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A Centrifuge-Compatible Impact Hammer for PULSE Pile Driving: Design, Specifications, and Initial Performance in Dense Sand

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ABSTRACT: In recent years, increasingly stringent environmental regulations have driven efforts to reduce noise emissions associated with the dynamic installation of offshore wind foundations. One approach to mitigating noise at the source is to cushion the collision between the drop weight and the anvil during impact hammering. An example of such a technology is PULSE, a commercial pile driving system developed by IQIP. This paper presents the results of a dynamic pile installation experiment conducted at 50 g in the geotechnical centrifuge facility of Delft University of Technology. An electro-mechanical actuator was used to install a 42 mm diameter model pile into dry GEBA sand at a relative density of approximately 80%. The model anvil is fitted with a buffer element manufactured from a synthetic polymer alloy, designed to reduce impact stress and prolong the impact duration. The results demonstrate that pile installation remains inertia-dominated despite the presence of a deformable buffer. A rebound of the drop weight following the primary impact is observed and is attributed to the release of elastic energy stored in the buffer during compression. The electro-mechanical actuation system performs reliably throughout the test, maintaining accurate pile tracking and a consistent blow rate. The study provides insight into the influence of impact cushioning on pile installation behaviour and demonstrates a promising experimental approach for investigating noise mitigation technologies in the geotechnical centrifuge.

1 INTRODUCTION

This paper presents the design and initial performance assessment of a retrofitted version of the electro-mechanical actuator developed at Delft University of Technology (DUT) for modelling impact-based pile installation with prolonged impact duration in a geotechnical centrifuge (Quinten, Askarinejad, & Gavin, 2022). Key innovations of the actuator include a tuneable drop-weight mechanism guided along a fixed rod, an eccentric flywheel-based lifting system, and a counterbalanced vertical positioning system that enables stroke-controlled pile installation under elevated gravity conditions. The hammer accommodates four interchangeable drop weights, ranging from 0.114 to 0.245 kg at model scale, and can deliver impact frequencies of up to 40 Hz at model scale, depending on drop height and centrifuge g-level. An overview of the actuation system is shown in Figure 1, with key components annotated.

This work describes one of the first experiments executed using this actuation system in which a blow cushioning technology is applied. The technology that inspired this system is seeing increased industrial adoption in response to evolving environmental regulations, particularly those related to the emission of underwater sound harmful to marine life (Tsouvalas, 2020).

2 METHODS

The experiments were conducted using DUT's electro-mechanical hammer, as shown in Figure 1. The actuator is driven by a brushless 1.2 kW motor operated by an ODrive S1 motor controller. To match the motor speed to the desired driving frequency (up to 40 Hz at 50g), the motor is connected to a gearbox with a mechanical advantage of 4.2.

The output shaft is connected to a flywheel fitted with a protruding notch near its outer perimeter (not visble in Figure 1). This notch is used to lift a pin protruding from the rear of the drop weight. The actuator has modular drop weights, which can be adjusted in discrete increments between 0.114 and 0.245 kg. As the notch moves in a circular path, the lifting motion is sustained during part of each flywheel revolution. Once the drop weight disengages from the notch, it accelerates under the centrifuge's gravitational field along a guiding rod, until it impacts the anvil. The drop weight remains there until it is re-engaged by the protruding notch on the flywheel.

The motor, gearbox, and flywheel are all secured inside a CNC-machined aluminium housing, hereafter referred to as the motor housing. The motor housing is balanced by two counterbalances and two linear springs, all connected by Dyneema cables. The springs compensate for the imbalance caused by the downward movement of the motor housing and the upward movement of the counterweights inside the centrifuge's rotating frame. This compensation results in a near-perfect static balance, allowing a stepper motor to translate the motor housing efficiently while the hammer is in operation.

This movement is facilitated by a leadscrew, which connects the motor housing to a stepper motor. The rotational velocity of the stepper motor is controlled by a PID controller. The controller is calibrated based on the difference between the pile position and the motor housing position at the start of the experiment. Any deviation from this setpoint during the experiment, resulting from downward pile movement during installation, activates the stepper motor to compensate for the displacement and thereby maintain the hammer stroke. The positions of both the pile and the motor housing are monitored using laser triangulation sensors (LTS).

To replicate the dynamic characteristics associated with prolonged impact duration, the model anvil is fitted with a deformable buffer made from a synthetic polymer alloy, shown as the champagne-colored hollow cylinder in the inset of Figure 1 (Quinten, Askarinejad, Gavin, et al., 2022). For the industrial application of PULSE driving technology, impact prolongation is achieved using a fluid-filled damper with tuneable stiffness (Bellmann et al., 2020). This fluid-based system is simplified to a synthetic polymer alloy buffer press-fit inside a stainless steel base element (see inset of Figure 1). The present configurtion accomodates the spatial and mechanical constraints of DUT's centrifuge, while preserving the blow prolonging (and thus sound mitigative) feature of the prototype technology.

The synthetic polymer alloy is characterized by a relatively low modulus of elasticity, E, of 3.1 GPa and a comparatively high yield stress, σ_y, equal to 310 MPa. This combination results in a high yield strain, ε_y, of 0.1, making the material well suited for blow prolongation while limiting buffer dimensions to a manageable size. The use of a synthetic polymer alloy buffer, fixes the axial stiffness at a predertermined value. The latter is a deliberate modelling simplification relative to the tuneable, fluid-filled damper used in the industrial system developed by IQIP (Bellmann et al., 2020).

3 CENTRIFUGE TESTING

The model-scale pile installation is conducted on an open-ended, stainless-steel pile. The pile is installed in dry, dense GEBA sand, prepared at a relative density (through dry pluviation) of 80% and tested at a centrifuge acceleration of 50 g. All variables reported hereafter relate to model scale unless stated otherwise.

The model pile dimensions are as follows: diameter D_P equals 42 mm; wall thickness t_P equals 2 mm; length L_P equals 175 mm. The test employed a 0.140 kg drop weight, a constant stroke of 40 mm. Under the specified operational conditions, the rated energy of the hammer is 2.75 J. The cross-sectional area of the buffer, A, equals 302 square millimetres, provided an outer diameter of 24 mm and an inner diameter 12 mm. The unstressed buffer length, $L_{0,}$ equals 16.5 mm (inset of Figure 1). The equivalent stiffness k_{eq} equals 56.8 kN/mm and is computed as EA/L_0. The energy capacity of the buffer E_{max}, corresponding to the maximum allowable blow energy, equals 36.3 J and is computed as the product K_c (material impact strength), equal to 120 kJ/m^2, and A. As the buffer's engery capacity is well above the hammer's rated energy (2.75 J), impact stresses during installation therefore remain within the safe operational bandwidth of the buffer.

Finally, the hammer is operated at a blow rate of 5 Hz, corresponding to a prototype-equivalent blow rate of approximately 6 blows per minute. This reduced blow rate is selected intentionally to enable detailed analysis of individual impact events without interference from residual dynamic effects between successive blows.

4 RESULTS

Figure 2 presents the normalized pile and ram displacement histories over the course of installation. The green line represents pile displacement, while the grey line represents ram displacement. The lower bound of the ram displacement coincides with the pilw displacement at the moment of impact, as all components move collectively upon contact. To emphasize this behaviour, the physical thickness of the anvil, which separates the target surfaces of the LTSs measuring the ram and pile displacements (see purple arrows in Figure 1), has been subtracted from the ram

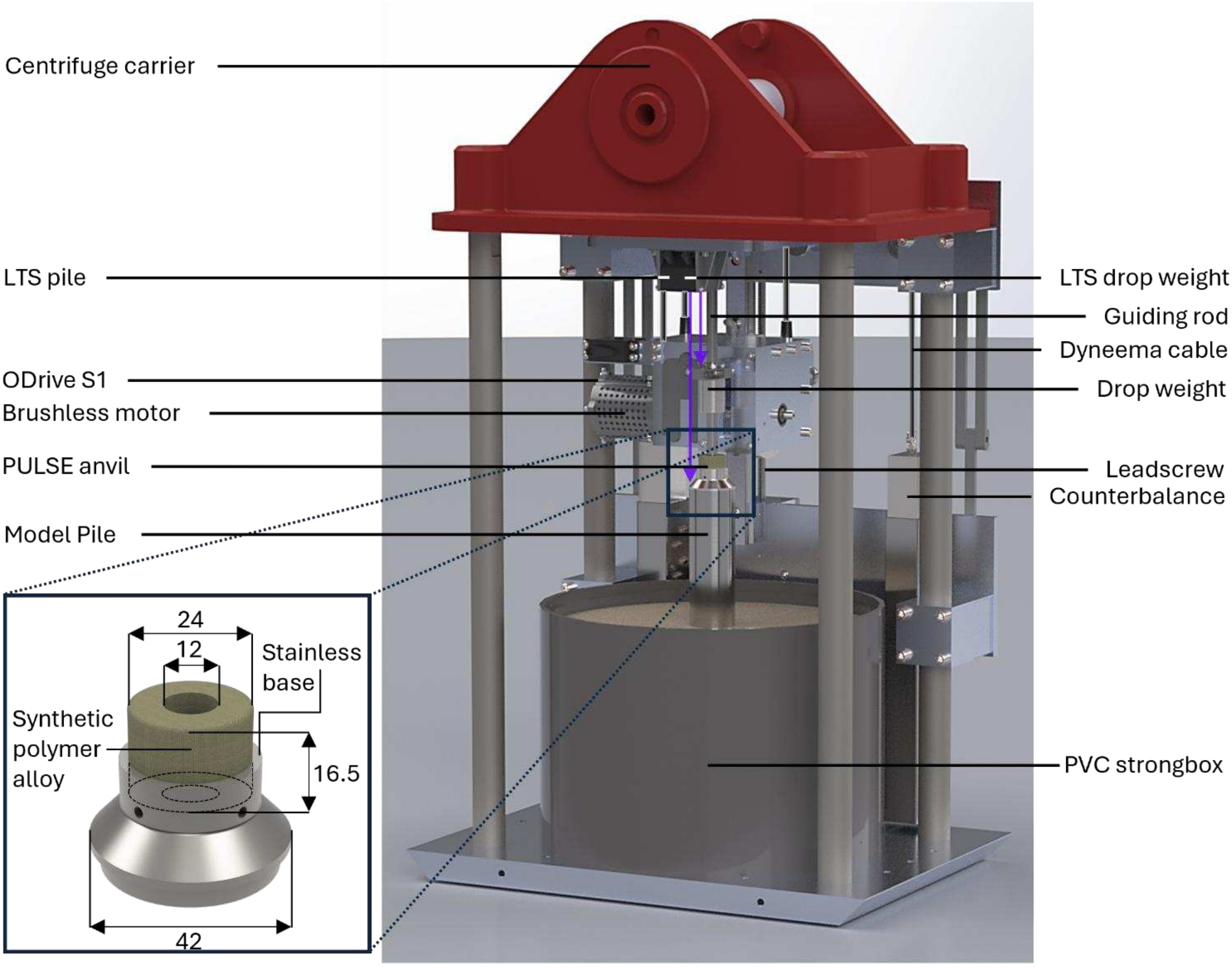

Figure 1: Annotated render of the DUT electro-mechanical hammer and PULSE anvil (as shown in inset, including relevant dimensions in millimetres). Please note that the stepper engine that drives the leadscrew, and the linear springs for static balancing, are not visible in this figure, as they are obscured by the strongbox.

displacement signal, resulting in partial overlap between the curves. Ram displacement measurements up to a model time of 1.8 seconds are capped by a black horizontal dashed line, indicating the lower limit of the laser triangulation sensor measurement range.

For model times greater than 1.8 seconds, the ram displacement amplitude remains constant relative to the pile displacement, indicating that the hammer stroke is maintained throughout operation. This demonstrates reliable performance of the PID-controlled pile-tracking system.

The pile displacement data start at an embedment ratio $L_P/D_P \approx 0.5$ due to self-weight settlement during centrifuge spin-up. Once the driving process is initiated, the penetration per blow decreases with increasing embedment depth, consistent with increasing mean effective stress and mobilized shaft resistance. Similar displacement histories have been reported previously (Fan et al., 2021a, 2021b; Maatouk et al., 2021; Nietiedt et al., 2023).

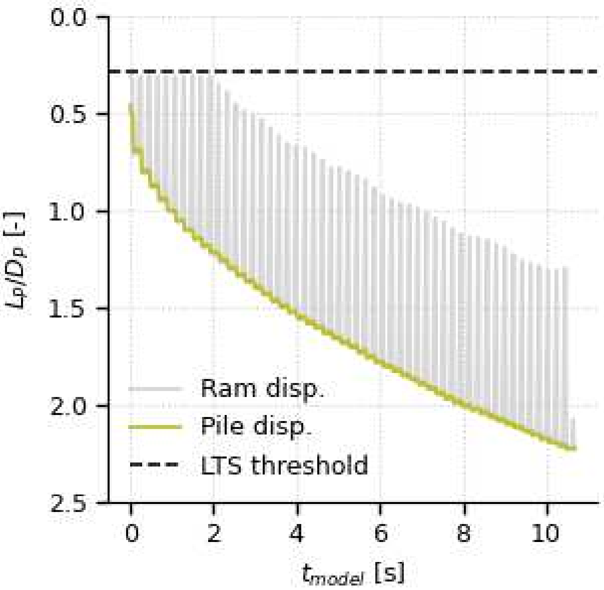

Figure 2: Normalized ram (solid gray line) and pile (solid green line) displacement as a function of (global) model time. Black dashed line indicates the lower limit of the laser triangulation sensor (LTS) measurement range.

A pronounced stepwise displacement pattern is observed, indicating rapid displacement increments coincident with impact events.

This illustrates that the installation process is inertia-dominated, with pile penetration governed by the dynamic response and momentum transfer of the hammer–pile system (Rausche & Webster, 2012), while the surrounding soil acts as a rate-dependent resisting medium. In this sense, the installation response closely resembles that of dynamically driven piles.

To further examine the interaction between ram and pile motion, Figure 3 shows a close-up of two consecutive blows at a normalized embedment depth of approximately L_P/D_P=1.5. A secondary axis showing global model time (t_{model}) is included for reference, while the primary horizontal axis represents local time (t^*_{model}), zeroed at the start of the leading blow cycle in the figure. The time interval between both impacts is approximately 0.2 seconds, consistent with the imposed blow frequency of 5 Hz. During the lifting phase, the ram displacement increases at a nearly constant rate. Upon release, the drop weight accelerates under the centrifuge gravity field, producing a parabolic displacement trajectory until impact with the anvil, resulting in a discrete step in pile displacement.

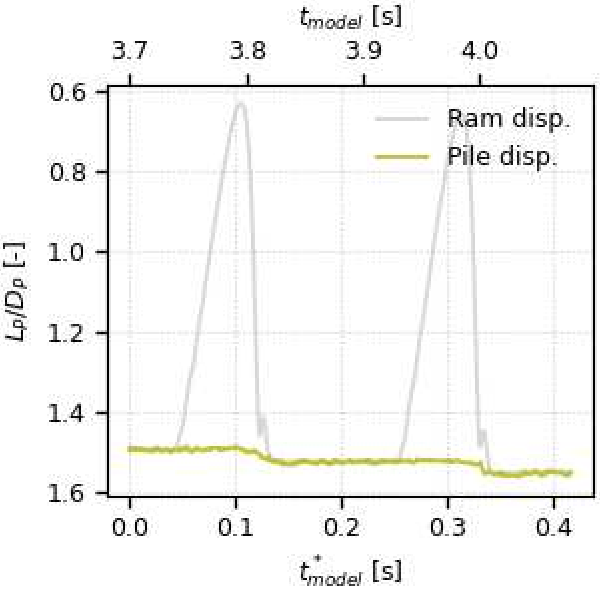

Figure 3: Detailed overview of normalized ram and pile displacement as a function of local model time (t^*_{model}). For reference, a global model time (t_{model}) axis has been included at the top of the figure. The data shown corresponds to two consecutive blows delivered at a normalized embedment depth (L_P/D_P) of roughly 1.5.

Immediately following the initial impact, the ram displacement reverses direction, indicating a rebound of the drop weight. This behaviour is attributed to the release of elastic energy stored in the deformable buffer during compression, which propels the drop weight upward as the buffer decompresses. The amplitude of this rebound is limited and does not result in additional pile penetration. Following this secondary impact, the drop weight comes to rest on the anvil, and the ram and pile displacement curves converge prior to initiation of the next lifting cycle.

5 CONCLUSIONS

The tests presented are among the first centrifuge experiments using the Delft University of Technology electro-mechanical hammer to install a pile fitted with a deformable anvil. Although the buffer is designed to prolong impact duration, the installation process remains distinctly dynamic. Drop weight rebound is observed as the result of the release of potential energy stored in the buffer during the primary impact. The actuator delivers repeatable, well-controlled blows with constant stroke length and frequency throughout the test, providing a reliable experimental platform for investigating rate-dependent soil–structure interaction and high-strain-rate installation processes in the geotechnical centrifuge.

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