Inflight installation of a jacked pile group for modelling installation effects

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ABSTRACT: An in-depth understanding of the performance of piled foundations due to lateral loading is relevant for the reliable design of new structures and for the assessment of the stability and serviceability of existing infrastructure.
Available investigations on laterally loaded pile groups and current empirical or analytical methods mainly focus on bored piles. Opposite to that, there is very limited knowledge about the performance of displacement pile groups although it can be expected that their behaviour is significantly influenced by the installation effects, like the change of stress-state and soil density. For realisation, tests on groups of 9 piles, installed as bored-piles and as displacement piles, are performed at Deltares Centrifuge, to picture the impact of installation effects on the lateral load-displacement behaviour of the pile groups. Therefore, the earth pressure was measured directly on the pile surface by small earth pressure cells and the lateral load versus pile head deflection was measured by strain gauges mounted on the inside of the pile. To model jacked, fixed-headed piles without stopping the centrifuge means that the piles have to be jacked, rigidly fixed and loaded laterally in flight, without stopping in between. If a stop for further installations is needed, this could cause changes of the stress state in the soil as well as for the soil-structure interaction.
In the paper the modelling technique is shown and the output of the centrifuge tests will be presented.

1 INTRODUCTION

Introducing the subject, Figure 1 illustrates schematically for a laterally loaded 3x3 pile group the pile-pile interaction by shadowing effects caused by adjacent piles when the pile-spacing (S/D) is close. There are various findings about the exact distance needed, to avoid interaction overlapping effects; In EA-Pfähle (2013) six times the diameter (6D) is suggested as minimum distance.

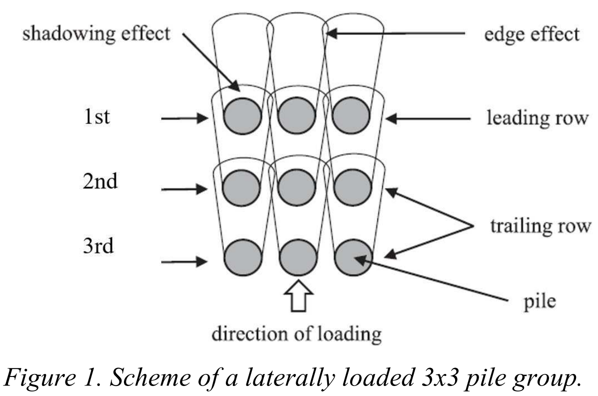

Figure 1. Scheme of a laterally loaded 3x3 pile group.

For jacked piles, no tests were done at 1g gravity and for jacked piles in the centrifuge, no pile-installation effects were considered (Brown, Morrison & Reese (1988), Huang et al. (2001), Klüber (1988), Kotthaus (1992), McVay et al. (1994, 1995, 1998), Rollins et al. (2005). Therefore, the performance of the piles in a group has to be reduced by a p-multiplier <1.0, in comparison to a single pile. Huang et al. (2001) first considered a factor for driven piles to consider the impact of the installation method.

Objective of the proposed physical testing methodologies is to picture the impact of pile group installation effects on the performance of laterally loaded pile groups covering replacement piles (bored piles) and displacement piles (jacked prefabricated piles).

2 EXPERIMENTAL METHODOLOGY

To realize the above-mentioned goals, six tests were performed in the Deltares Centrifuge, Table 1.

Table 1. Test program centrifuge tests.

Test	Pile installation	Type of pile	I_D [%]
1	re- & displacement	single pile	58
2	re- & displacement	single pile	29
3	replacement	pile group 3x3	32
4	replacement	pile group 3x3	56
5	displacement	pile group 3x3	32
6	displacement	pile group 3x3	54

Besides the already mentioned aspects of improving the understanding of the performance of laterally loaded pile groups, the way of performing this kind of pile group tests in a centrifuge is highly challenging. To model jacked, fixed-headed piles in a centrifuge without stopping means that the piles have to be jacked, rigidly fixed and loaded laterally in flight, without stopping the centrifuge in between. If the centrifuge has to be stopped for further installations, this could cause significant changes of the stress state in the soil as well as for the soil-structure interaction. Due to the relaxation, the behaviour of the soil-structure interaction will fundamentally change. The results of the created output would be hardly definable. Outcomes could range from resembling jacked piles to, in worst case, behaving like a bored pile group due to relaxation. Therefore, no installation effects would be figured out in the end. That's why maybe former research couldn't picture significant differences, affected by the method of pile installation.

2.1 Model scaling

The scaling of the model is 1:50. The prototype of the piles is 18,75 m in length and 0.75 m in diameter. So, the model piles are scaled down to 37,5 cm in embedded-length and 1.5 cm in diameter.

Table 2. Dimension analysis.

Parameter	Unit	Scale	Model pile	Prototype
Material	*[-]*	-	Al	RC*
Diameter	*[m]*	λ	0,015	0,75
length	*[m]*	λ	0,375	18,75
EI	*[kNm²]*	$\lambda^{4,5}$	0,1236	580000
Wall thickness	*[mm]*	-	2,0	-

*RC = reinforced concrete

2.2 In-flight pile installation

To enable in-flight installation and loading of the pile group construction, a special coupling system with a plug-in method was developed. The method allows to keep the piles in place, install them separately, fix the piles and the head plate together and load the system in horizontal direction at the pile-head level. Therefore, quick couplings for compressed air were used, to get a fixed connection of pile-cap and piles after the installation. The nipples or also called plugs are mounted on the pile-cap and the coupling sockets are fixed on top of the piles. Some modifications were necessary regarding the inside of the quick couplings, such as removing valves and seals, to get the pile through it, as can be seen in Figure 2 . Also, a side outlet was required to route the cables out, to enable a vertical pushing of the piles for the installation.

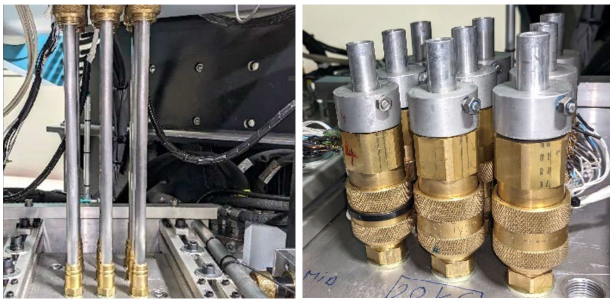

Figure 2. Plug-in method: open system before pile installation (left), coupled system after pile installation (right).

The pile-cap is guided on linear rails to allow lateral movement in loading direction, but to avoid tilting of the plate and to carry it. The pile-cap itself is not in contact with the sand, to exclude any load-carrying-effects. Since it wasn't possible to move the adapter transversely to the load direction, the piles had to be installed three by three, starting with the centre-row, followed by the back-row and at least the front-row. The installation-speed was 1 mm/s.

2.3 Application of strain gauges

For the measurement of the bending line, strain gauge half-bridges have been mounted. Affected by the small scale, the high acting forces and the way of installations, as fixed-headed piles, the mounting of the strain gauges on the inside-wall was indispensable. Otherwise, the intactness of the sensors after installation isn't guaranteed and as well the impact of any installation notches on the bending behaviour of the pile wouldn't have been estimable. Therefore, the sensors were installed on the inside-wall of the piles by an inflating machine-hose. Both, the pile and the machine-hose were fixed with shaft bearings and were guided on a linear rail system. In the next step, the wired strain gauges are placed back-sided on the machine-hose on the intended markings, the glue is added, the tube is pushed in place and the machine-hose is blew up by air pressure. A similar technique was used by Bransby & Springman (1997).

The most challenging tasks for this method are the handling of the wires and the non-linear behaviour of the machine-hose. When used several times, the expanding causes permanent deformations mainly in longitudinal direction, but also in radial direction.

To handle the imperfections, caused by the installation method, the piles have been x-rayed by radiography, Figure 3, to determine the exact position of the strain gauges and to do the calibration. The shape of the strain gauges in Figure 3 is highlighted for a better understanding. The maximum resulting deviations from the correct positioning are about 3 mm in longitudinal axis and out of axis. The embedded depth of the strain gauges in prototype scale is 0 m, 3 m, 6 m, 9 m and 12 m.

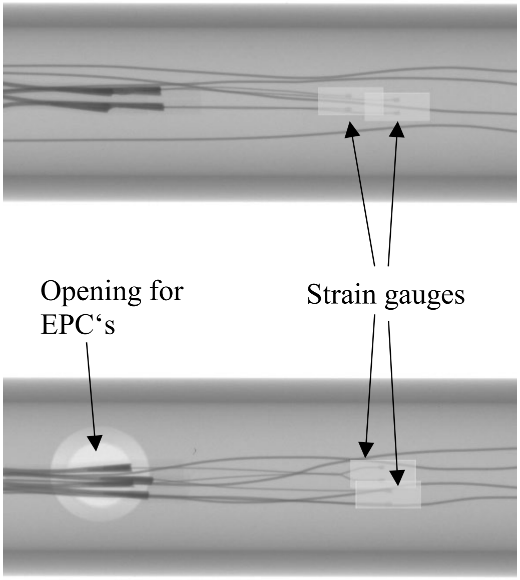

Figure 3. Radiography: X-ray picture of piles

2.4 Application of Earth pressure cells (EPC)

By measuring the horizontal earth pressure at the surface of the pile shafts, the stress development during the horizontal pile deflection can be monitored. Conclusions can be made by the soil pressure acting on the piles at different positions within the pile group. Similar measurements have been made by Burali d'Arezzo et al. (2015). Therefore, small pressure sensors with a diameter of 6 mm are integrated in the pile surface, Figure 4. Talesnick (2014) recommended a minimum of between six to eight particle grains must fit across the sensing diameter to ensure reliable results. Considering the maximum grain size of Bascarp Sand No.15, a value of smaller than 0,2 mm is determined.

3 EXPERIMENTAL LAYOUT

As pictured in Figure 4, three levels of earth pressure cells (EPC) were mounted in the pile surface of the leading pile (LP) in the middle of the 1st row and the centre pile (CP) of the 3x3 pile group. The embedded depth of the EPC‘s in prototype scale is 1,5 m, 4,5 m and 7,5 m.

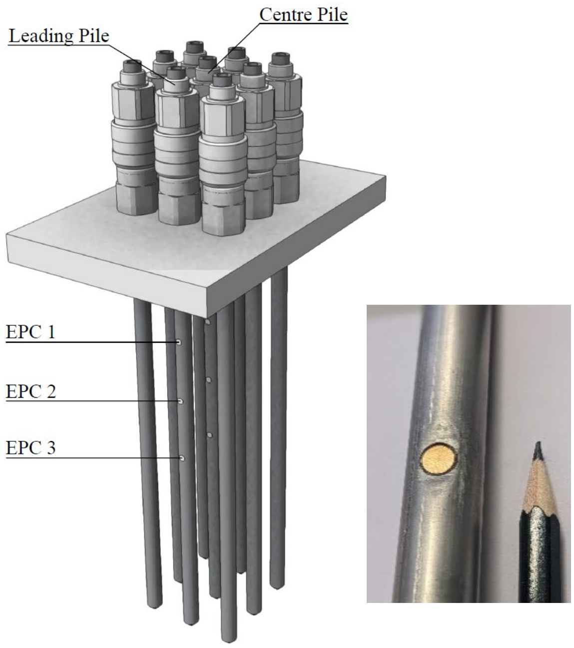

Figure 4. Model of fixed-headed pile group with applicated Earth pressure cells (EPC) in 3 levels at the centre pile (CP) and the leading pile (LP).

4 PREPARATION TEST SAND – INSTALLATION 1G SAND RAINER

The centrifuge tests take place in dry, Baskarp Sand No. 15 (Table 3). The relative density of the sand was about ID = 55% and ID = 30%. For sample preparation, the sand raining method was used.

Table 3. Properties of model sands for centrifuge tests (Nielsen & Nielsen (2018))

Parameter		
Mean grain size (mm)	d_{50}	0,132
Maximum void ratio (-)	e_{max}	0,84
Minimum void ration (-)	e_{min}	0,56
Angle of repose (°)	φ	30,1
Critical state friction angle (°)	φ_c	34
Specific gravity (-)	G_s	2,63
Coefficient of uniformity (-)	U	1,53

For the preparation of the test sand, the 1g sand rainer from Actidyn Systèmes SAS was first used at Deltares Geo-Centrifuge. Therefore, a short pre-testing was carried out, to adapt the guiding boundary conditions to enable a repeatable test sand preparation. The findings from that pre-testing and the results for the prepared test sand are presented in Figure 5.

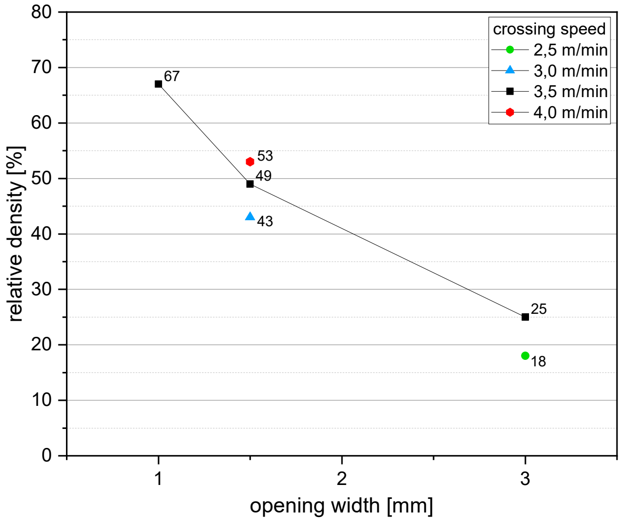

Figure 5. Results of relative density pre-testing

Figure 6. Sand-rainer; Sand-curtain; cylindrical test-box.

Limited by the height of the cylindrical container-rings, the installation height of the sand-curtain is chosen at a constant height of 60 cm, Figure 6. To control the density of installation, two guiding parameters were chosen: the volume outflow, guided by the slotted opening width and the crossing speed of the sand-rainer. The results by variation of these two parameters are plotted in Figure 5. For the installation of the medium dense to dense sand, an opening width of 1,5 mm and a crossing speed of 4,0 m/min were chosen. For the loose sand, an opening width of 3 mm and a crossing speed of 3,5 m/min were chosen.

5 LOADING OF PILE GROUP

The lateral load was applied path controlled with 0,1 mm/s. Kotthaus (1992) captured, that the load distribution stays constant at a pile-head deflection of 10% of the pile diameter. Up to 10% deflection, the piles are acting as single piles in the beginning with no interaction, by increasing the deflection, the interaction of the piles develop and a reduction of the load-bearing capacity for the following piles takes place. For these tests, the horizontal deflection was chosen with 0,1·D, 0,2·D and 0,3·D. The deflection was applied successively starting with the lowest deflection and was kept for 40 to 70 seconds until the measured earth pressure showed a constant value (Figure 7). After every load step the piles were unloaded to the starting position.

6 DATA OUTPUT & MEASUREMENT RESULTS

Following, the data output for the earth pressure cells (EPC) and the strain gauges for test 4 are presented (Figure 7 and Figure 8). The output of the data measured by the earth pressure cells clearly displays the process of the up-spinning and down-spinning of the centrifuge (Figure 7). Also the three levels of loading and unloading to the initial stress state can be captured.

In Figure 8, the output data for the 5 levels of strain gauges on the centre pile are plotted. Depending on the direction of the wiring, the output values are positive or negative. At level 5, some of the strain gauge measurements show inconsistant values, even when no load is applied. These problems did not occur at the measurements at the 1g state, so it is reasonable to assume that these errors are due to the dynamic effects and the high loads in the centrifuge, particularly when the strain gauges are not properly attached. However, it should be mentioned that this method is very complex, and many errors can occur when attaching the strain gauges. Handling the cabling was a particular challenge.

In Figure 9 and Figure 10 the initial stress state for Test 4 (bored piles) and Test 6 (jacked piles) in medium dense sand are plotted. Notably here is the change of the maximum acting earth pressure on the pile surface after pile installation. While with bored piles there is a maximum acting earth pressure on the leading pile (LP), with a significant reduction of the earth pressure for the center pile (CP), with displacement piles a changing of the maximum initial stress state can be spotted.

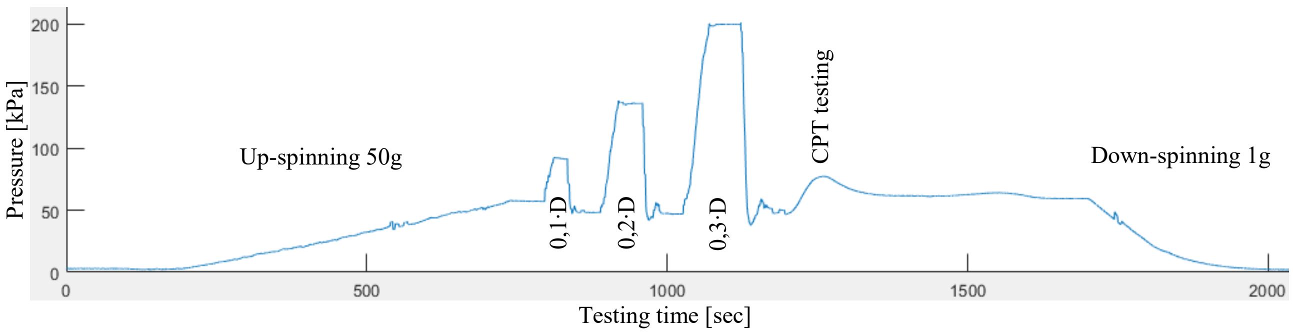

Figure 7. Output earth pressure cell measurement - Test 4 - Centre pile - EPC 2

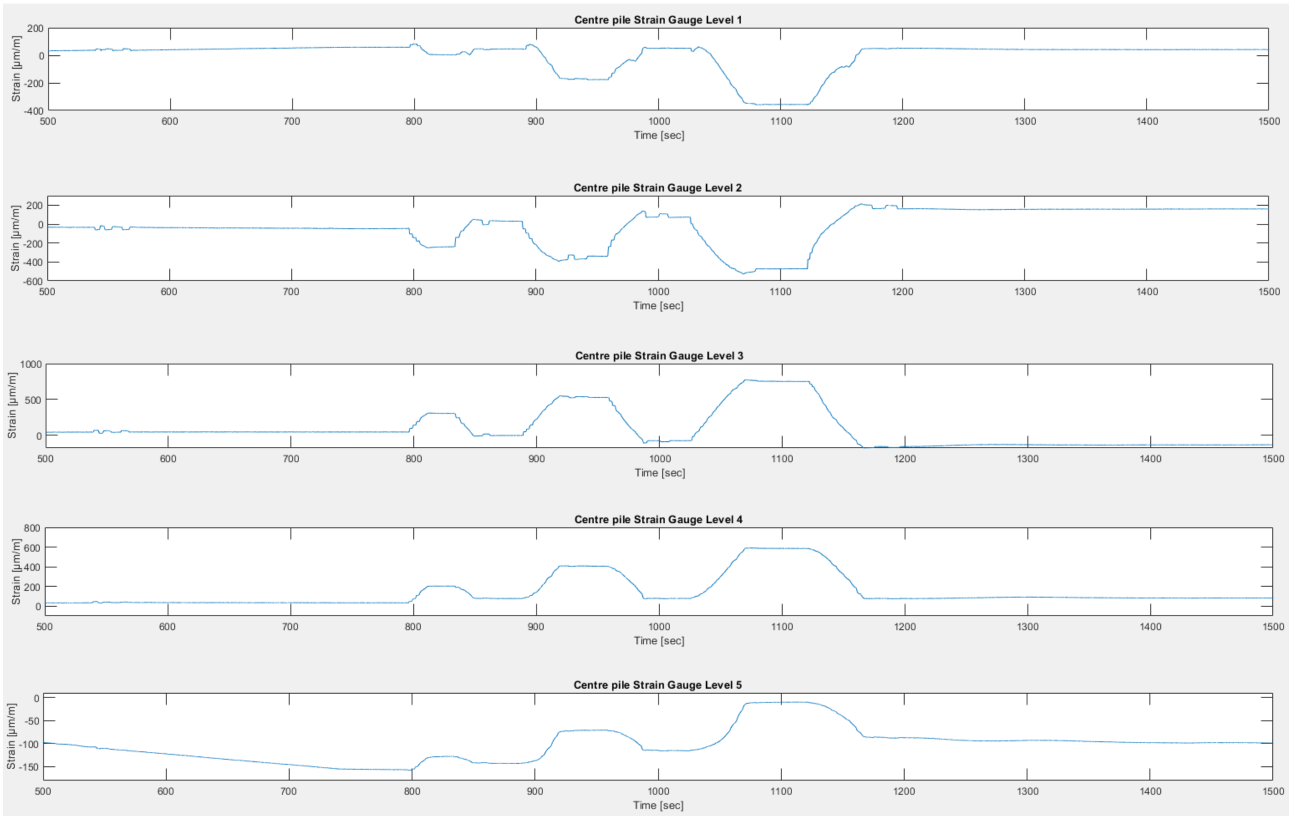

Figure 8.Output strain gauge measurement - Test 4 - Centre pile - Level 1-5

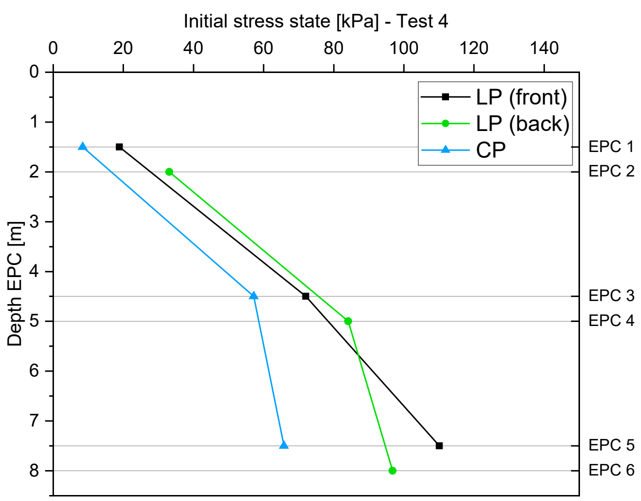

Figure 9. Initial stress state after installation - bored piles

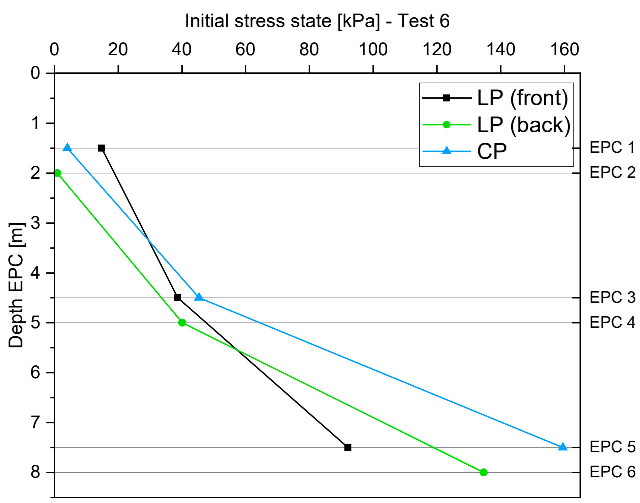

Figure 10. Initial stress state after installation - jacked piles

For the second and third level of EPC‘s, the centre pile experiences a higher acting earth pressure. Especially for the third level there is a significant increase of earth pressure, caused by installation effects.

7 CONCLUSIONS

To model the lateral bearing behaviour of a pile group in a centrifuge and how it is affected by the way of installation, the two presented sensing methods offer good options to investigate the impact of installation effects on pile groups and enables new insights in the different load bearing behavior for various types of piles depending on their installation method.

Further it is shown, that the density of the test sand can be controlled, when the height is limited. Two other guiding parameters were chosen: the volume outflow, guided by the slotted opening width and the crossing speed of the sand-rainer.

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