impact forces are measured using strain gauges and load cells at the anvil–pile interface, while laser displacement sensors track ram motion and pile penetration. Accelerometers mounted on the ram and anvil provide impact acceleration histories. The vertical positioning system is controlled by an electric actuator operating in displacement control, using feedback from laser sensors to follow the penetration profile. Control strategies are still under development and will be refined as further test data become available.

4 COMMISSIONING

Commissioning is currently in its initial phase and has so far involved off-flight calibration and a limited number of in-flight trials. Off-flight tests focused on verifying the energy delivery system, basic control stability, and sensor functionality. Early in-flight trials at elevated g-levels were used to assess impact repeatability, achievable penetration rates, and mechanical robustness under enhanced gravity. These early tests have highlighted key challenges, including scaling impact energy with g-level, managing increased friction and wear of moving parts, and maintaining stable control of the vertical positioning system. The results provide a first validation of the concept, while also defining priorities for the next design and testing iterations. Figure 2 illustrates a photograph of the current impact hammer system at Deltares.

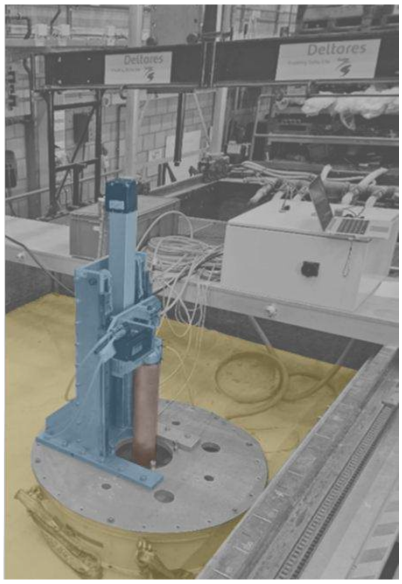

Figure 2. A photograph of the impact hammer system tested under 1-g conditions (in blue shading: the support and actuation system; in red shading: the 100 mm diameter pile).

5 CONCLUSIONS

A high-energy impact hammer for in-flight installation of large-diameter monopiles is under development at Deltares. First trials demonstrate the feasibility of driving 0.1 m diameter model piles under high g-levels, while also revealing critical technical challenges related to energy scaling, control stability, and mechanical durability. Ongoing work will focus on iterative design refinement and expanded testing, with the long-term aim of providing a robust experimental capability.

ACKNOWLEDGEMENTS

This research is supported by HybridLabs, NWO project NWA.1518.22.066. Authors are grateful for the financial support provided.

REFERENCES

Maatouk, S., Blanc, M., Thorel, L., 2024. Effect of embedding depth on the monotonic lateral response of monopiles in sand: centrifuge and numerical modelling. Géotechnique 74, 1111-1126.

Nietiedt, J.A., Randolph, M.F., Gaudin, C., Doherty, J.P., 2024. Development of a high-energy centrifuge model impact hammer for pile-driving. International Journal of Physical Modelling in Geotechnics 24, 56-65.

Quinten, T., Ioannou, C., Cabrera, M., Askarinejad, A., Gavin, K., van Wijk, J., 2024. Performance of the BLUE blow generator for centrifuge modelling at Delft University of Technology (DUT), Proc. 5th Eur. Conf. Phys. Mod. Geotech.