Designing PULSE and BLUE blow generators for experimental research in the geotechnical centrifuge

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ABSTRACT

The next generation of monopiles for the offshore wind market will exceed 12 m in diameter. These foundations will facilitate the transition of bottom-founded offshore wind mills into deeper waters as well as enable the installation of larger turbines. There are questions whether conventional dynamic installation techniques can be used to install these foundations, mainly due to challenges related to sound emissions and fatigue. New dynamic installation equipment, that rely on the prolongation of the impulse duration, are therefore under development. PULSE and BLUE technology, both developed by IQIP, are examples of such equipment. Both strive to reliably drive large monopiles while drastically reducing sound emissions and fatigue manifestation. However, little is known about the practical implications of impulse prolongation of pile-soil-water interaction, which plays a critical role during installation. To study this, Delft University of Technology (DUT) is developing the hardware required to simulate the installation of monopiles with PULSE and BLUE technology in the centrifuge. By fitting a 16.4 mm synthethic polymer buffer between the hammer and the anvil, PULSE-blow characteristics can be replicated. The resulting system can be installed by DUT's miniature electro-mechanical pile driver. To simulate a BLUE-blow, the anvil is fitted with a stiff linear spring. For installation a dedicated actuator used which is currently under development. Both designs are verified by means of numerical simulation.

Keywords: Monopile, sound emissions, offshore wind, dynamic installation, centrifuge modelling

1 INTRODUCTION

The drive to reduce greenhouse gas emissions continues to fuel the demand for offshore generated wind energy. Monopiles remain the most popular type of substructure even though wind farms are moving into deeper waters, farther offshore. In 2019, over 70% of newly constructed offshore wind-mills were founded on monopiles (Wind Europe, 2019). The majority of monopiles are installed dynamically by large hydraulic hammers (Thomsen, 2012).

Dynamic installation is characterized by short, high amplitude force pulses which are administered to the pile head. With each blow, stentorian, impulse-like sound is emitted from the installation site. These emissions have been the focus of several studies (Herbert-Read et al., 2017; Leunissen & Dawson, 2018; Madsen et al., 2006), which classified them as potentially harmful to marine life. Consequently, countries have imposed stricter environmental regulations on offshore construction activities (Erbe, 2013; Williams et al., 2015). Additionally, the dynamic load conditions during installation approach the pile's yield stress, thereby resulting in fatigue damage. The latter is a limiting factor to the operational lifetime of the foundation (Chung et al., 2013).

Both of the aforementioned factors lead to questions on the possibility to use dynamic installation to drive the next generation of monopiles. This has resulted in an interest for alternative installation methods that limit shock loads in the pile. Two examples of such technologies are PULSE and BLUE piling (Perrow, 2019), both developed by IQIP (formerly part of Royal IHC).

To investigate the implications of PULSE and BLUE driving technology on soil-structure-water interaction, two actuators were developed for the geotechnical centrifuge at TU Delft. Respectively, the devices aim to accurately replicate the blow characteristics associated PULSE and BLUE piling technology inside a laboratory environment. Details on the concept, design and, as well as their role in facilitating the deployment of aforementioned technologies in industry, are presented in this paper.

2 INCREASING SOUND EMISSIONS

In contrast to its onshore counterpart, offshore wind plants tend to generate more energy due to higher wind speeds, reduced turbulence and lower wind-shear (Bilgili et al., 2011). Momentarily, the majority of newly constructed offshore wind mills are founded on monopiles up to 8 m in diameter and 80 m (total) length. Scarcity of suitable near-shore installation sites, more stable wind conditions and demand for higher capacity turbines, have introduced the need for larger substructures. Presently, the steel industry is about ready meet this demand.

The upcoming generation of monopiles will enable the installation of 12-14 MW turbines in increasingly deeper water. Consequently, monopiles are expected to grow to >100 m in length and a >12 m diameter. Impulse pile driving remains the best-suited installation methodology. However, it is characterized by high levels of (underwater) sound pollution as shown in Figure 1. The high intensity sound has the potential to cause (permanent) disruptions to the aquatic ecosystem.

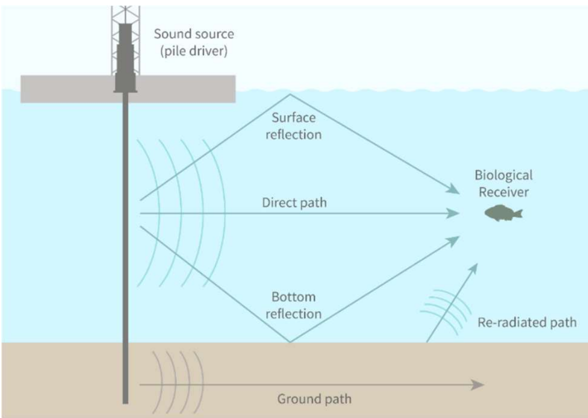

Figure 1: Sound propagation paths towards aquatic animals (Z. Li & McPherson, 2018)

For impulse pile driving, there exists a positive correlation between the pile diameter and the recorded sound pressure level (SPL), as shown in Figure 2. Therefore, it is likely that the continued scaling of monopile dimensions will elevate sound emissions during dynamic installation (Bellmann et al., 2020).

Without changes, environmental measures like Big Bubble Curtains (BBC), isolation casing and hydro sound dampeners, are set to become a critical to economical viability of future offshore wind endeavors. To sustain the next generation of offshore wind mills, a new set of sound mitigation technologies is therefore required (Wagenknecht, 2021).

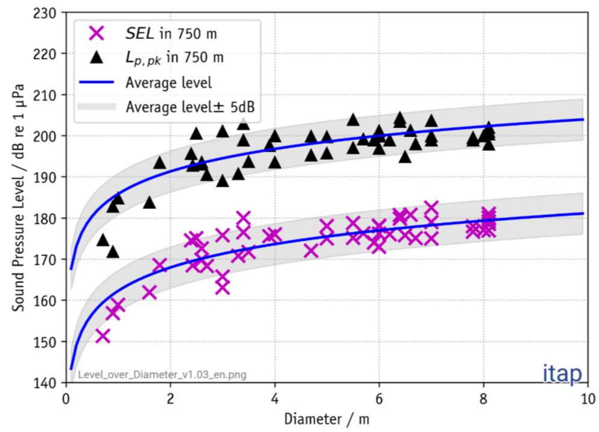

Figure 2: Recorded SPL as a function of pile diameter, at a distance of 750 m from the source. All piles were installed dynamically, without the application of technical noise abatement systems (Bellmann et al., 2020)

3 NEW INSTALLATION TECHNOLOGIES

IQIP, formerly part of Royal IHC, has intensified its efforts to mitigate sound emissions associated with offshore piling works. Their efforts have materialized in PULSE and BLUE technology. Both leverage the prolongation of the ram impulse to achieve significant sound reductions directly at the source.

For hydraulic hammers, the impact duration consists of the time is takes a stress wave to travel up and down the length of the hammer (Massarsch & Fellenius, 2008). For state-of-the-art offshore hammers, impact durations extend up to 10 ms approximately. Through the application of a cushioning element between the ram and the anvil, driving force is reduced while the impact duration is increased. Noise reductions of up to 26 dB have been reported for pile cushions (Laughlin, 2006). However, until recently, durability issues and converns surrounding pile drivability have prevented industry-wide adoption.

PULSE is one of the first commercially available technologies that reliably combats sound emissions by cushioning the ram impulse. The system consists of an add-on to a standard hydraulic hammer and is installed between the hammer and sleeve. It consists of a pair hydraulic pistions, which enclose a body of water. Impact characteristics are controlled through variation of the water volume. Early results show a significant reduction of Sound Equivalent Sound Level (L_{eq}), Sound Peak Pressure level (SPL) and fatigue damage. Compared to a standard hammer, the impact duration is increased by a factor of 3, to roughly 30 ms.

BLUE Piling Technology further leverages the principle of ram impulse prolongation. The novel installation method relies on the deceleration of a large vessel filled with water to deliver a prolonged blow to the pile. Due to the gradual build-up of force in the pile over a long time interval, the resulting impact

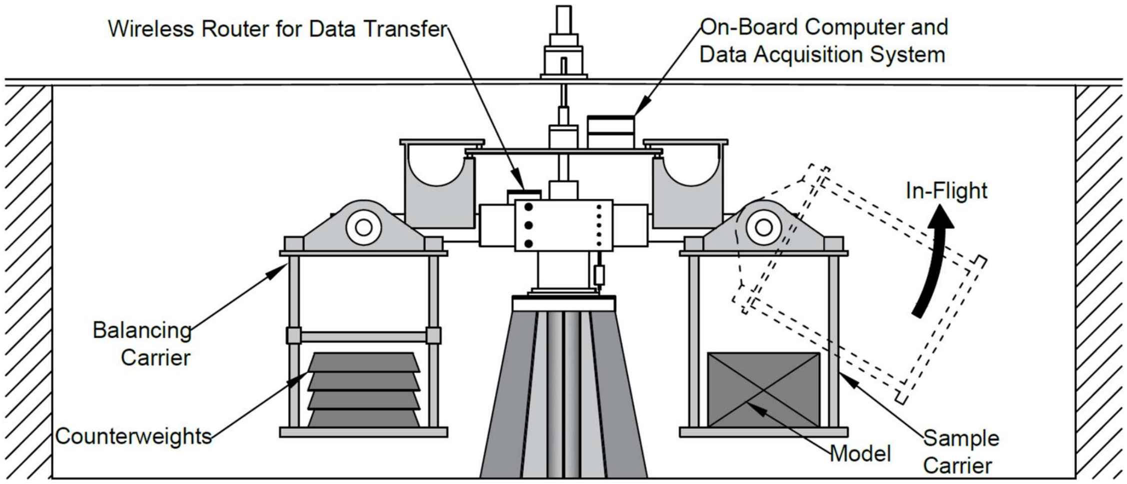

Figure 3: Schematic illustration of DUT beam centrifuge, adapted from Q. Li (2020*).*

characteristics dramatically reduce sound emissions and fatigue manifestation.

A full scale test of the technology was performed in 2018 on a 6.5 m diameter pile. The trial showed potential to reduce underwater sound emissions by 19-24 dB (L_{eq}) over the full frequency spectrum spanning from 10 Hz to 20 kHz (Winkes, 2018). Referenced to a conventional hydraulic hammer, the impact duration is increased by a factor of 20 to approximately 200 ms.

3 PHYSICAL MODELLING

3.1 Centrifuge modelling

Although the first results of field applications of PULSE and BLUE technology look promising, little is known about the how pulse prolongation affects pile-soil-water interaction. To study the process in a laboratory environment, centrifuge modelling is used. This methodology allows for the replication of a representative soil stress state in a small scale model.

Table 1: DUT beam centrifuge properties, adapted from Q. Li (2020*).*

Property	Symbol	Value	Unit
Centrifuge radius	R	1195	mm
Design acceleration	a_d	300 · 9.81	m/s^2
Design payload	F_d	9000	kgf
Carrier height (H)	H	500	mm
Carrier width (W)	W	240	mm
Carrier depth (D)	D	380	mm

DUT's beam centrifuge facility (Figure 3) has a radius (R) of 1195 mm and capacity of 9000 kgf (at 300g acceleration). The carrier can accommodate models with dimensions up to 500 x 240 x 380 mm (H x W x D). Aforementioned characteristics are summarized in Table 1.

For the centrifuge experiments, the multiplication factor (N) of earth's gravitational coefficient (g) is equal to 50. N is the defining parameter used for scaling of other physical properties in accordance with the so-called centrifuge scaling laws. For this study, Scaling laws relevant to the conversion of Prototype to Model characteristics are summarized in Table 2.

Table 2: Relevant scaling relationships for Prototype-Model conversion (N = 50) (Garnier et al., 2007).

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

3.2 Model soil

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. A complete list of soil properties is presented in Table 3.

Table 3: Properties of GEBA sand (De Jager et al., 2017) (Maghsoudloo et al., 2018).

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	-

3.3 Model pile

The model pile consists of a steel, open-ended tube. It has a length of 175 mm and external diameter of 42 mm. The wall thickness equals 2 mm. The corresponding Prototype pile has (embedment) length of 8.75 m, diameter of 2.10 m (L/D ≈ 4.4) and wall thickness of 0.10 m. As the thickness of the interface layer of around the pile does not scale in the centrifuge, the pile thickness should be chosen such that it spans >15 times the d_{50} of the model soil (Oveson, 1979). Consequently, the stiffness of model pile is slightly elevated which could result in minor deficiencies in soil-structure interaction.

3.3 Prototypes

At an acceleration of 50g, spatial restrictions in the DUT centrifuge facility prevent the ono-to-one scaling of offshore (mono)pile installation equipment. The largest hydraulic hammer currently used in the field is the IQIP S-5500 Hydrohammer (. Its maximum strike power is 5.5 MJ per blow. The BLUE hammer is expected to deliver >4 times more energy. Its (preliminary) energy rating is 25 MJ (Winkes, 2018). The authors therefore settled for an approach in which relative differences between the installation systems are maintained, while ensuring compatibility with the centrifuge facility by reducing the overall dimensions. In this respect, the industrial reference for the centrifuge study is the IQIP S350 Hydrohammer, which has a 17.8 t ram, maximum striking energy of 350 kJ at an impact velocity (*v_0*) of 6.3 m/s and operates at up to 40 blows per minute. It's BLUE equivalent has a 220 t ram weight, maximum impact velocity of 6,5 m/s and operates at <10 blows per minute. By approximation, the ratio of impact duration between impact, PULSE and BLUE driving is 1:9:98.

3.4 Buffer design

The blow duration for the PULSE and BLUE hammer is regulated by the buffer which cushions the blow of the ram mass. The material and geometry are selected in function of the desired impact duration. The buffers are installed in between the anvil and ram mass. Upon impact of the ram mass, the buffers deform which results in impulse prolongation and decreases driving force.

Theoretical framework

Buffer design is conducted within an idealized framework, which consists of a linear mass-spring system. In the system, energy dissipation and the effect of gravity are not considered. Lastly, it is assumed that an impulse cycles encompassed both the compression and decompression of the buffer. Provided the aforementioned conditions, system behaviour is governed by the following equation:

$$m\frac{d^2u(t)}{dt^2} + k \cdot u(t) = 0 \tag{1}$$

Where, *m* is the mass of the ram [kg], *k* is the stiffness of the buffer and *u(t)* is the deformation of the buffer as a function of time. The general solution to Equation (1) is:

$$u(t) = A \cdot \cos\left(\sqrt{\frac{k}{m}} \cdot t + \theta\right) \tag{2}$$

To obtain the specific solution the following initial conditions ($t=t_0$) are considered: (i) $u(t_0) = 0$; (ii) $v(t_0) = v_0$. Where v_0 is the impact velocity of the ram mass. The latter yields to the following specific solution:

$$u(t) = -v_0 \cdot \sqrt{\frac{m}{k}} \cdot \cos\left(\sqrt{\frac{k}{m}} \cdot t + \frac{\pi}{2}\right) \tag{3}$$

Within the aforementeioned idealized framework, the velocity of the ram mass is $-v_0$ when the buffer has fully rebounded. By differentiating Equation (3), equating the outcome to $-v_0$ and rearranging terms, an expression for the impact time is obtained:

$$\delta t = \pi \cdot \sqrt{\frac{m}{k}} \tag{4}$$

From Equation (4), it follows that the impact duration is a function of buffer stiffness. Therefore, it is possible to tune the buffer stiffness to the desired impact duration as follows:

$$k = \frac{m\pi^2}{\delta t^2} \tag{5}$$

To evenly cover the bandwidth of impact durations between the different types of installation equipment, the authors strived to design the buffers such that they are separated by roughly one order of magnitude. Target impulse durations were therefore set to 8 ms and 80 ms for PULSE and BLUE respectively. From Equation (5) an indicative buffer stiffness of 2862 MN/m is obtained for PULSE. For BLUE, this is reduced to 357 MN/m. At model scale, a dedicated buffer design is therefore required for both PULSE and BLUE. For PULSE this buffer is fabricated form a deformable yet high strength material. Whereas for BLUE, a high stiffness spring is used to attain the desired driving characteristic.

PULSE buffer and actuator

For PULSE, it was determined the buffer could be fabricated from deformable yet high strength material. In selection process, two considerations played a role of importance:

1. To avoid plastic deformation, the buffer's internal stress should not exceed the yield stress of the material.
2. It is preferred to use a material with high deformability (yield strain) to optimize the buffer dimensions.

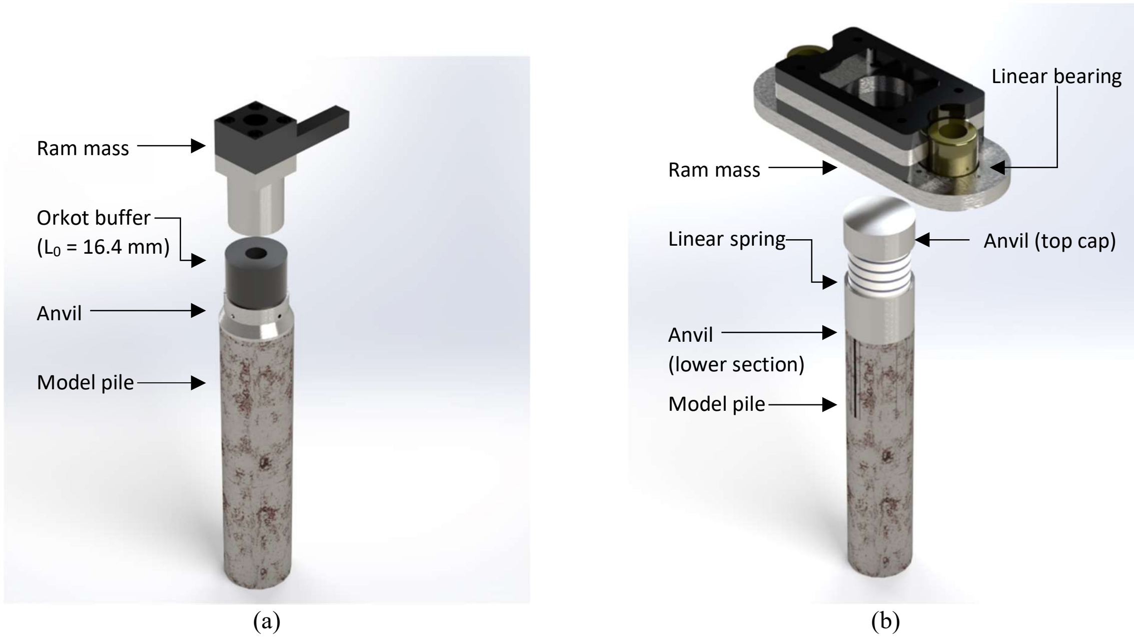

Figure 4: Pile assemblies for the replication of PULSE- (a) and BLUE-blow (b) characteristics in DUT's centrifuge facility.

The internal stress is computed through division of the maximum buffer force, F_{max}, by the buffer's cross-sectional area, A_b (3.02E-04 m^2), as shown in Equation (6).

$$\sigma = \frac{F_{max}}{A_b} \tag{6}$$

F_{max} is computed obtained from the maximum deformation of the buffer, u_{max} as shown in Equation (7).

$$F_{max} = k \cdot u_{max} \tag{7}$$

Where u_{max} is obtained by maximizing Equation (3), which results in the following expression:

$$u_{max} = v_0 \cdot \sqrt{\frac{m}{k}} \tag{8}$$

Multiple materials met the stress requirement. Therefore, remaining materials were rank-ordered to their yield strain. This demonstrated that Orkot, a thermoset composite material, possessed the most favourable properties, namely: a yield stress of 280-350 MPa; a yield strain of 8-12 %. Required buffer height (L_0) is caltucated from Equation (9).

$$L_0 = \frac{E \cdot A_b}{k} \tag{9}$$

From Equation (9) it is found that L_0=16.4 mm, results in the desired impact duration. Figure 4a schematically illustrates the incorporation of the buffer into the pile-anvil system. The pile is installed by the electro-mechanical miniature hammer. The authors refer to previous publications by Azúa-González et al. (2019) and Van Zeben et al. (2018) for detailed information on the driving system.

BLUE buffer and actuator

For BLUE, a high stiffness spring was deemed the best alternative to replicate its impact characteristics in the centrifuge. The authors settled for a compact, HSW38-040 spring, manufactured by TEVEMA. This ISO die spring has a stiffness of 7.14 MN/m. The maximum travel of 3.5 mm is sufficient to meet the deformation requirement which follows from Equation (8). The resulting pile-anvil system is shown in Figure 4b.

To install the pile, a dedicated actuator is developed in consultation with the electronic and mechanical support division (DEMO) of DUT. The actuator (Figure 9) permits the installation of the model pile by means of a single blow at 50g acceleration. The system consists of a modular ram mass (1.1-3.4 kg), which is held in place by an 24V electromagnet (1670 N holding force) during spin-up. Both the electromagnet and the ram mass are connect to a pair of linear guides. The purpose of the linear guiding system is twofold: (i) it allows for a free choice of the falling height (and thus impact energy) of the ram; (ii) it absorbs the Coriolis force acting on the ram mass during free fall, thereby ensuring the ram hits the pile-anvil-buffer system head-on. Two high frequency (9.4 kHz) laser displacement sensors (Althen FDRF602-65/250) track the displacement of the pile and the ram mass. The velocity of the ram mass is obtained through analogue differentiation of its displacement. Multiple blows can be applied to the pile by intermittently stopping the centrifuge to reset the release

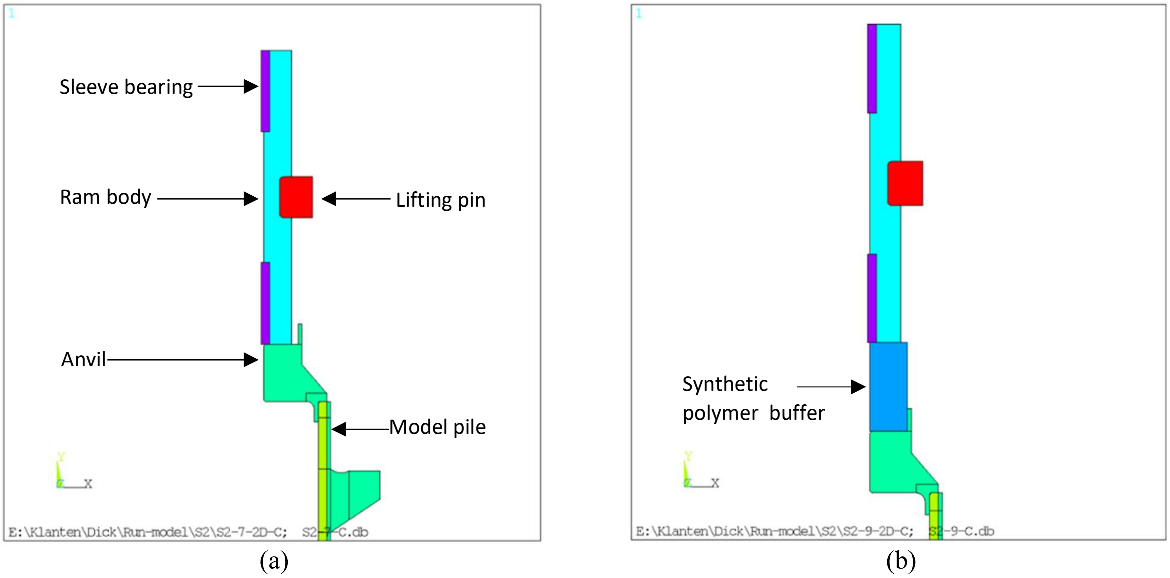

Figure 5: (Axisymmetric) model geometry of the numerical model used to simulate a conventional (a) and PULSE (b) blow in the centrifuge.

mechanism of the ram mass. Provided the system performs as intended, modifications to the system are foreseen to allow for the application of multiple blows in-flight.

Numerical validation

To validate the impact characteristics and the integrity of the PULSE and BLUE buffer designs, numerical simulations are conducted. In both instances,

an axisymmetric model is used, where the pile is rigidly fixed at the bottom. The entire domain is the subjected to an acceleration of 50g, the effect of a gravity curve as present is the centrifuge is thereby disregarded.

For the PULSE system, the simulated impact corresponds to a blow of the IQIP S350 hammer, operating at 100% capacity (v_0 = 6.3 m/s). For comparison, a simulation without Orkot buffer was also conducted. The latter replicated the blow characteristics of a conventional Hydrohammer. Figure 5 shows the annotated cross-sections of the (axisymmetric) models corresponding to the conventional and PULSE blow simulations. The corresponding force-time responses are presented in Figure 6. The effect of the buffer is clearly visible in the results, which shows a tripling of the impact duration and a >50% reduction of the impact force. Although not shown in Figure 6, the efficiency of the energy transfer between the ram and the pile is negatively impacted by the buffer and reduces from 89 to 69%. Consequently, the hammer rebound is larger for the PULSE system.

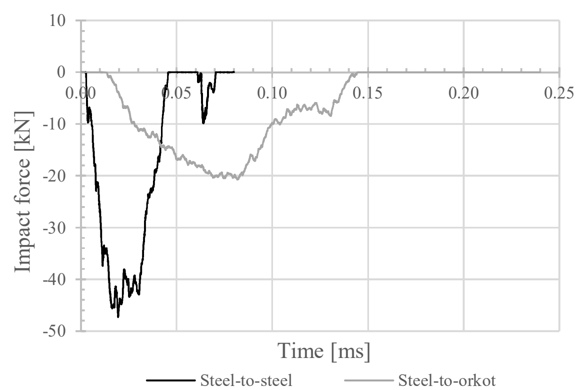

Figure 6: Impact force as a function of time (both at Model scale) for a conventional (steel-to-steel) and PULSE (steel-to-orkot) blow.

Using a similar numerical framework, the impact of the BLUE hammer is also simulated. Figure 7 shows the axisymmetric cross-section of the corresponding model. Boundary conditions are the same as those used for the analysis of the PULSE system. The impact velocity of the ram is 6.5 m/s, which represents a blow at full capacity. Figure 8 shows the associated force-time response of the system. Relative to a the conventional hammer, the impact duration is increased by a factor of 25. In addition, an 80% reduction of the maximum impact is observed. Lastly, from the simulations it follows that the predicted efficiency of the system is 19%.

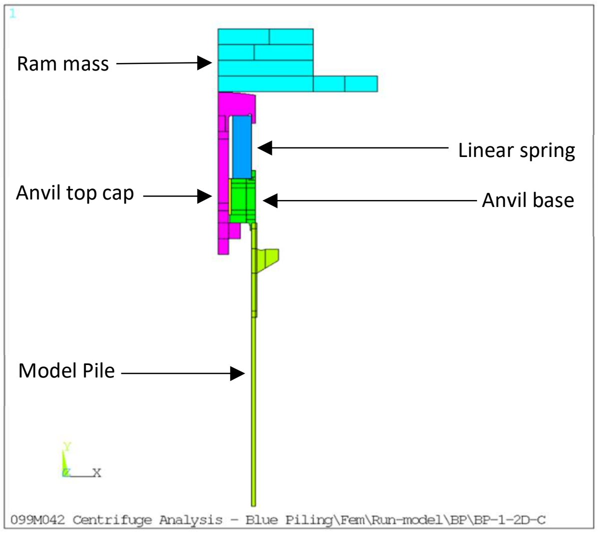

Figure 7: (Axisymmetric) model geometry of the numerical model used to simulate a BLUE Piling blow.

Analysis of the stress state inside the ram, anvil and pile demonstrated that plastic deformation thresholds are respected during the entire simulation for both PULSE and BLUE technology. Oscillations ofhe aforementioned components are also kept to a minimum. Based on the aforementioned results, the authors are reasonably confident about the performance of both systems in the centrifuge; though it is recognized that this expectation demands experimental verification, which is part of the next project phase.

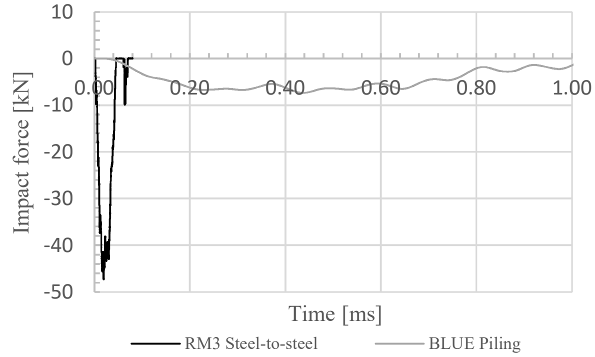

Figure 8: Impact force as a function of time (both at Model scale) for a conventional (steel-to-steel) and BLUE Piling blow.

4 CONCLUSIONS

To maximize their yield, offshore wind farms are being developed in deeper water, further offshore. This trend has resulted in the need for larger monopoles to support the next generation of 12-14 MW turbines. Consequently, a further increase in sound emission is anticipated. Existing sound mitigation technologies are closing in on their operational limits. The development of new techniques is therefore necessary to sustain the further adoption of offshore wind energy.

Significant sound reductions can be realized by

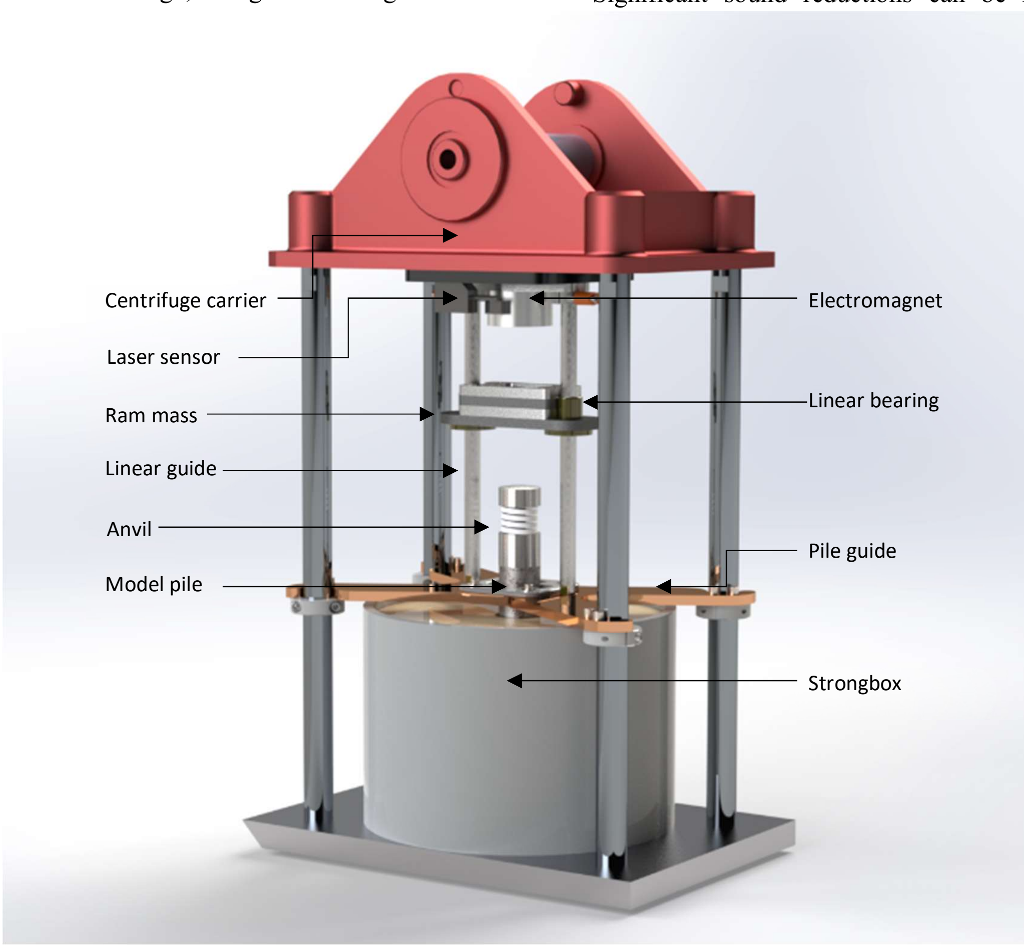

Figure 9: BLUE piling actuator for the centrifuge facility of DUT.

prolonging the impulse of an offshore hammer. PULSE and BLUE, both developed by IQIP, are examples of techniques which are based off the aforementioned principle. Apart from the promise of lower sound emissions and fatigue, little is known about the implications of pulse elongation on pile-soil-water interaction. It is DUT's ambition to close this knowledge gap by a conducting a comparative centrifuge study. To realize this ambition, miniature buffers were designed to replicate of PULSE and BLUE blow characteristics in the centrifuge. Both the underlying theoretical framework and final design of the buffers were presented in this paper.

The 30 mm Orkot buffer as used to replicate PULSE blow characteristics. The corresponding pile assembly will be installed using DUT's miniature electro-mechanical pile driver. For BLUE, the anvil is fitted with a stiff linear spring. Due to due to the increased blow energy of the BLUE hammer, a dedicated actuator is under development. This single blow simulator uses an electromagnet to hold and ultimately release the ram mass onto the pile. The performance of the designs was evaluated by means of numerical simulations. These demonstrated that the advocated designs are successful at replicating the impulse characteristics of PULSE and BLUE technology in the centrifuge.

5 OUTLOOK

In order to gather insight into pile-soil-water interaction as a function of impulse duration, a significant number of centrifuge tests are planned. Following the realization of the actuators and pile systems, tests are performed on saturated samples. The saturation medium consists of either water or viscous fluid. This makes it possible to isolate the effect of pore pressure development on installation behavior. Pore pressures will be recorded by pressure transducers which are installed at various depths and radii (with respect to the pile's center). Furthermore, fiber optic pressure transducers will be embedded into the pile shaft. This allows for the sensors to penetrate with the pile while measuring pressure fluctuations directly at the pile-soil interface (Askarinejad et al., 2018). Finally, pile deformation and acceleration are also recorded.

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