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

Mechanical behaviour of caisson foundations: insights from centrifuge tests

G. Boccieri
Università degli Studi di Roma Tor Vergata, Rome, Italy, gabriele.boccieri@uniroma2.it

P. Marveggio, G. Della Vecchia
Politecnico di Milano, Milan, Italy, pietro.marveggio@polimi.it, g.dellavecchia@polimi.it

R. Cesaro, R. Di Laora
Università della Campania Luigi Vanvitelli, Aversa, CE, Italy, raffaele.cesaro@unicampania.it raffaele.dilaora@unicampania.it

G. Boccieri, R. Conti
Università degli Studi di Roma Tor Vergata, Rome, Italy, riccardo.conti@uniroma2.it

L. Flessati
Delft University of Technology, Delft, The Netherlands, l.flessati@tudelft.nl

ABSTRACT: Caisson foundations are an efficient solution for offshore structures due to their installation simplicity and the possibility of reuse or controlled decommissioning. However, their mechanical behaviour still presents open challenges, such as the role of the soil enclosed within the caisson, the effect of installation on the stress state, the influence of soil foundation stiffness, and, more generally, the response under inclined and eccentric cyclic loads. Key design issues include the definition of failure conditions, the accumulation of permanent rotations under cyclic loading, and the interaction between vertical, horizontal and moment components, which remain only partially resolved despite past numerical and experimental studies.
To address these aspects, a centrifuge test campaign was carried out at TU Delft. Small-scale caisson models were tested in sand deposits prepared at controlled density and subjected to monotonic and cyclic inclined loading. Cyclic tests explored different load amplitudes and sequential stages, aiming to reproduce progressive deformation accumulation and the probabilistic nature of wind-induced actions.
Preliminary findings indicate that the ultimate capacity under eccentric loading is strongly influenced by the applied vertical load. The experimental results provide a valuable benchmark for the calibration of advanced numerical models and for the definition of interaction domains, supporting the development of simplified but reliable design tools for offshore geotechnical applications.

1 INTRODUCTION

In the framework of the Sustainable Development Goals (SDGs), the exploitation of marine resources for renewable energy production represents a strategic priority for the transition towards a cleaner, more resilient, and more efficient energy system (SDG 7 – Affordable and Clean Energy; SDG 9 – Industry, Innovation and Infrastructure). In this context, offshore transport and energy infrastructures, such as platforms, subsea pipelines, transmission cables, fixed foundation systems, and anchoring systems for wind or marine devices, are taking on an increasingly central role.

Among the most versatile foundation systems in the marine environment, caisson foundations offer significant advantages in terms of intallation simplicity, bearing capacity, and the possibility of decommissioning or reuse. These structures are used both as fixed foundations and as anchoring and support systems for pipelines, cables, and floating or semi-submersible energy systems (*e.g.*, offshore wind, wave energy, temporary platforms).

The behaviour of foundation caissons subjected to cyclic loading has received growing attention in the scientific community (Byrne and Houlsby, 2004, Villalobos et al., 2009, LeBlanc et al, 2010). Numerous experimental and numerical studies have investigated the effects of cyclic loading on rotational response, stiffness, and bearing capacity of caissons in different soil types, highlighting the importance of soil mechanical properties, soil–structure contact models, and foundation geometry (Achmus et al, 2013, Zhu et al, 2013, Ibsen et al., 2014). This interest stems from the need to predict the accumulation of rotations, the evolution of stiffness, and the interaction between inclined and eccentric loads, key aspects to ensure the long-term functionality and durability of offshore turbines. Recent studies have explored alternative configurations (*e.g.*, tripod or hybrid caisson), different loading conditions (unidirectional, bidirectional, irregular), and also critical scenarios such as seismically induced liquefaction (Gao et al., 2021, Shakeran and Soroush, 2024), underscoring the complexity of the problem and the need for integrated and validated models (Villalobos, 2006, Wang et al., 2017, Ueda et al., 2020).

Despite their apparent simplicity, the mechanical behaviour of caissons under realistic loading conditions is influenced by several factors that are not yet fully understood. Key design uncertainties include the contribution of the cap, the actual contribution of lateral friction, the role of relative stiffness between the foundation and the soil, and, above all, the response under cyclic actions. In particular, many questions remain open regarding how to define a failure criterion under cyclic loading, how accumulated rotations affect capacity over time, and what the actual interaction is between inclined and eccentric loading, which reflects the most common operating conditions in offshore systems. In many cases, the vertical bearing capacity of the caisson is relatively easy to estimate, but the interaction among horizontal, vertical, and moment components makes the design complex and highly sensitive to the assumptions adopted. The lack, on the one hand, of rigorous analytical models to define ultimate conditions, and, on the other, of integrated models capable of accurately representing the deformational response under cyclic loads typical of the offshore environment, makes this topic particularly relevant and still the subject of intensive research.

To address these challenges, an experimental centrifuge campaign has been carried out at Delft University of Technology (Technische Universiteit Delft) within a PRIN 2022 research project led by the University of Campania “Luigi Vanvitelli”, with the University of Rome Tor Vergata and Politecnico di Milano as scientific partners. This note presents the testing system used to conduct the experimental campaign, together with some preliminary test results that have highlighted aspects useful for understanding the physical mechanisms governing the system response.

The experimental programme includes small-scale physical models tested in a centrifuge at 50g, with geometries representative of the most commonly used caissons. The foundation models, installed inside a strongbox filled with dense sand, are subjected to vertical and inclined loads through an actuator mounted on an arm rigidly connected to the strongbox.

The programme includes two main types of tests:

- Eccentric inclined loads, progressively applied up to failure to analyse the response under pseudo-static conditions;
- Cyclic inclined and eccentric loads, performed with a gradual increase of amplitude at each cycle, in order to investigate the accumulation of irreversible displacements and stiffness degradation.

2 EXPERIMENTAL SETUP

The experimental campaign was carried out using the geotechnical centrifuge at Delft University of Technology (Fig. 1a), which has a nominal radius of 1.3 m. The model was spun up to an acceleration level of 50*g* to reproduce the monotonic and cyclic response of a suction caisson embedded in dry sand. The suction caisson model, manufactured by aluminium 3D printing to prevent structural deformations during testing, had an L/D ratio of 0.5 (Fig. 2), with D = 7 cm, L = 3.5 cm, and a cap thickness of 0.5 cm at model scale.

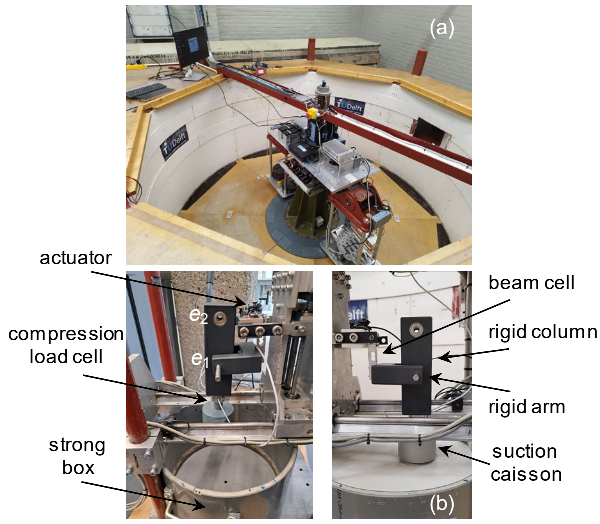

Figure 1 - (a) TU Delft geotechnical centrifuge and (b) model setup.

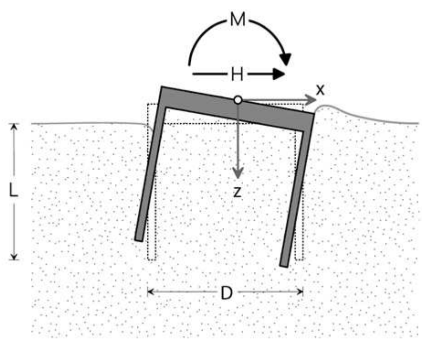

Figure 2 - Suction caisson model geometry

Figure 1b shows the experimental setup, consisting of a cylindrical strongbox with a diameter of approximately 30 cm and a height of about 20 cm, and a loading system designed to apply controlled inclined loads with two different eccentricities (e_1 = 11.2 cm and e_2 = 18.2 cm from the caisson cap, at model scale). The loading system consists in a rigid column and a rigid arm connected through a hinged joint, in order to prevent the development of undesired bending moments. The rigid column was connected to the actuator through a beam load cell, which measured the horizontal component of the applied load. In addition, a compression load cell was installed between the rigid column and the caisson model to measure the vertical load component. Two laser displacement sensors were positioned at the top of the rigid column to monitor horizontal displacement and rotation of the caisson model, while also a horizontal displacement transducer was installed to provide an additional, independent measurement of horizontal displacements.

The dry sand deposit was prepared using a bottom-tamping procedure to achieve a homogeneous and repeatable soil layer in terms of overall height and relative density. A target relative density of 75–80% was adopted for all tests, with the sand layer height ranging between 14.5 and 15.5 cm at model scale.

In this experimental campaign, Geba sand and Karlsruhe sand were used. Both materials have been widely investigated in the literature through oedometer tests as well as monotonic and cyclic triaxial laboratory testing (Wichtmann et al., 2005, 2010, Wichtmann and Triantafyllidis, 2016a, 2016b, Liu et al., 2026). The main physical and mechanical properties of the two sands are reported in Table 1.

Table 1. Geba sand and Karlsruhe properties. G_s = specific gravity; e_{max}, e_{min} = maximum and minimum void ratio; ϕ'_{cv} = constant-volume friction angle.

Parameter	Geba sand	Karlsruhe sand
G_s [-]	2.67	2.66
e_{max} [-]	1.07	0.874
e_{min} [-]	0.64	0.577
ϕ'_{cv} [°]	31.15	33.10

The caisson model was installed at 1g by jacking it into the sand bed, while carefully monitoring its vertical alignment.

3 PRELIMINARY RESULTS

In this section, the first outcomes of the experimental campaign are outlined and briefly discussed. For consistency, all quantities are expressed at prototype scale.

Figure 3 presents a set of four moment–rotation relationships obtained from different tests. In each test, the vertical load was first applied and then maintained constant, whereas the horizontal action was imposed by incrementally increasing the horizontal displacement at a prescribed eccentricity.

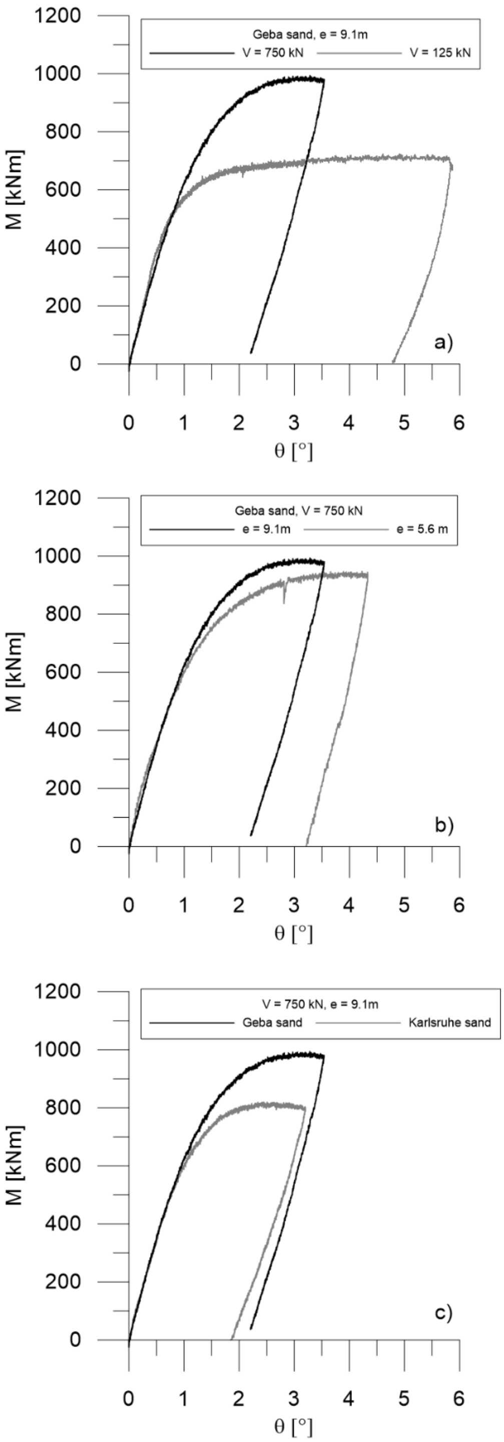

Figure 3 - Comparison of moment-rotation response curves at prototype scale for: (a) different applied vertical loads, V; (b) different eccentricities, and (c) different sand.

The role of the vertical load is illustrated in Fig. 3a through the comparison of two tests. Both results were obtained using the same caisson specimen installed in a Geba sand deposit, with horizontal displacement applied at the same eccentricity (e = 9.1 m), but under two distinct vertical load levels (V = 750 kN and V = 125 kN). Even though both values remain well below the caisson vertical bearing capacity, the maximum moment mobilized by the soil–foundation system clearly depends on the magnitude of V. In contrast, the initial rotational stiffness is practically unaffected by the applied vertical load.

The sensitivity to load eccentricity is addressed in Fig. 3b. The two tests share identical caisson geometry, the same soil type (Geba sand), and the same vertical load (V = 750 kN), while differing only in the eccentricity of the imposed horizontal displacement (e = 9.1 m versus e = 5.6 m). Within the range explored, changing eccentricity produces no appreciable variation, neither in the initial stiffness nor in the ultimate moment capacity, plausibly because the two eccentricities are relatively close.

Lastly, Fig. 3c compares responses obtained for the same caisson model embedded in two different sands, keeping the loading programme unchanged (V = 750 kN and e = 9.1 m). The initial portion of the curves indicates similar rotational stiffness in both deposits; however, the peak moment is higher for the caisson installed in Geba sand.

Figure 4a reports the time evolution of the caisson rotation, θ, for two one-way cyclic tests conducted in load control on models installed in Geba sand. In both cases, the vertical load was kept constant at V = 125 kN and the loading programme was organised into four blocks. Within each block, a horizontal cyclic load with constant amplitude was applied. Each block consisted of 2450 cycles, and the prototype cycling frequency was 0.01 Hz throughout. The horizontal load, H, was applied at a constant eccentricity (e = 9.1 m), while its amplitude was changed from one block to the next (7.5, 15, 22.5 and 30 kN). Once the four cyclic blocks were completed, the tests were extended under displacement control until reaching the ultimate moment capacity of the soil–foundation system.

The two tests differed only in the ordering of the load amplitudes. In test C1 the amplitudes increased from block to block (7.5 → 15 → 22.5 → 30 kN), while in test C2 they were applied in the reverse sequence (30 → 22.5 → 15 → 7.5 kN). In C2, the first cycle of the initial block generated a markedly larger irrecoverable rotation than the cycles that followed; thereafter the rotation continued to build up at a progressively lower rate, and the subsequent blocks produced only minor additional permanent rotation. A similar behaviour is visible in C1, but it repeats at the beginning of each block: rotation increases rapidly during the first cycles of a given amplitude level and then tends to stabilise as the number of cycles grows.

At the end of cycling, the residual rotation obtained in the two tests differs by about 20%. These early indications should be verified with further experiments, especially to assess whether Miner's rule can be applied to the cyclic response of suction caissons in dry sand.

In Figure 4b the moment–rotation envelopes from the two cyclic tests is compared with the corresponding monotonic curve (black line in Fig. 3a). The initial rotational stiffness is consistent between monotonic and cyclic conditions, whereas both cyclic tests show a lower ultimate moment capacity. This decrease is ascribed to the permanent rotation accumulated during the cyclic phase.

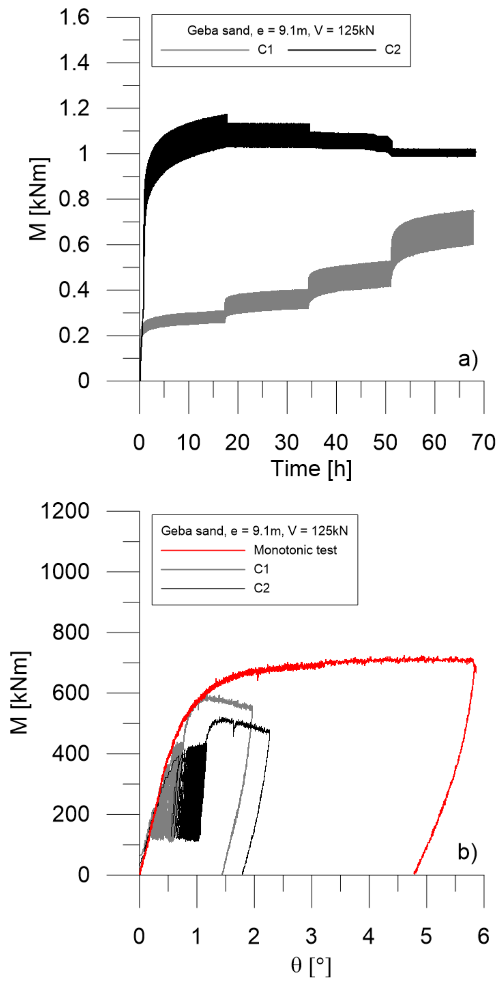

Figure 4 - (a) Time evolution of caisson rotation, θ, for two cyclic tests and (b) comparison between the moment-rotation response curves obtained from cyclic tests and the corresponding monotonic test, at prototype scale.

4 CONCLUDING REMARKS

The paper provides initial evidence from a centrifuge experimental programme on suction caissons installed in dry sand, aimed at capturing both monotonic response and cyclic degradation mechanisms. Particular attention was placed on the development of residual (permanent) rotations under combined inclined loading and horizontal actions applied with eccentricity, in line with demand conditions expected for offshore wind turbine foundations.

Results from monotonic loading show that the peak moment resistance mobilised by the soil–foundation system depends on the level of the imposed vertical load, even though the applied values remain far from the vertical capacity of the caisson. In contrast, the small-rotation stiffness is essentially unchanged. For the eccentricity interval explored, modifying the lever arm of the horizontal action did not lead to appreciable changes in the measured moment–rotation response.

Under cyclic loading, the tests reveal substantial build-up of irreversible rotation, with most of the accumulation taking place within the earliest cycles. In these preliminary data, the ordering of the amplitude blocks affected the residual rotation at the end of cycling: sequences with increasing versus decreasing amplitudes resulted in differences on the order of 20%. When compared with the monotonic reference response, the cyclic tests exhibited similar initial stiffness but a lower ultimate moment capacity after cycling, which is consistent with the permanent rotations accumulated during the cyclic stages.

Further centrifuge testing is needed to verify these tendencies and to provide a sound basis for the development of predictive tools aimed at assessing the long-term performance of suction caisson foundations for offshore wind applications.

ACKNOWLEDGEMENTS

This work was carried out within the framework of the PRIN 2022 project, INTERACT – "Innovative Design Approach for Offshore Wind Turbine Founda-tions," with support from the Italian Ministry of University and Research (MUR). It was funded by the European Union's NextGenerationEU, Mission 4, Component 1, CUP B53D23005530006.

REFERENCES

Achmus, M., Akdag, C. T., & Thieken, K. (2013). Load-bearing behavior of suction bucket foundations in sand. *Applied Ocean Research, 43*, 157–165. https://doi.org/10.1016/j.apor.2013.09.001

Byrne, B. W., & Houlsby, G. T. (2004). Experimental investigations of the response of suction caissons to transient combined loading. *Journal of Geotechnical and Geoenvironmental Engineering, 130*(3), 240–253. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:3(240)

Gao, B., Ye, G., Zhang, Q., Xie, Y., & Yan, B. (2021). Numerical simulation of suction bucket foundation response located in liquefiable sand under earthquakes. *Ocean Engineering, 235*, 109394. https://doi.org/10.1016/j.oceaneng.2021.109394

Ibsen, L. B., Larsen, K. A., & Barari, A. (2014). Calibration of failure criteria for bucket foundations on drained sand under general loading. *Journal of Geotechnical and Geoenvironmental Engineering, 140*(7), 04014033. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000995

LeBlanc, C., Houlsby, G. T., & Byrne, B. W. (2010). Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique, 60*(2), 79–90. https://doi.org/10.1680/geot.7.00196

Liu, H., Konstadinou, M., Wang, H., Jostad, H. P., & Pisanò, F. (2026). 3D FE cyclic modelling of monopiles in sand using SANISAND-MS: calibration and validation from soil element to pile-interaction scale. *Soil Dynamics and Earthquake Engineering*. https://doi.org/10.1016/j.soildyn.2026.110177

Shakeran, M., & Soroush, A. (2024). Centrifuge testing on ordinary and hybrid suction caissons subjected to cyclic lateral loading. *Ocean Engineering, 300*, 117471. https://doi.org/10.1016/j.oceaneng.2024.117471

Ueda, K., Uzuoka, R., Iai, S., & Okamura, T. (2020). Centrifuge model tests and effective stress analyses of offshore wind turbine systems with a suction bucket foundation subject to seismic load. *Soils and Foundations, 60*(6), 1546–1569. https://doi.org/10.1016/j.sandf.2020.08.007

Villalobos, F. A. (2006). *Model testing of foundations for offshore wind turbines* (Doctoral thesis, University of Oxford).

Villalobos, F. A., Byrne, B. W., & Houlsby, G. T. (2009). An experimental study of the drained capacity of suction caisson foundations under monotonic loading for offshore applications. *Soils and Foundations, 49*(3), 477–488. https://doi.org/10.3208/sandf.49.477

Wang, X., Yang, X., & Zeng, X. (2017). Centrifuge modeling of lateral bearing behavior of offshore wind turbine with suction bucket foundation in sand. *Ocean Engineering, 139*, 140–151. https://doi.org/10.1016/j.oceaneng.2017.04.046

Wichtmann, T., Niemunis, A., & Triantafyllidis, T. (2005). Strain accumulation in sand due to cyclic loading: Drained triaxial tests. *Soil Dynamics and Earthquake Engineering, 25*(12), 967–979. https://doi.org/10.1016/j.soildyn.2005.02.022

Wichtmann, T., Niemunis, A., & Triantafyllidis, T. (2010). Strain accumulation in sand due to drained cyclic loading: On the effect of monotonic and cyclic preloading (Miner's rule). *Soil Dynamics and Earthquake Engineering, 30*(8), 736–745. https://doi.org/10.1016/j.soildyn.2010.03.004

Wichtmann, T., & Triantafyllidis, T. (2016a). An experimental database for the development, calibration and verification of constitutive models for sand with focus to cyclic loading: Part I—tests with monotonic loading and stress cycles. *Acta Geotechnica, 11*(4), 739–761. https://doi.org/10.1007/s11440-015-0402-z

Wichtmann, T., & Triantafyllidis, T. (2016b). An experimental database for the development, calibration and verification of constitutive models for sand with focus to cyclic loading: Part II—tests with strain cycles and combined loading. *Acta Geotechnica, 11*(4), 763–774. https://doi.org/10.1007/s11440-015-0412-x

Zhu, B., Byrne, B. W., & Houlsby, G. T. (2013). Long-term lateral cyclic response of suction caisson foundations in sand. *Journal of Geotechnical and Geoenvironmental Engineering, 139*(1), 73–83. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000738