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

Development of an integrated pile driving and loading system for centrifuge tests

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ABSTRACT: An integrated pile driving and loading system has been developed at Zhejiang University for centrifuge tests. The system comprises modular components for impact piling, vertical tracking, uninterrupted loading, and integrated data acquisition and control. It enables in-flight impact pile driving under the in-situ soil stress state, simulating realistic installation of marine piles. Hammer drop height is precisely controlled, and vertical guidance ensures accurate, stable penetration. Flexible switching between penetration and loading avoids soil disturbance from repeated spin-down and spin-up. An example centrifuge test demonstrates the system's performance, achieving well-controlled impact piling followed by successful load testing. The system provides a versatile platform for investigating pile installation and loading, with potential to address engineering challenges such as pile run and premature refusal.

1 INTRODUCTION

Given the limited offshore construction window and the challenging site conditions, impact pile driving is commonly employed for marine pile installation due to its relative operational simplicity and high installation efficiency (Staubach et al., 2022; Zhang et al., 2025). However, frequent engineering issues, such as pile run and premature refusal, highlight the limited understanding of impact pile driving processes. In addition, the influence of pile installation on subsequent loading, as well as the aging effects on pile capacity, remain poorly understood (Dyson et al., 2025; Kashichenula et al., 2025; Zhang et al., 2025). This lack of understanding makes it difficult to determine when pile capacity satisfies design requirements. It also complicates the establishment of appropriate safety factors for later modifications to the superstructure. Consequently, experimental investigations of impact pile driving and the subsequent pile bearing behavior are crucial. Compared to small-scale model tests and full-scale field tests, centrifuge tests enable realistic replication of in-situ stress conditions at a relatively low cost.

In the existing literature, Van Zeben, J. (2017) developed a centrifuge pile driver based on an electromechanical system with a flywheel. Pore pressure transducers were installed around the pile, which had a prototype diameter of 2.07 m at 50g, to investigate the development of pore pressure during impact pile driving. Nietiedt et al. (2024) developed an in-flight pile-driving device utilizing a dual-cam mechanism. Under an acceleration level of 80g, the device simulated the hammer-driven penetration of a pile with a diameter of 4 m at prototype scale. Furthermore, Fan et al. (2021) and Maatouk et al. (2022) achieved impact installation of piles with a prototype diameter of 5 m. Both devices were further capable of performing horizontal loading following pile driving. At present, few systems allow the continuous execution of impact driving and vertical load testing of large-diameter offshore piles in centrifuge tests.

In this paper, an integrated in-flight pile driving and vertical loading system is developed. The design of the functional modules, including impact piling module, vertical tracking module, uninterrupted loading module, and integrated data acquisition and control module, is described in detail, with emphasis on their key features. An example centrifuge test is also presented, in which stable operation and well-controlled system performance are demonstrated.

2 DESIGN OF FUNCTIONAL MODULES

2.1 Overview

The integrated pile driving and loading system, as illustrated in Figure 1, consists of four main functional modules, namely the impact piling module, the vertical tracking module, the uninterrupted loading module, and the system control and data acquisition module.

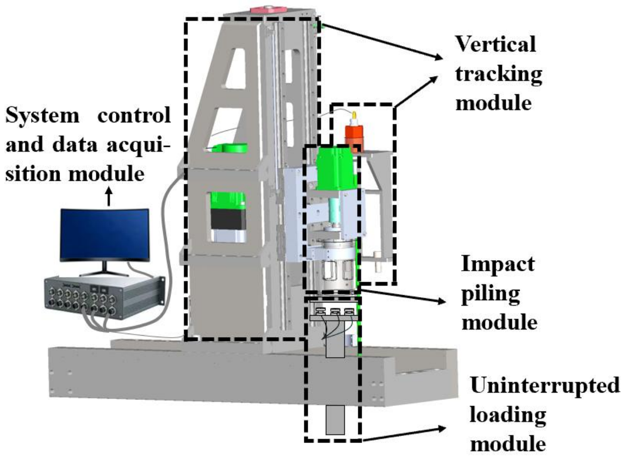

Figure 1. The integrated pile driving and loading system.

The pile installation process is achieved by the impact piling module, with the vertical tracking module actuating it downward to ensure that the hammer can effectively strike the pile. Then vertical loading can be applied immediately without stopping the centrifuge. Throughout the entire process, the system control and data acquisition module regulates both piling and loading operations, with test data being collected and transmitted in real time to a central computer.

2.2 Impact piling module

The impact piling module is designed to apply thousands of hammer blows to the pile until it reaches the target depth. Under a gravitational field of *N*g, the hammer weight increases by a factor of *N*. Consequently, rapidly and repeatedly lifting the hammer in the *N*g gravitational field represents the most critical and challenging aspect of in-flight impact piling. Cam mechanisms, wave-shaped supports, and flywheels have been proven to be effective means in addressing this challenge (Nietiedt et al., 2024; Maatouk et al., 2020; Van Zeben, 2017). As shown in Figure 2, the module employs a rotary hammer configuration, in which a motor-driven rotating fork drives the hammer to move along a curved guide path (Maatouk et al., 2020). The hammer is detachable and can be replaced to accommodate different test conditions. A guiding sleeve is installed beneath the curved guide path to maintain vertical pile penetration during installation.

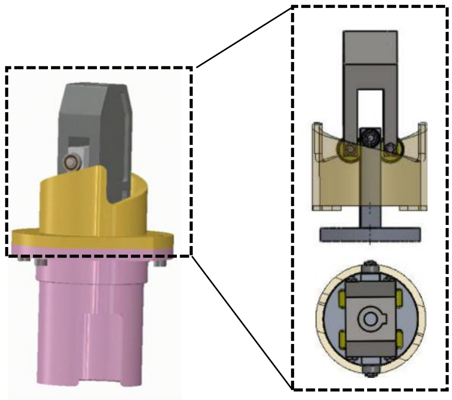

Figure 2. Rotary hammer with a guiding sleeve.

2.3 Vertical tracking module

Under continuous impacting, the pile penetrates progressively with rebound. If the impact piling module remains at a fixed position, variations in hammer drop height occur, which may even cause the hammer to fail to strike the pile head. The vertical tracking module is therefore designed to maintain a prescribed relative distance between the hammer and the pile in real time.

The vertical tracking module is connected to the impact piling module via a slider running on a lead screw. Changes in the pile position are captured and fed back to the central control computer. The computer decodes the signal and sends commands to a servo motor, which rotates the lead screw so that the impact piling module follows the pile along the guide rail with the same displacement.

During the tracking process, the pile displacement is measured by a magnetostrictive displacement sensor in real time. The sensor consists of a metal rod and a magnetic ring, with the rod vertically inserted into the magnetic ring attached to the pile, as shown in Figure 3. The circumferential magnetic field generated by electrical pulses in the metal rod interacts with the axial magnetic field of the magnetic ring to excite stress waves. The time difference between the emission and detection of these waves allows the sensor to determine pile displacement with high precision. Compared with conventional methods, which measure the relative displacement between laser sensors and metal strips mounted on the pile, this magnetostrictive measurement approach avoids errors caused by vibrations of the metal strips. Moreover, while laser sensors often suffer from reduced accuracy over a wide measurement range, the magnetostrictive sensor maintains high precision within a wide range.

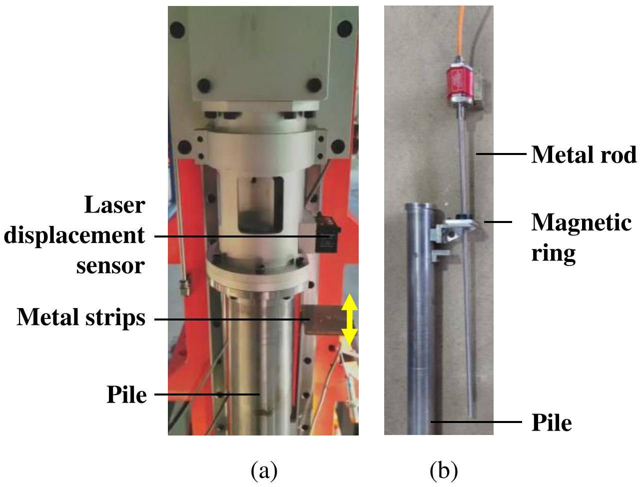

Figure 3. Measurement of pile displacement: (a) conventional method; (b) proposed method.

2.4 Uninterrupted loading module

Spin-down and subsequent restart operations alter the stress state of the soil in centrifuge tests, thereby affecting pile–soil interaction (Sinha et al., 2022). Therefore, applying vertical loading without stopping the centrifuge is essential, which is the primary function of the uninterrupted loading module (Figure 4).

Once the pile has been installed at the target position, a servo motor drives the entire impact piling module downward, causing the loading plate mounted beneath the module to press against three load cells installed on the bearing plate attached to the test pile. The signals measured by the load cells are transmitted to the central control computer in real time, where displacement-controlled or force-controlled loading is implemented according to the prescribed loading amplitude and frequency. Since the hammer remains in contact with the pile head during loading, the actual vertical load applied to the pile consists of the resultant force measured by the three load cells plus the self-weight of the hammer.

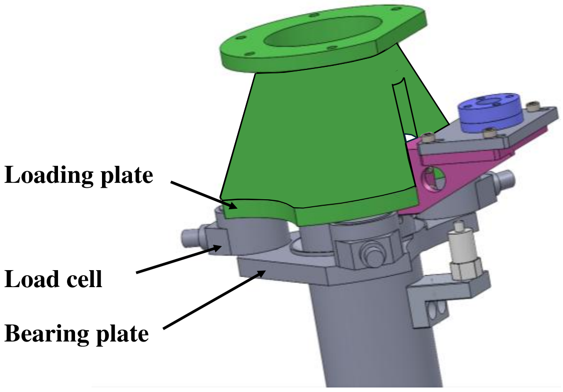

Figure 4. Uninterrupted loading module.

2.5 System control and data acquisition module

The system control and data acquisition module receives and processes signals from all sensors and governs the operation of the integrated pile driving and loading system. The pile and hammer displacements, hammer rotation count, and applied loading force are visualized in real time within the control software, allowing continuous monitoring of system operation. Piling frequency, loading rate, and other operational parameters can be adjusted, and the system can switch between piling and loading modes through the module.

3 EXAMPLE TEST

3.1 Test setup and procedure

An example test was conducted using the marine geotechnical centrifuge at the Hainan Institute of Zhejiang University. The centrifuge has a capacity of 200 g·t, a maximum centrifugal acceleration of 200 g, a maximum payload of 2000 kg, and a rotation radius of 4 m. The present test was conducted at 100 g.

The test setup is shown in Figure 5. The hammer had a mass of 289.66 g and a drop height of 24 mm, corresponding to a prototype hammer mass of 289.66 t and a drop height of 2.4 m. The hammering frequency ranged from 2 to 6 Hz, which scales to 0.02–0.06 Hz in the prototype. Although this range is lower than typical field frequencies, it is commonly adopted in centrifuge model tests. A steel pipe pile with an outer diameter of 60 mm and a length of 800 mm was used, representing a prototype pile with a diameter of 6 m and a length of 80 m. The diameter-to-wall thickness ratio of the test pile was 12, which is larger than that of typical monopiles. The test was conducted in medium-dense fine sand prepared using the dry pluviation method, with a median grain size of 0.138 mm.

The test procedure consisted of the following steps. The test pile was installed at 1g by static jacking to an embedment depth of 76.5 mm. The centrifuge was subsequently accelerated to 100g, and the pile was allowed to self-penetrate until a stable condition was reached. Impact driving was then applied in stages, with 500 hammer blows at frequencies of 2 Hz, 4 Hz, and 6 Hz, respectively. Hammering was subsequently resumed at 2 Hz and continued until refusal. Following the driving process, a pile load test was conducted to determine the bearing capacity of the pile.

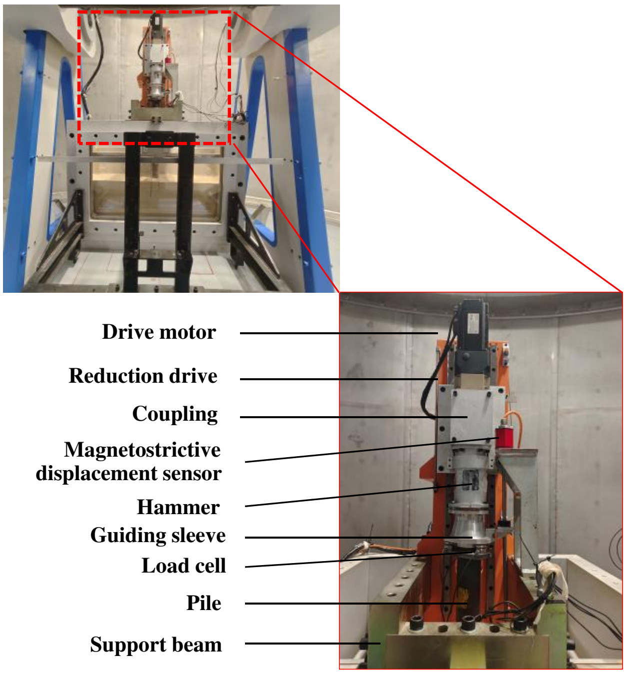

Figure 5. Test setup.

3.2 Test results

During centrifuge spin-up, the pile settled under its own weight and gradually reached a stable displacement at 100 g. The total self-settlement of the test pile was 1.62 mm, representing 0.162 m in the prototype.

Once the pile displacement stabilized, impact pile driving commenced at a frequency of 2 Hz. As shown in Figure 6, the pile began to penetrate rapidly under the repeated impacts, but the penetration rate gradually decreased. After 500 blows, the pile reached a prototype depth of 8.447 m. When the impact frequency was increased to 4 Hz, the penetration rate accelerated significantly. Given that the energy per blow remained nearly constant, this suggests a reduction in soil resistance to a certain degree. After 500 blows at 4 Hz, the test pile reached a prototype depth of 8.623 m. Increasing the impact frequency to 6 Hz slightly increased the penetration rate, which then gradually slowed. After 500 blows at 6 Hz, the pile penetrated only an additional 0.0539 m in the prototype. Interestingly, when the frequency was reduced back to 2 Hz, the penetration rate increased again, which may be attributed to an increase in the effective energy transmitted to the pile.

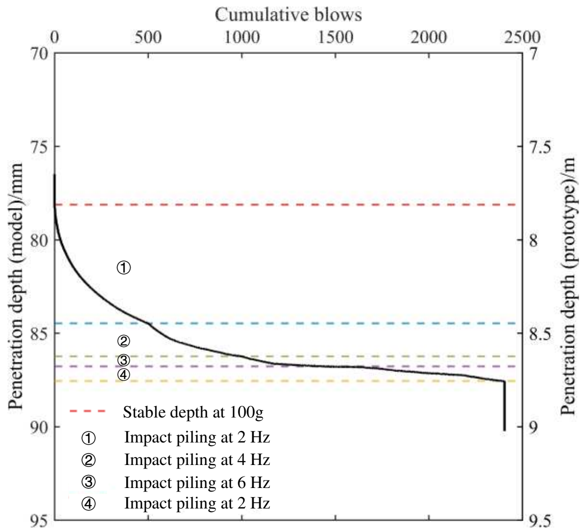

Figure 6. Cumulative blows plotted against the penetration depth.

Following impact pile installation, the loading plate was moved downward to conduct a trial pile load test. The load-settlement curve is shown in Figure 7. The vertical load was applied under displacement control at a rate of 0.05 mm/s. Owing to the load capacity limitation of the load cells, the applied loading displacement was less than 0.1*D*. Nevertheless, the maximum applied load reached approximately 124 MN in the prototype, indicating an axial bearing capacity of at least this magnitude for the test pile.

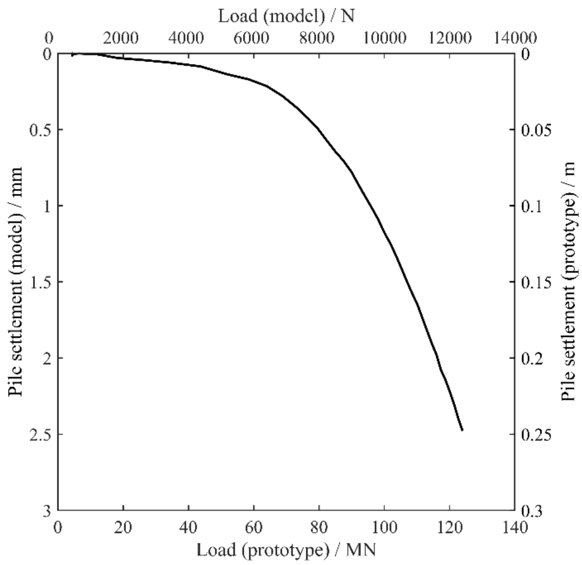

Figure 7. Load-settlement curve.

During the example test, the performance of each functional module was monitored and evaluated. Among them, the tracking performance of the vertical tracking module was one of the most critical aspects, as it directly governs the effective control of the hammer drop height. Figure 8 presents a typical segment of the pile–hammer relative displacement during impact pile driving. It can be seen that the relative displacement remains within 0.05 mm. Compared with the prescribed hammer drop height of 24 mm, the maximum relative error is less than 0.2% and can therefore be considered negligible. This demonstrates that the hammer drop height is well controlled during the piling process.

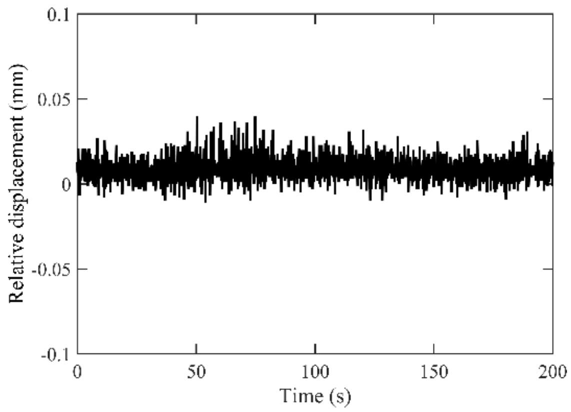

Figure 8. A typical segment of pile–hammer relative displacement during impact piling.

4 CONCLUSIONS

An integrated pile driving and loading system has been developed at Zhejiang University for centrifuge tests, enabling impact pile installation and subsequent vertical load testing to be performed continuously without spin-down. The system consists of modular components for impact piling, vertical tracking, uninterrupted loading, and system control and data acquisition, which provides several key features:

- In-flight impact pile driving can be achieved under the in-situ stress state of the soil, allowing realistic simulation of piling processes.
- Continuous impact pile driving with precise control of hammer drop height can be achieved through the vertical tracking module.
- Pile guidance is maintained, ensuring verticality consistent with practical engineering requirements.
- Pile load tests can be conducted after installation without stopping the centrifuge. The system allows flexible switching between penetration and loading modes, avoiding soil disturbance caused by repeated spin-down and spin-up operations.

An example test demonstrated that the system can perform stable and well-controlled impact piling followed by a pile load test without centrifuge spin-down.

Overall, the developed system provides a versatile experimental platform for investigating the effects of pile installation procedures, loading protocols, and key parameters on pile behavior in centrifuge tests. It enables future studies on pile installation mechanisms and capacity evaluation, and has the potential to address practical engineering challenges such as pile run and premature refusal during impact piling.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by Oil&Gas Major Project (Grant No. 2024ZD1403304). The authors also wish to thank Changsha Senji Technology Co., Ltd. (Jinshu Huang, Dongjian Nie, et al.) and the Marine Geotechnical Centrifuge Centre at Hainan Institute of Zhejiang University (Yujing Hou, Haiquan Sun, Houhong Liu, Wenzhe Xu, Wentao Wang, Hai Luo, et al.) for their assistance and support during the centrifuge tests.

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