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Development of an impact pile driving system for the geotechnical centrifuge at Delft University of Technology

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ABSTRACT: The dynamic installation of large tubular piles in saturated soil is associated with complex hydro-mechanical behaviour. Athough the installation method has an important effect on soil behaviour, this influence is not accounted for within the existing soil behavioural framework for pile installation. As part of an effort to close this knowledge gap, Delft University of Technology (DUT) has retrofitted an existing electro-mechanical miniature pile hammer with new sensors and control equipment. The resulting device gives users near full control over the driving frequency (5-40 Hz) and falling height (10-50 mm). Moreover, three interchangeable ram masses were developed to simulate pile installation with IQIP S280, S350 and S500 Hydro-hammers. Results demonstrate that the resulting device has an efficiency of 88%, which is comparable to its counterparts from the industry and can adequately maintain driving frequency and impact energy in operation.

Keywords: centrifuge, hammer, open-ended pile, sand, offshore wind

1 INTRODUCTION

The effect of operational parameters (e.g. driving frequency, falling height and ram weight) of an offshore hammer on soil-structure interaction during monopile installation, is not fully understood.

Presently, conceptual knowledge exists on phenomena such as pore pressure changes (Iskander, 2010; J. van Zeben, 2017), cavity expansion and friction fatigue (Basu et al., 2014; White & Lehane, 2004). However, a comprehensive framework which takes into account these phenomena alongside the installation characteristics, does not exist.

To support the development of such a framework, high-quality experimental data should be gathered. For centrifuge studies in particular, this requires a highly flexible pile driving set-up, which can reliably simulate a wide range of dynamic pile installation regimes.

To this end, an existing pile driving actuator for geotechnical centrifuge was revised and equipped with state-of-the-art sensory and control equipment. The entire system was designed to perform tests in the geotechnical centrifuge of Delft University of Technology (DUT) up to 50g acceleration.

2 PHYSICAL MODELLING

2.1 Centrifuge modelling

Experiments are conducted in the 9 ton.g beam centrifuge facility of DUT (Allersma, 1994) as shown in Fig. 1.

The centrifuge is a unique tool which can be used to subject a small-scale model to an artificial gravitational field. This allows researchers to accurately replicate the soil stress states (and thus soil behavior) of real-world geotechnical applications in a controlled environment. The enhancement coefficient of Earth's gravity is commonly denoted as N, and governs the scaling of a multitude of physical constants in accordance with so-called "centrifuge scaling laws", of which the relevant ones are summarized in Table 1.

The centrifuge actuator presented in this paper is designed to simulate the installation of steel, tubular, open-ended piles at 50g acceleration (N=50). The flexible design of the actuator allows for the modification of the ram mass, impact energy and driving frequency and can therefore simulate a large variety of pile installation regimes.

Table 1: Relevant scaling relationships for Prototype-Model conversion (N = 50)

Parameter	Symbol	Dimension	Scaling law
Acceleration	a	L/T^2	N
Length	x	L	1/N
Density	ρ	M/L^3	1
Stress	σ	M/LT^2	1
Strain	ε	-	1
Mass	m	M	$1/N^3$
Energy	E	ML^2/T^2	$1/N^3$
Velocity	v	L/T	1
Force	F	ML/T^2	$1/N^2$
Stiffness	k	M/T^2	1/N
Frequency	f	1/T	N

2.2 Pile driving actuator

Prototypes

The miniature pile driver is designed based on the specifications of the S280, S350 and S500 Hydrohammers as manufactured by IQIP. Due to their size, aforementioned hammers are predominantly used in offshore applications. Respectively, the maximum impact energy of the hammers are 280, 350 and 500 kJ, which are applied to the pile head by a 14-, 28- and 25-ton ram. The maximum impact velocity of all hammers is about 6.3 m/s at a driving frequency of 45 blows per minute.

IQIP hydro-hammers are double acting, which means that the effective acceleration of the ram mass is 2g. The additional acceleration is realized by means of a gas buffer located above the ram mass. With respect to a gravity-based (single-acting) hammer, this leads to a more compact device. It was infeasible to incorporate the double-acting functionality into the centrifuge actuator. The stroke of the centrifuge hammer is therefore double that of the prototype.

Principle

The miniature pile driving actuator as discussed in this paper is an evolution of the electro-mechanical hammer developed by J. C. B. van Zeben et al. (2018). This device was developed to accurately simulate the change in pore pressure during impulse pile driving. The latter is challenging as dynamic processes as sped up by a factor of N in the centrifuge, resulting in the requirement to install the model pile at a driving frequency up to 37.5 Hz.

The actuator (Fig. 2) lifts the ram mass by means of a flywheel. To facilitate the linear translation of the ram mass along a central guiding rod, a linear bearing is incorporated into its design. The guiding rod is fabricated from abrasion resistive CF53 steel and has a diameter of 10 mm.

Power for the lifting process is supplied by an electric 1.5 kW brushless motor. As optimum performance of the engine is achieved at high RPM, the connected gearbox has been purposely designed to achieve the appropriate hammering frequency (5-40 Hz at Model scale). To maintain hammering frequency, the motor is controlled by a PID system[1]. The latter uses the output of an RPM sensor as the controlling parameter. To allow the system to spin-up to the right RPM freely, the ram mass is initially supported outside the path of the flywheel. Upon initiation of the experiment, it is electronically released relay-operated servo.

As the actuator is installed next to the pile rather than

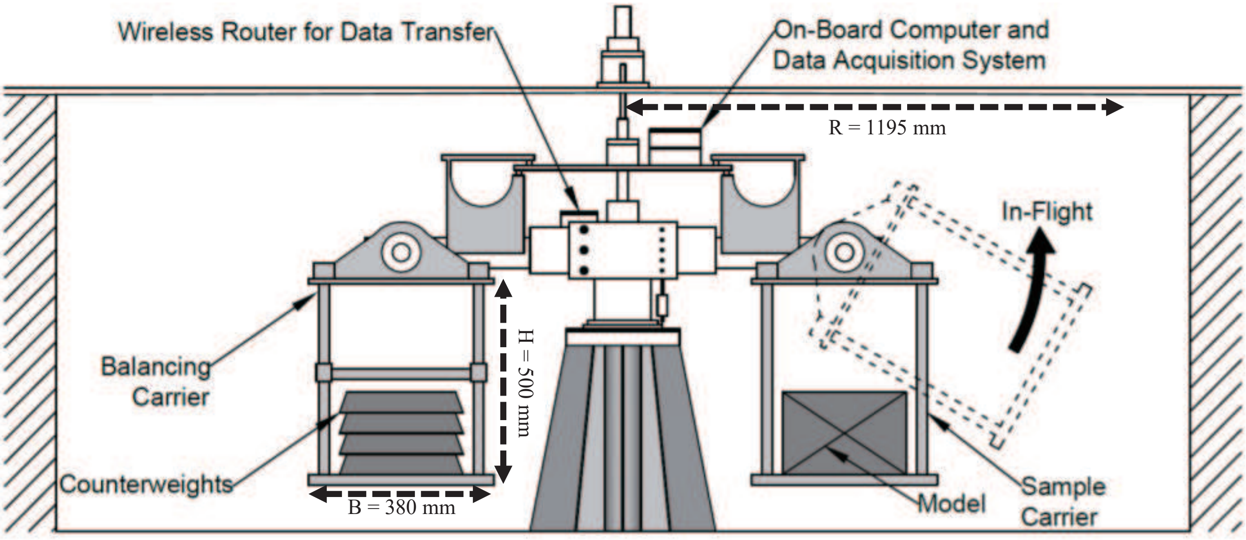

Fig. 1: Schematic illustration of DUT beam centrifuge (Li et al., 2020)

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[1] The function of a proportional–integral–derivative controller (PID), is to keep a system variable close to a predefined set-point value. This requires the continuous measurement of system variable by means of an appropriate sensor. The output of the sensor is compared to the set-point in real-time. Regulatory logic incorporated into the PID, enables the system to compensate for any identified difference between the two.

on top of it (de Nicola & Randolph, 1994; Maatouk et al., 2020) there is a need for a system which allows the actuator to track the movement of the pile in real-time. To this end, a PID controlled actuation system was developed together with the Electronic and Mechanical Support Division (DEMO) of DUT. This system consists of a stepper engine which is connected to a leadscrew. The leadscrew nut is incorporated into a brace which is attached to the actuator. As the actuator is mounted on a monorail, it can translate linearly when the stepper engine is engaged. To limit the axial force on the leadscrew, the actuator is balanced by a counterweight. This ensures that the torque required to operate the system does not exceed the capabilities of the stepper engine.

The velocity and direction of the actuation system are controlled by a PID controller which requires two input parameters, namely: (i) the position of the model pile; (ii) the position of the actuator itself. Both are continuously measured by means of draw-wire sensors. Prior to spin-up, the positions of both the actuator and pile are saved internally, this subsequently acts as the set point of the system. Once in operation, the pile will start to penetrate into the soil, thus resulting in a deviation from the set-point. The sign and magnitude of the deviation determine the rotational direction and velocity of the stepper engine, respectively.

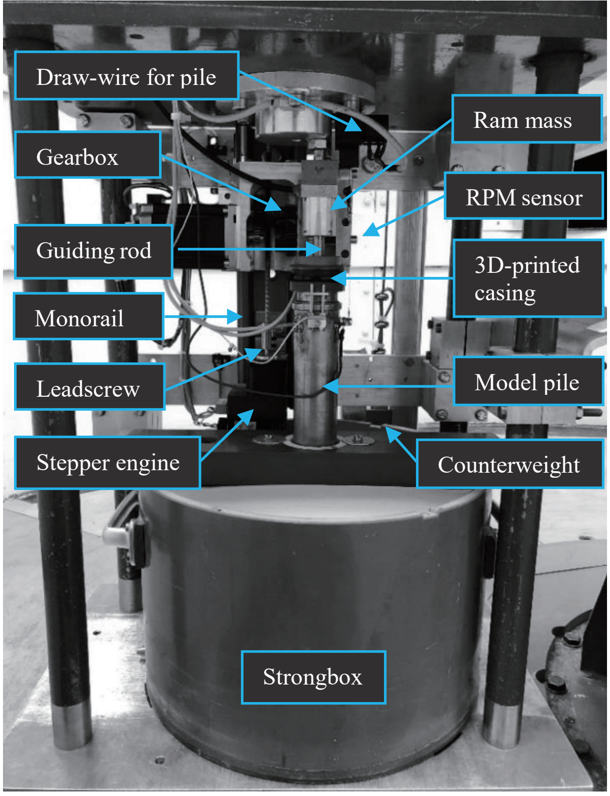

Fig. 2: DUT electro-mechanical miniature hammer.

Adaptability

The presented actuator design is highly flexible and gives the end-user near-full control of the driving parameters:

- For each prototype hammer, a dedicated ram mass was developed. Respectively, the weight of each ram amounts to 130 (Type I), 160 (Type II) and 220 (Type III) grams. Theoretically it is possible to add new ram masses to simulate other prototype hammers.
- The PID system which controls the driving frequency allows the user to freely select the driving frequency between 5 and 40 Hz.
- Due to the decoupling of the hammer from the model pile, the falling height can be varied by altering the initial position of the actuator with respect to the pile. Each configuration will yield a unique set point for the linear actuation system, which also ensures the chosen falling height is maintained during operation. This feature greatly increases the flexibility of the system and allows for a free selection of the stroke between 10 and 50 mm.

2.2 Model pile

The model pile consists of a steel, open-ended tube. It has a length of 185 mm and external diameter of 42 mm (D). The wall thickness equals 2 mm.

The impact velocity of the ram mass is measured by an infrared LED and phototransistor. Two of these pairs were installed at a spatial offset of 15 mm, right above the contact surface between the anvil and ram mass. A 3D-printed casing, which sits on top of the anvil, is used for sensor installation (Fig. **2**). The passage of the ram mass causes the (delayed) interruption of light travelling between the emitter and the sensor. These interruptions are recorded by the data acquisition system, from which the elapsed time is obtained. Ultimately, this allows the impact velocity to be computed.

To record the force applied to the pile head, the pile is fitted with four strain gauges. In addition, the pile is equipped with two (for symmetry) placeholders which can be used to install an accelerometer. The authors are currently working on the design of a mechanical dampener for an Endevco 7270A-200K accelerometer. Upon completion this should result in the first miniature Pile Driving Analysis (PDA) system suitable for centrifuge testing.

2.3 Sample preparation

Samples are prepared form GEBA sand. The latter is a fine, uniform silica sand with an internal fiction angle of 35 degrees and a D_{50} of 0.110 mm. Relevant soil properties are summarized in Table **2**.

The samples are contained in a HDPE strongbox, which has a diameter of 315 mm and height of 210 mm. Samples were prepared using submerged pluviation and subsequently densified to a height of 170 mm at D_r=80%

by shockwave compaction (Rietdijk et al., 2010). To correctly capture the generation of pore pressures, the samples were saturated using a 50 cSt viscous fluid (Askarinejad et al., 2015). The fluid consists of an aqueous solution of Hydroxypropylmethylcellulose (HPMC).

Table 2: Material parameters of GEBA sand (de Jager et al., 2017).

Parameter	Symbol	Value	Unit
Void ratio (max)	e_{max}	1.07	-
Void ratio (min)	e_{min}	0.64	-
Specific gravity	ρ_s	2.65	-
Friction angle	φ	35	°
Median grain size	D_{50}	0.110	mm
Coefficient of uniformity	C_u	1.55	-
Coefficient of curvature	C_c	1.24	-

3 PERFORMANCE

The actuator can install the model pile up to a depth of 126 mm in the soil, which is equal to 3D. This section illustrates the performance of the actuator over a 1D installation interval, provided a pre-installation depth of 50 mm. The experiment is conducted using the Type II ram at a target blow energy of 1.87 J and 10 Hz driving frequency.

3.1 Linear actuation system

Fig. **3** shows the (fitted) displacement of the model pile and actuator. The difference between the two is a measure of the performance of the linear actuation system. It follows that at the onset of driving, the system response is slightly delayed, which causes a minor increase in hammer stroke. Low soil resistance due to limited pile embedment and limitations to the ramp-up speed of the stepper engine underlie this observation. , Soil stress state disturbance (associated with pre-installation of the pile) could be a third contributing factor, though this effect was not measured directly.

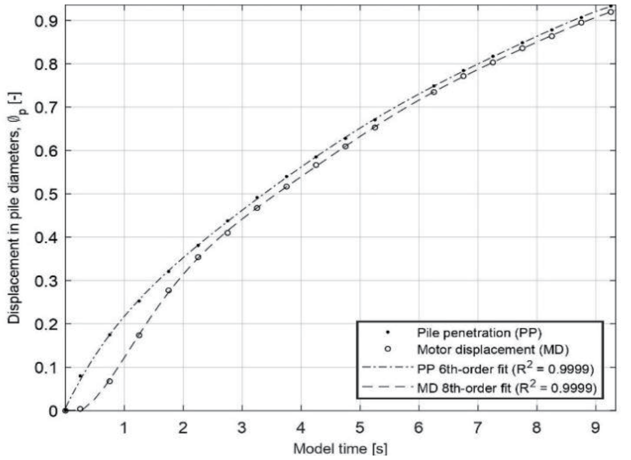

Fig. 3: Normalized pile and actuator displacement vs. model time.

As time progresses, the system catches up and maintains the desired stroke for the continuation of the experiment. In addition, it can be observed the pile penetration rate decreases with time. Provided blow rate is constant (idealized scenario), there exists an exponential relationship between the number of blows per unit of penetration and the pile embedment level.

3.2 Frequency control

The performance of the driving frequency controller is illustrated in Fig. 4. At the start of driving, the ram mass is released from the suspend position. As the flywheel was previously spinning freely, the release of the ram mass causes a loss of momentum, which leads to a frequency drop of 5 Hz. The correct driving frequency is restored after approximately 6 seconds (model time) after which it was maintained for the remainder of the experiment. The reduced driving frequency at the start of the experiment, is insufficient to compensate for the lag of the linear actuation system as discussed in 3.1.

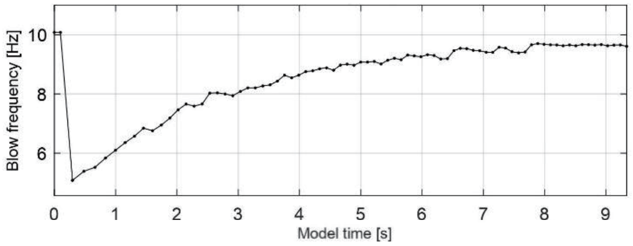

Fig. 4: Blow frequency as a function of model time.

3.3 Hammer efficiency

Fig. **5** illustrates the impact energy obtained from back-analysis of the impact velocity data. The data is plotted against the cumulative blow number. From the latter it is found the hammer efficiency is around 88% for a mean impact velocity of 4.5 m/s. The obtained efficiency falls slightly below that of the prototype, which is about 95%.

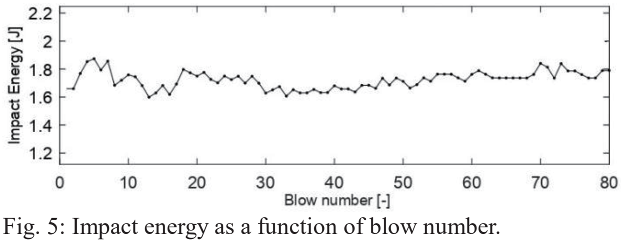

Fig. 5: Impact energy as a function of blow number.

4 CONCLUSIONS

For the dynamic installation of piles, the influence of the operational configuration of the hammer on pile installation behavior is not fully understood. To facilitate experimental research in this field, the miniature pile driver of DUT was retrofitted with new sensors and control equipment. The resulting device provides a high degree of flexibility in terms of ram mass, impact energy and driving frequency selection. Based on preliminary experiments, the performance of the linear actuation system as well as the frequency controller are promising. Furthermore, analysis of the impact velocity data demonstrated that the efficiency of the hammer and its prototype are comparable.

5 OUTLOOK

Further refinement of the linear actuation system and frequency controller are ongoing. Proposed improvements include a revision of the PID software, in addition to the following hardware changes:

- Installation of a more potent battery pack for the main motor to reduce the time required to reinstate the desired driving frequency.
- Fitting a more capable stepper engine linked to a high-pitch leadscrew. These measures should result in higher translational velocities of the linear actuation system.

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