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Centrifuge tests to investigate pile run risk in transitional soils

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ABSTRACT:
Monopiles, commonly adopted as substructures in wind farms, are typically installed via impact driving. The heavy self-weight of the monopile and the impact hammer required for installation increase the risk of pile runs. Pile runs have been reported in cases of stronger soils overlying weaker layers, as well as in heterogeneous soil deposits (*e.g.*, chalk). However, recent experience from the field showed that none of the reasons above could satisfactorily explain the observed pile run in the presence of silty or fine sandy soils, typically referred to as transitional soils. Conversely, back analysis of the driving data revealed a high dependency of the Soil Resistance to Driving (SRD) on the pile penetration rate. This behaviour is believed to be linked to the drainage response of the transitional soils and pile driving parameters, including impact energy and blow rate. The latter may combine so that Excess Pore Water Pressures (EPWP), without dissipating sufficiently, accumulate to the extent a pile run can be triggered, due to the reduction of the available shear strength of the soil. To investigate this hypothesis, an experimental testing program was conducted using the geotechnical centrifuge. The tests, involving a model monopile driven in a natural silt sample, aimed at demonstrating that the soil conditions believed to contribute to a pile run can be replicated in the centrifuge. Preliminary results of a testing sequence of single blows suggest that the EPWP accumulated around the pile between consecutive blows is responsible for a reduction of the unit shaft resistance.

Keywords: pile run; impact hammering; single blow; silt; excess pore water pressure

1 INTRODUCTION

Monopiles, commonly used as substructures in wind farms, are typically installed using impact driving. The heavy self-weight of the monopile and the impact hammer required for installation increase the risk of pile runs. Back-analysis work has demonstrated that some pile runs can be explained by heterogenities within soil units and in other cases have been reported to occur when stronger soils overlay weaker layers (Carotenuto *et al*., 2018).

Recent experience showed that none of the above reasons could satisfactorily explain why a pile run had occurred. Back analysis of the driving data revealed a high dependency of the Soil Resistance to Driving (SRD) on the penetration rate of the pile, with a similar dependency observed on the self-weight penetration as well. The hypothesis put forward for this dependency is that during driving in transitional soils (*i.e.*, silty and fine sandy soils) Excess Pore Water Pressures (EPWP) accumulate *pro rata* to the hammer energy and blow rate, leading to a gradual reduction in driving resistance and eventually even to a pile run if the blow rate is maintained.

In the absence of other studies addressing this mechanism, a series of centrifuge tests were performed to investigate this hypothesis. In these tests, a monopile was driven into a stratified soil deposit constituted by a natural silt sample overlain by a dense sand layer. The tests explored whether the accumulation of EPWP and the associated reduction in driving resistance could be observed experimentally. To the best of the Authors' knowledge, this represents a novel contribution to the existing literature.

2 EXPERIMENTAL METHODOLOGY

The experiments were performed inside the 9g-ton, 1.215 m radius geotechnical centrifuge available at Delft University of Technology. The experiments aimed to replicate the mechanical and hydraulic behaviour reproduced during the installation of an open-ended pile using impact driving. The foundation soil was soft silt overlain by a dense sand layer. Under conventional scaling factors applicable (*e.g.*, Garnier *et al.*, 2007), the models resembled a hypothetical prototype steel pile with an outer diameter of 2.1 m, a wall thickness of 0.1 m, and a length of 8.75 m. The sand and silt foundation soil layers had a thickness of 2.9 m and 4.85 m, respectively. The model was spun to simulate a gravitational acceleration field of 50g ($N = 50$) at the top of the silt layer.

This study used the setup shown in Figure 1, which consisted of three main parts: the model container, the pile assembly, and the blow generator (Quinten *et al.*, 2024). The model container was cylindrical, with an inner diameter of 25 cm and an inner height of 17 cm. The pile assembly consisted of an open-ended, stainless-steel pile with an outer diameter (D_{pile}) of 42 mm, a wall thickness of 2 mm, and a length (L_{pile}) of 17.5 cm. The pile was attached to a solid, stainless-steel anvil, resulting in a total length for the pile assembly of 20 cm. The masses of the anvil and pile were 282.7 g and 355.9 g, respectively.

The blow generator was fixed to the centrifuge basket and included an electromagnet and a ram mass of 900 g, which travels vertically along two guiding columns. The actuator allowed inducing a single-blow impact to the head of the pile assembly by fixing the electromagnet to a selected elevation and then remotely releasing the ram mass. During the tests, several single-blow impacts were reproduced at 50g to drive the pile into the soil model, which required spin-down and spin-up sequences between consecutive blows. Two safety belts surrounding the electromagnet and the ram mass limited the travel distance of the ramming mass after release. The belts also prevented additional dead load at the head of the pile assembly while displacing. This study used impacts with falling heights ranging from 9 to 36 mm (see Table 3), resulting in an approximate delivered energy ranging from 3.1 to 14.4 J (200 to 1000 kJ at the prototype scale, typical for the driving of monopiles in weak soils or small-diameter jacket piles).

The setup included a series of pore water pressure (PWP) transducers (*i.e.*, PPT1-PPT3) at relevant sections of the model to monitor the evolution of PWP during the tests. Two laser sensors monitored the vertical displacement of the pile assembly and the ram mass. In addition, a series of strain gauges placed near the top of the pile estimated the axial load during driving.

Unless otherwise specified, all quantities in the following sections are presented at the model scale.

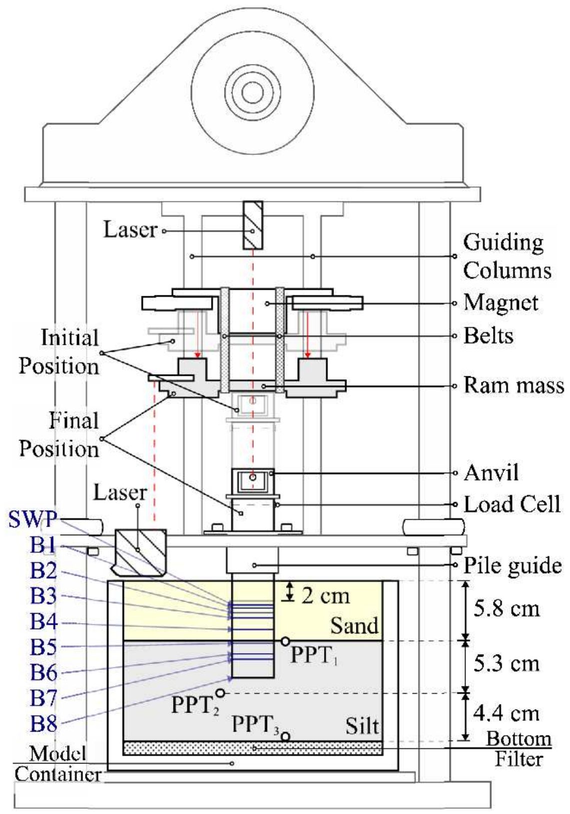

Figure 1. Experimental setup in centrifuge basket.

3 MATERIALS AND MODEL PREPARATION

Geba Sand, native to Germany, and Viterbo Silt, sourced from the Lazio region of Italy, were used in this study. As collected from the field, the Viterbo Silt was subjected to an extended sedimentation period to reduce the existing clay content. The resulting material was oven-dried, pulverized, and mixed with de-mineralized water to a water content, w, between 28 and 29 % in the laboratory. The wet mixture was carefully stored in plastic bags for over 24 hours prior to model preparation to ensure homogeneity. Tables 1 and 2 show the relevant parameters of both materials after being put into the strong box adopted as model container in the centrifuge tests, while the Particle Size Distribution (PSD) and plasticity chart are shown in Figure 2.

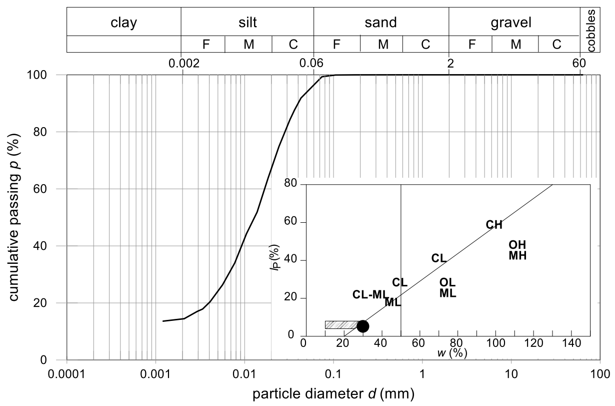

Figure 2. Viterbo silt: average PSD and plasticity chart.

The model was prepared directly inside the model container. A filter and drainage layer with a thickness of 1.5 cm was placed at the bottom of the container using uniform, coarse-grained sand. The filter was saturated with water by upward flow from the bottom of the container. The silt layer was prepared atop the bottom filter by placing thin slabs of silt mixture inside the container, forming individual layers with a 2.5 to 3.0 cm thickness. Each layer was tampered with a rubber hammer and carefully vibrated to seal potential gaps between slabs and reduce larger voids.

Table 1. General Geba Sand parameters and properties

Parameter	Value	Parameter	Value
G_s	2.67	D_R (%)	88.0
e_{max}, e_{min}	1.07, 0.64	γ_{sat} (kN/m^3)	19.5
e	0.69	φ'_{cv} (°)	36.0

G_s = specific gravity; e_{max}, e_{min}, e = maximum, minimum and current void ratio; D_R = relative density; γ_{sat} = saturated unit weight; φ'_{cv} = constant-volume friction angle

Table 2. General Viterbo Silt parameters and properties

Parameter	Value	Parameter	Value
G_s	2.69	I_P (%)	5.0
w_L, w_P (%)	30.0, 25.0	γ_{sat} (kN/m^3)	20.5
w (%)	22.0	c_v (m^2/s)	1.1e-7

G_s = specific gravity; w_L, w_P = limit and plastic limit; w = current water content; I_P = plasticity index; γ_{sat} = saturated unit weight; c_v = consolidation coefficient

Water was continuously added to maintain a clear water table above the surface. The process was repeated for four layers, resulting in an initial height of 10.5 cm. Afterwards, the silt layer was subject to a one-dimensional consolidation inside the centrifuge for a total duration of two days, including an overnight stop at 1*g*. During the consolidation, the silt sample was subject to the combined weight of a plate and water on top, which was designed to reproduce the weight of the sand poured after consolidation. This was done to obtain an almost normally consolidated soft silt sample. The resulting value of the pre-consolidation stress, σ'_p, was therefore nearly 60 kPa. At the end of consolidation, the surcharge load was removed, and the sand layer was placed using wet pluviation and tampering to a relative density of about 90 % (see Table 1).

It is noted that viscous fluid was not used as pore fluid in this study. Instead, water was used, and the low permeability of the Viterbo Silt allowed the EPWP during the single blow events to be considered decoupled from the subsequent EPWP dissipation.

After model preparation, the container was placed in the centrifuge basket, and a CPT probe, having a diameter of 7.5 mm, was placed at an adequate distance (*i.e.*, 40 mm from the edge of the box and hence 114 mm from the monopile) not to disturb the soil sample where the monopile was subsequently installed. The tip resistance obtained is plotted at model and prototype scale in Figure 3 ($z_{prot.} = N\, z_{model}$).

Finally, the pile assembly was pre-embedded 2 cm into the sand layer at 1*g* using a frictionless pile guide to prevent undesirable inclinations.

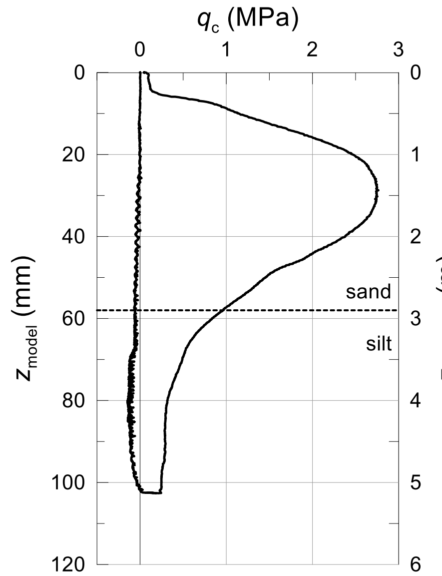

Figure 3. Tip resistance from the in-flight CPT test.

4 DISCUSSION OF THE EXPERIMENTAL RESULTS

The test strategy included a self-weight penetration (SWP) stage followed by a sequence of 8 single blows (B1 to B8), driving the pile to a depth of approximately 2.3 D_{pile}. During SWP, the pile was allowed to settle freely under its self-weight starting from the imposed pre-embedment, until a final embedment of 24 mm (1.0 m at prototype scale) was reached. A summary of the key parameters for the blow sequence is given in Table 3. Due to the reduced

Table 3. General parameters of the blow sequence at model (prototype) scale

Blow	N	Falling height mm (m)	Input energy* J (kJ)	Pile final embedment mm (m)
B1	40.2	9 (0.3)	3.1 (204)	27 (1.1)
B2	40.1	22 (0.9)	7.5 (485)	32 (1.3)
B3	40.3	22 (0.9)	8.3 (541)	37 (1.5)
B4	40.3	33 (1.3)	13.0 (845)	49 (2.0)
B5	40.8	36 (1.5)	14.4 (972)	63 (2.6)
B6	41.9	15 (0.6)	5.0 (369)	74 (3.3)
B7	42.5	11 (0.5)	4.1 (311)	79 (3.4)
B8	42.2	34 (1.4)	13.9 (1041)	98 (4.1)

** input energy is the energy carried by the ram at an infinitesimal instant before impact*

gravity level at the blow generator, the scale factor (*N*) is also included in the table.

Between two blows, the centrifuge had to be halted and restarted to manually reset the ram falling height for the subsequent blow. Each pause lasted approximately 5 minutes (excluding the spin down and spin up time). The recording of the position of the ram mass and the pile, the pile head force and the PWP, was never interrupted.

The unloading-reloading cycle imposed on the soil by intermittently halting the centrifuge is likely to have influenced the magnitude of the EPWP. However, upon restarting the experiment and recovering the *g*-level, only part of the EPWP induced by the blows was lost, as shown in Figures 5i-6.

A single-blow procedure allows to replicate much slower driving conditions than those obtained using an impact hammer that in the field would typically operate at least at 20 blows/minute. However, as the EPWP were not entirely lost during the blow sequence, and since applying blows faster within the setup of the experiment was not possible, the single blow experiment was still considered valuable enough to test the initial hypothesis.

The blue lines in Figure 1 show the pile embedment cumulated over the SWP and the sequence of blows B1-B8. The different settlements achieved at the end of each blow can be attributed to the following reasons: (*i*) different input energy transferred to the pile between B1 to B8; (*ii*) the reduction in soil resistance at the transition from sand to silt, being the two materials characterised by significantly different strength (see the CPT profile in Fig. 3). For instance, in spite of similar input energies in blows B4 and B8 (Table 3), the pile settlement at the end of B8 was almost double than the one at B4. Moreover, an input energy approximately 2.6 times higher was needed in B4 to end up with almost the same set as in B6.

4.1 Pile and ram displacement, velocity and driving force

Figure 4 shows the pile (black line) and ram (red line) displacement (Fig. 4i) and velocity (Fig. 4ii), as well as the internal axial force measured at the head of the monopile by means of the strain gauges (Fig. 4iii) for blow B8. These quantities are plotted at both model and prototype (*N* = 42.2) scales. This data was recorded at a sampling rate of 100 kHz. The signal measured by the strain gauges shows a high-frequency response superimposed over the expected signal. A band-pass filter was applied to remove the high-frequency content, which is ascribed to the high-frequency vibration modes triggered by the high energy delivered in the blow. Both the as-recorded and filtered signals are plotted for the driving force in Figure 4iii. The velocity profiles of the pile and the ram were obtained by differentiation of the corresponding displacement profiles.

The ram mass release coincides with the moment when the ram displacement and velocity start to ramp up, as highlighted by the grey arrows in Figure 4. At the same time, a sinusoidal-shaped signal is recorded for the axial force. As discussed by Quinten *et al.* (2024), such a signal is likely to be the result of

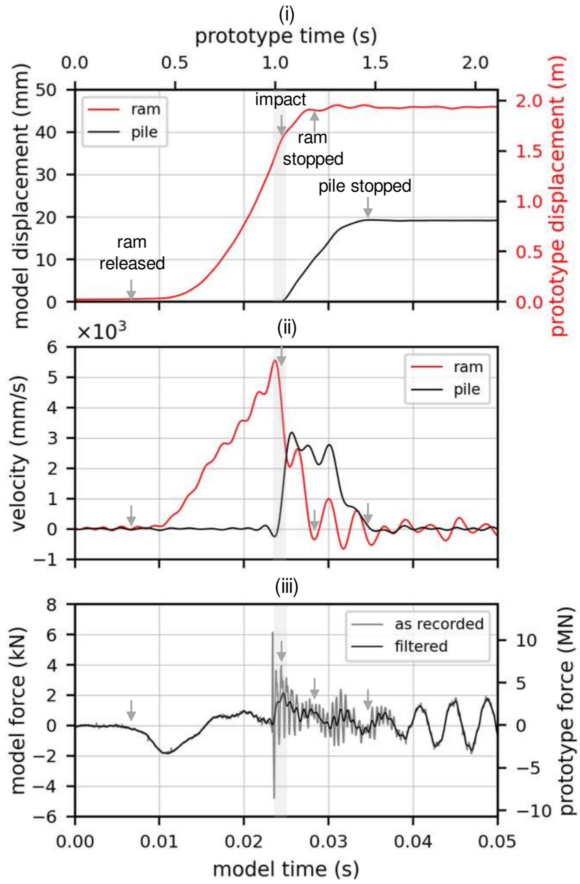

Figure 4. Pile (black) and ram (red) displacement (i) and velocity (ii); driving force (iii)

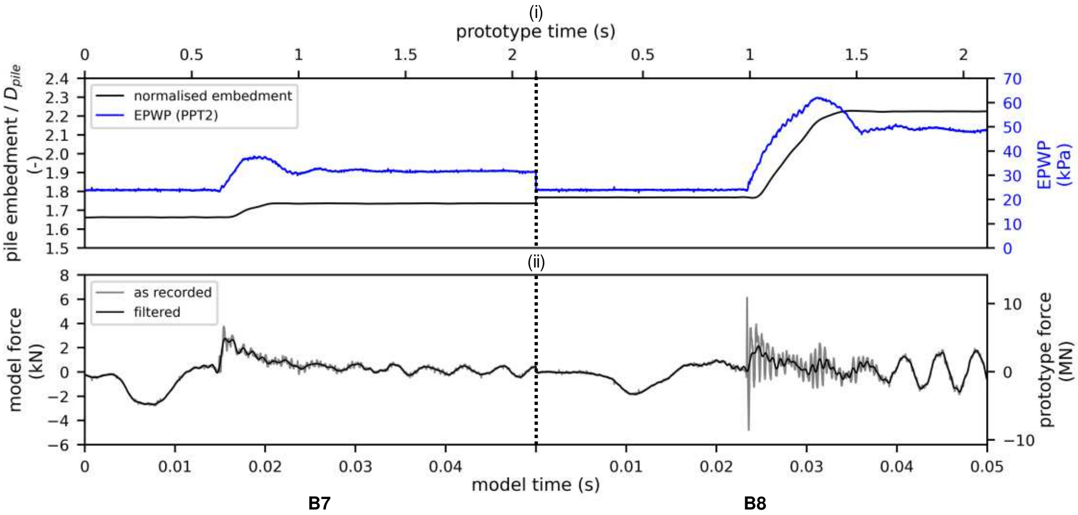

Figure 5. Pile normalised embedment (black) and EPWP measured by PPT2 (blue) (i); driving force (ii)

electromagnetic interference emitted during the ram release and hence is not physically relevant.

The impact has most likely occurred over the time interval (+/-1.4 ms) highlighted by the shaded grey area plotted in Figure 4, starting where a peak is attained in the ram mass velocity and an increase in the pile head force is registered. As the momentum is transferred to the pile, the ram velocity decreases while the pile velocity picks up. As the pile velocity exceeds that of the ram, most likely their contact must have temporarily ceased for approximately 1.4 ms, after which the velocities reach the same value again. This can be interpreted as a secondary blow, visible as a slight increase in the measured force in Figure 4iii. After this, the pile displacement is completed in approximately 10 ms, with a final settlement of 19 mm. The contact between the ram and the pile is ultimately lost when the ram is stopped by the belt and its velocity decreases until the pile stops.

The high impact duration compared with the travel time of the stress wave generated at impact along the pile (L_{pile}/c = 0.03 ms, with c = 5189 m/s being the phase velocity of the stress wave in the pile) makes the installation mode somewhat quasi-static, falling between impact driving and jacking, with the pile being stress wave-driven in the former and acting as a rigid body in the latter (Huy 2010). Whether this warrants a different processing approach is still under investigation. However, to allow making a relative comparison of the resulting soil resistance between two consecutive blows, this should - in the Authors' opinion - not matter as long as the same approach and assumptions are made to analyse each blow.

4.2 Behaviour between consecutive blows

Figure 5 shows the pile embedment, normalised with respect to the pile diameter (Fig. 5i), and internal pile force (Fig. 5ii) across blows B7 and B8, characterised by the pile tip being embedded in the silt layer at the start of each blow. These quantities are plotted at both model and prototype (N = 42.2) scales. Strictly speaking, a higher scaling factor (N = 53.6) would be needed for the EPWP measurements of PPT2.

The falling height was set equal to 11 and 34 mm for B7 and B8, respectively, thus delivering an energy in B8 of more than 3 times higher than that in B7. As a result, a pile settlement equal to 3 and 19 mm was measured. The higher impact energy in B8 resulted in a much noisier force signal than the one recorded in B7. Moreover, it is likely that the exact maxima of the pile head force may not have been always captured, even at a sampling rate of 100 kHz. However, the comparison between the filtered signals plotted in Figure 5ii shows a peak value of 2.1 kN (3.7 MN at prototype scale) in B8 lower than the 2.8 kN (5.1 MN) in B7. Such a difference can be interpreted in light of a lower shaft resistance offered by the soil surrounding the pile despite the higher pile embedment, while assuming a constant capacity at the pile tip with depth, as supported by the constant q_c = 300 kPa profile in the silt layer (see Fig. 3). The reduction in the unit shaft resistance is a consequence of the reduction in the soil effective stress state due to EPWP accumulation, which is supported by the PPTs measurements during the blow sequence. As an example, Figure 6 shows the EPWP measured by PPT2, i.e. the PWP net of the value measured at the end of SWP for the whole blow sequence. An extract is also shown in Figure 5i (blue) for B7 and B8. The gap observed between the end of a blow and the start of the following one is a measure of the EPWP lost over the spin-down-spin-up sequence (not shown in Figs. 5-6) required to manually reset the hammer between two consecutive blows.

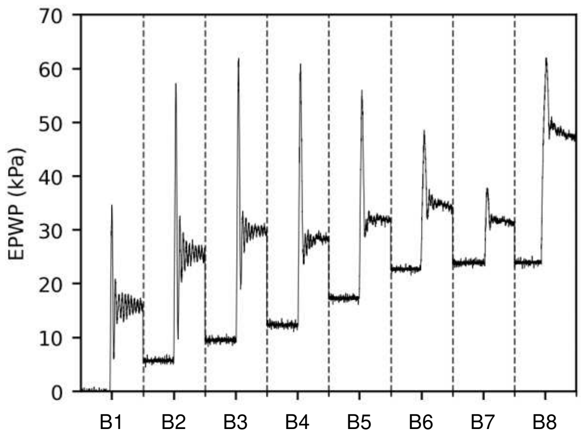

Figure 6. EPWP measured by PPT2 over the blow sequence

5 CONCLUSIONS

Pile runs during impact hammering installation are a major concern for the offshore industry. In the presence of transitional soils, it is believed that the accumulation of excess pore water pressure (EPWP) induced by consecutive blows causes a reduction in driving resistance (and eventually even pile free-fall). The scarcity of studies addressing this type of pile run has motivated an experimental testing program, conducted at the centrifuge facility of TU Delft, serving the aim to understand whether the drainage soil conditions believed to contribute to a pile run can be replicated in the centrifuge.

This paper presents an extract of the results of the installation sequence of a 42 mm model pile driven in a water-saturated soil model through 8 single blows using a centrifuge blow generator. The soil sample consisted of normally consolidated Viterbo silt overlain by a dense GEBA sand layer. The sample preparation adopted in the testing program was meticulously designed to overcome challenges in achieving full saturation of the silt and ensuring sufficient capacity to support the self-weight of the pile-anvil-ram assembly, all while maintaining the silt in a normally consolidated state.

Preliminary results show accumulation of excess pore water pressures (EPWP) during consecutive blows as measured by the transducers embedded in the silt layer. Positive EPWP build-up directly resulted from the low permeability and contractive behaviour of the silt, which induced a partially drained response between consecutive blows. The decreasing driving force measured in two consecutive blows performed in the silt suggests a reduction in the unit shaft friction.

AUTHOR CONTRIBUTION STATEMENT

First and Second Author (AR, DG): Funding acquisition, Conceptualisation, Investigation, Formal Analysis, Writing-Original draft, Writing-Review & Editing. **Third Author (HF)**: Conceptualisation, Formal Analysis, Writing-Original draft. **Additional Author (WOV)**: Resources, Investigation, Writing-Original draft. **Last Authors (SM, MC)**: Project administration, Supervision, Writing-Review & Editing.

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