ACPMG 2024

Proceedings of the 4th ACPMG 2024
4th Asia-Pacific Conference on Physical Modelling in Geotechnics
11-13 December 2024, Abu Dhabi, UAE

Recent innovations in the geotechnical centrifuge modelling at IWHR

Z.-T. Zhang, X.-D. Zhang, J. Hu, Y.-K. Wang and W.-K. Yang
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China, zhangzt@iwhr.com

ABSTRACT: China Institute of Water Resources and Hydropower Research has an advanced centrifuge modelling platform featuring three cutting-edge geotechnical centrifuges: the 450g-ton large centrifuge, the 1000g high-speed centrifuge, and the 1000g-ton super-large centrifuge. This paper presents recent innovations in centrifuge modelling at IWHR. The first innovation is an experimental device designed to characterize the responses of ultra-large diameter monopiles under complex lateral loadings conditions, such as multi-directional and multi-amplitude lateral loading. Hydraulic actuators are employed to apply lateral loads to the model pile, while MFB electrohydraulic servo-valves and controllers enable closed-loop position or load control. A specially designed module with a spherical hinge is used to connect model pile to the actuator shafts. This allows the pile to rotate and move vertically freely, mimicking prototype conditions accurately. This device has been successfully utilized to investigate the mechanical behaviour of ultra-large diameter monopiles under complex loading conditions. The second innovation is an upgraded tilting box used to study the failure behaviour of soil slopes. An electric motor is utilized to adjust the tilt box to the desired inclination at a specified centrifugal acceleration. Inner deformations of the slope are monitored using high-resolution distributed optical fibre based on optical frequency domain reflectometry and optical heterodyne detection methodologies. This upgraded apparatus has been effectively utilized to explore the failure mechanisms of both unreinforced and reinforced soil slopes.

1 INTRODUCTION

Due to the inherent nonlinearity and stress dependency of the mechanical properties of granular materials, such as sand and clay, accurately capturing their true mechanical behaviour necessitates a precise reproduction of their stress state. In geotechnical centrifuge modelling, the centrifugal force generated by the centrifuge amplifies the volume forces within the model, thereby replicating the stress conditions of the prototype. This enables the simulation of the mechanical behaviour of the prototype under natural gravitational fields. Over several decades, the development of relevant similarity theories has become progressively refined, alongside significant advancements in instrumentation. Consequently, centrifuge testing has emerged as a viable technique for physically simulating the stress and deformation behaviour of geotechnical materials.

China Institute of Water Resources and Hydropower Research (IWHR) has an advanced centrifuge modelling platform featuring three cutting-edge geotechnical centrifuges: the 450g-ton large centrifuge, the 1000g high-speed centrifuge, and the 1000g-ton super-large centrifuge. The 450g-ton centrifuge features a radius from the base plate of the test bucket to the rotational axis of 5.0 m, with a maximum centrifugal acceleration of 300g. The 1000g centrifuge is distinguished as the world's first geotechnical centrifuge capable of achieving a maximum centrifugal acceleration of 1000g in high-speed mode. Additionally, this centrifuge operates in a normal-speed mode, where it can achieve a maximum centrifugal acceleration of 200g while accommodating a payload capacity of 2 t. The 1000g-ton centrifuge has a radius of 9.5 m and a maximum centrifugal acceleration of 350g.

This paper presents recent innovations in centrifuge modelling at IWHR. The first innovation is a device to characterize the responses of ultra-large diameter monopiles under complex lateral loading conditions, such as multi-directional and multi-amplitude lateral loading. The second innovation is an upgraded tilting box used to study the failure behaviour of soil slopes. The design concepts, features and technical specifications of both innovations will be presented in the following.

2 DEVICE FOR TESTING ULTRA-LARGE DIAMETER MONOPILES

In offshore wind power development, increasing the capacity of individual turbines is a critical strategy for enhancing energy output density and reducing the levelized cost of electricity, thereby yielding substantial economic benefits. Consequently, there is a pronounced trend towards the larger sizing of offshore wind turbines. According to the latest report from the Global Wind Energy Council (GWEC), the largest wind turbines had a capacity of only 6 MW a decade ago. This figure has now increased to 18 MW, representing a threefold increase in capacity. As the structural dimensions of offshore turbines continue to expand, rotor diameters have now reached 280 m, with projections indicating that they may surpass 350 m in the near future (GWEC 2024).

Those large-scale towering structures are subjected to intricate wind, wave, and current loads, which impose stringent requirements on their foundations (Richards et al. 2020). Among the various foundation types, this study focuses on monopiles, which are the most widely utilized foundation solution for offshore wind turbines. As turbine capacity has increased, the dimensions of monopiles have also expanded, with diameters now reaching approximately 10 m. Ultra-large diameter monopile foundations are progressively exceeding the applicable water depth limits, approaching depths of 50~60 m, thereby underscoring their continued viability as a foundation solution. However, our understanding of the load-bearing performance of ultra-large diameter monopiles, particularly under complex loading conditions, necessitates further investigation. For example, the experimental conditions illustrated in this figure encompass both laboratory tests (including 1g tests and centrifuge tests) and field pile testing. Notably, the diameters of the tested piles are generally less than 6.5 m, highlighting a significant discrepancy when compared to the dimensions of ultra-large diameter monopiles (Wang et al. 2024). To improve our understanding of the performance characteristics of ultra-large diameter monopiles under relevant load conditions, a dedicated testing device was specifically designed at IWHR. The overall structure and features will be firstly introduced, followed by the technical specifications.

2.1 Overall structure and features

The overall structure comprises six principal components. The first component is a barrel-shaped soil container specifically designed for the preparation of pile foundation models. The second component includes a reaction frame and hydraulic actuators, which are employed to apply loads during testing. The third component consists of the connection assembly between the hydraulic actuators and the model pile; this element is critical as it significantly influences the testing outcomes. The fourth component comprises the servo valve, controller, and data acquisition instruments, which are strategically positioned adjacent to the rotational axis of the centrifuge. The fifth component is the upper computer, situated in the central control room on the first floor, which facilitates remote operation of the lower computer throughout the testing process. Finally, the sixth component is the hydraulic station, located on the second basement level below the centrifuge chamber, which supplies the system with necessary hydraulic fluid.

Compared to existing devices developed by other researchers, e.g., Rudolph et al. (2014), Bayton et al. (2018) and Truong et al. (2018), the device designed by IWHR demonstrates several distinguishing features:

(1) Independent reaction frame: In previous experimental designs, the soil container frequently functioned as the reaction frame, leading to the container bearing the weight of the loading apparatus. This arrangement has the potential to influence the deformation behaviour of the soil model. Furthermore, the reaction forces applied during loading could disturb the soil model, potentially introducing systematic biases. The incorporation of a separate reaction frame in the current design serves to minimize these disturbances, thereby enhancing the accuracy and reliability of the experimental results (see Fig. 1).

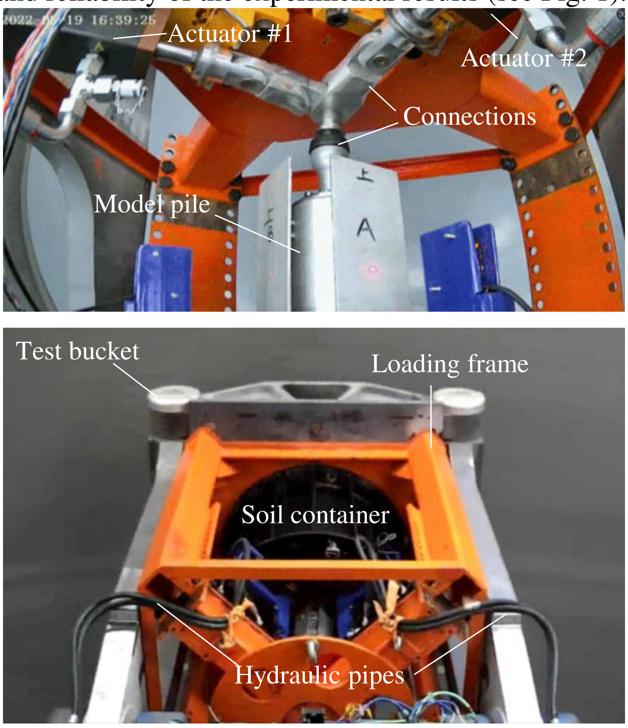

Figure 1. Photos of the in-flight device for testing extra-large diameter monopiles

(2) Sensors on the model pile for servo control: In order to accommodate hypergravity environments, we have shortened the length of the loading rod. To facilitate loading in multiple directions, the loading rod has been designed in an irregular shape (see Fig. 1), which precludes the installation of conventional sensors on those rods. As a result, our sensors are directly affixed to the model pile, enabling effective signal transmission to the controller for servo control.

(3) Free rotation and axial movement at the pile head: In conventional testing apparatus, the loading force is typically applied directly to the sidewalls of the model, which can result in stress concentrations near the loading points. This arrangement also complicates the application of multi-directional cyclic loading. In contrast, our design utilizes a specialized structure that integrates spherical hinges and linear bearings (see Fig. 1). This configuration allows for the loading point to be positioned along the longitudinal axis of the pile, facilitating free rotation at the pile head and permitting axial movement. Such constraints provide a more accurate representation of field conditions, enhancing the validity of the experimental results.

(4) Optimized space utilization: Given the limited space in the test bucket, we have arranged the actuators along the diagonal axis to maximize accommodation. Additionally, cavities within the columns of the reaction frame have been utilized for the installation of actuators.

(5) Strong scalability: The system is engineered for straightforward expansion. As illustrated in Fig. 1, the reaction frame consists of two primary components: the upper section, designed for the installation of hydraulic actuators, and the lower section, which comprises four columns and a base plate. The upper section is interchangeable, allowing for modifications to accommodate diverse requirements regarding the orientation or configuration of the actuators. Furthermore, due to the separable and liftable design of the upper section, it facilitates the convenient replacement of the soil container, thereby addressing various experimental demands. For example, by adjusting the actuators to a vertical orientation, it facilitates the execution of vertical pull-out tests. Additionally, the soil container can be readily replaced to accommodate the specific requirements of various experimental configurations.

2.2 Technical specifications

We have recently employed this new apparatus to conduct approximately 20 centrifuge model tests, investigating a diverse array of foundation types, including sandy soils, clay soils, and layered soils. In addition to conventional pile configurations, we have also evaluated monopiles with wings. The loading protocols utilized in our experiments include unidirectional step loading and cyclic loading with varying directions. Under conditions of 100g, the cumulative number of cycles for the variable direction cyclic loading has exceeded 100,000. Those centrifuge tests demonstrate that rotation accumulation or ratcheting behaviour is observed in both the direction of cyclic loading and the perpendicular constant loading direction for monopiles subjected to perpendicular cyclic loading. The mechanisms of deformation accumulation in clay differ markedly from those observed in sand. Notably, there appears to be a parabolic relationship between the rotation increment induced by cyclic loading and the number of loading cycles when represented on a log-log scale, prior to the rotation increment reaching its peak value. Furthermore, monopiles equipped with wings demonstrate a reduced number of loading cycles required to achieve rotational saturation. Additionally, the maximum rotation increment for piles with wings is significantly smaller than that recorded for piles without wings.

The tests conducted validated both the functionalities and capabilities of the device, as well as confirmed its technical specifications, which are presented below:

(1) Maximum allowable centrifugal acceleration: 100g;

(2) Maximum loading force: 5 kN;

(3) Maximum loading frequency: 5 Hz;

(4) Maximum number of loading cycles per single test: 10,000;

(5) Displacement control capability;

(6) Force control capability;

(7) Capability for variable direction loading;

(8) Loading speeds ranging from 0.005 mm/s to 10 mm/s.

3 TILTING BOX TO MODEL SOIL SLOPE FAILURE

Investigating the limit states and failure modes of slopes through centrifuge model tests has historically presented significant challenges. Traditionally, researchers have aimed to induce slope instability by increasing the centrifugal acceleration; however, this method frequently results in low success rates. In response to this issue, IWHR developed a rotating model box. This apparatus utilizes an electric motor to rotate the model box, thereby allowing for the adjustment of the slope angle to promote instability and failure (see Fig. 2). Utilizing this innovative device, Chen et al. (2015) successfully simulated the overturning failure of slopes constructed from aluminum blocks and LEGO plastic modules. This device has undergone significant upgrades in recent years. The main upgrades and technical specifications of the device will be presented in the following sections.

3.1 Main upgrades

Two main upgrades have been made. The first one is to install a slope surface displacement measurement frame. The frame allows installation of a series of laser displacement sensors. The locations of the sensors can be easily adjusted for different slope profiles. This enables high-density measurements of horizontal and vertical displacements at slope surface (see Fig. 2).

The second upgrade involves high spatial resolution measurements of internal deformations. Due to the potential disturbance of the original strain field in soils caused by the installation of sensors, accurately measuring internal deformations in soils remains a challenging task. This study employs distributed optical fibre technology to achieve the desired outcomes (see Fig. 2). The optical fibres are relatively flexible and small in size, which minimizes disturbances to the internal deformations. To validate this approach, calibration tests have been conducted within a specially designed calibration box.

The distributed optical fibre technology is founded on optical frequency domain reflectometry (OFDR) and optical heterodyne detection methodologies. This technology has reached a mature stage under 1g conditions and has been extensively utilized for monitoring internal deformations in geotechnical structures, including earth-rock dams, slopes, and subgrades. However, its application in centrifuge testing remains relatively limited. The primary challenge arises from the requirement that, in centrifuge model tests, the distributed fibre optic demodulator must be positioned near the rotation axis of the centrifuge, while the sensing fibre is embedded within the soil model in the test bucket. This arrangement results in a relatively long lead between the demodulator and the sensor, which can introduce noise due to vibrations of the leads during centrifuge rotation.

Utilizing the 1000g high-speed centrifuge with a capacity of 400g-ton, the absence of vibration isolation measures presents significant difficulties in obtaining accurate strain data at approximately 20g. After the implementation of rigorous vibration isolation techniques for the leads, this threshold can be increased to around 40g. Further optimization of the vibration isolation measures may enhance the system's adaptability to higher gravitational fields, which will be the focus of future research.

3.2 Technical specifications

Using the upgraded tilting box, centrifuge model tests were conducted on sandy slopes as well as on corresponding reinforced slopes. These tests further validated the technical specifications of the device. The main technical specifications are as follows:

(1) Internal dimensions of the model box: 600 mm × 300 mm × 300 mm;

(2) Mass of the model box: 80 kg;

(3) Maximum inclination angle: 30°;

(4) Highest spatial resolution for internal strain measurements: 5 mm.

(5) Rotation rate: 1.5°/min.

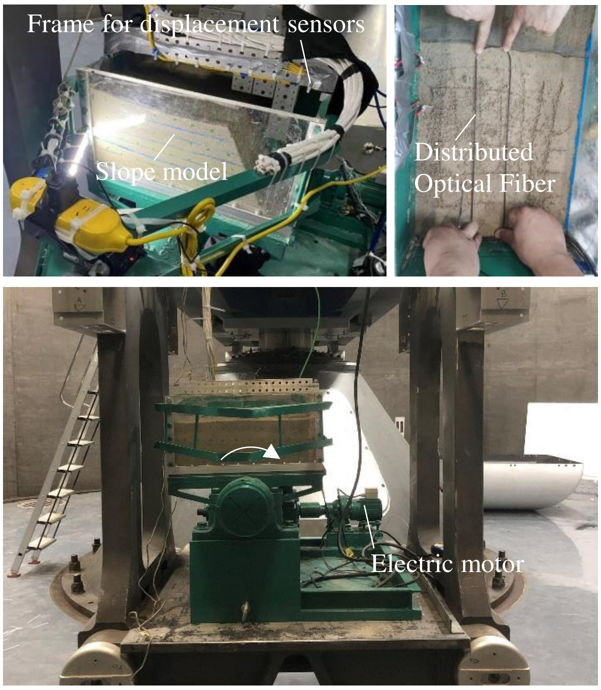

Figure 2. Photos of the tilting box to model soil slope failure

4 CONCLUDING REMARKS

This study presents two recent innovations in geotechnical centrifuge modeling at IWHR. The first innovation is a device designed for testing ultra-large diameter monopiles, which employs electro-hydraulic servo control technology. This device has been successfully utilized to investigate the mechanical behaviour of ultra-large diameter monopiles under complex loading conditions. The number of actuators is planned to be increased in the future to enhance collaborative control capabilities, thereby creating a more realistic simulated loading environment.

The second innovation involves an upgraded tilting box for modeling soil slope failure. This upgraded apparatus has been effectively utilized to explore the failure mechanisms of both unreinforced and reinforced soil slopes. One of the main upgrades is the implementation of high spatial resolution measurements of internal deformations, achieved through distributed optical fibre technology. Future work will focus on improving vibration isolation measures to enhance its adaptability to higher supergravity conditions.

ACKNOWLEDGEMENTS

This research was supported by the research project of China Three Gorges Corporation (202103016). The authors are also grateful to reviewers for valuable comments.

REFERENCES

Bayton, S. M., Black, J. A. and Klinkvort, R. T. (2018). Centrifuge modelling of long term cyclic lateral loading on monopiles. In *Proceedings of the 9th International Conference on Physical Modelling in Geotechnics*, London, UK, 689-694. CRC Press.

Chen, Z.-Y., Gong, W.-J., Ma, G.-W., et al. (2015). Comparisons between centrifuge and numerical modeling results for slope toppling failure. *Science China: Technological Sciences.* 58(9): 1497-1508.

GWEC (2024). GWEC global wind report 2024. Global wind energy council: Bonn, Germany.

Richards, I. A., Byrne, B. W. and Houlsby, G. T. (2020). Monopile rotation under complex cyclic lateral loading in sand. *Géotechnique* 70(10), 916-930.

Rudolph, C., Grabe, J., and Bienen B. (2014). Response of monopiles under cyclic lateral loading with a varying loading direction. In *Proceedings of the 8th International Conference on Physical Modelling in Geotechnics*, Perth, Australia, 453-458. CRC Press.

Truong, P., Lehane, B. M., Zania, V., et al. (2019). Empirical approach based on centrifuge testing for cyclic deformations of laterally loaded piles in sand. *Géotechnique* 69(2), 133-145.

Wang, W., Zhang, Z.-T., Yu, G.-M., et al. (2024). Small-displacement behaviour of offshore wind power monopiles subjected to static lateral loading. *Chinese Journal of Geotechnical Engineering*. http://kns.cnki.net/kcms/detail/32.1124.TU.20240717.1033.006.html. (in Chinese).