

Influence of installation effects on the performance of laterally loaded pile groups

Influence des effets de l'installation sur les performances des groupes de pieux chargés latéralement

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ABSTRACT: A profound knowledge of the performance of laterally loaded piled foundations is important for the assessment of critical infrastructure which is mostly founded on deep foundations and which to an increasing extent has to resist lateral loads resulting from structures, variable loads and geohazards. 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 full 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 full-displacement piles, are performed at Deltares Centrifuge, to quantify the impact of installation effects on the lateral load-displacement behaviour of the pile groups. Therefore, the horizontal soil pressure was measured directly on the pile surface by small earth pressure cells. The pile installation and the loading were executed during spinning, enabled by an innovative experimental system. In the paper based on a state-of-art assessment of the design of laterally loaded pile groups, the concept and the results of the centrifuge tests are analysed demonstrating the characteristic differences between bored and displacement piles.

RÉSUMÉ: Une connaissance approfondie des performances des fondations sur pieux chargés latéralement est importante pour l'évaluation des infrastructures critiques qui reposent principalement sur des fondations profondes et qui doivent de plus en plus résister aux charges latérales résultant de géorisques. Une compréhension approfondie des performances des fondations sur pieux dues aux charges latérales est pertinente pour la conception fiable de nouvelles structures et pour l'évaluation de la stabilité et de l'aptitude au service des infrastructures existantes. Les recherches disponibles sur les groupes de pieux chargés latéralement et les méthodes empiriques ou analytiques actuelles se concentrent principalement sur les pieux forés. À l'opposé, les connaissances sur les performances des groupes de pieux à déplacement complet sont très limitées, bien que l'on puisse s'attendre à ce que leur comportement soit influencé de manière significative par les effets de l'installation, tels que le changement d'état de contrainte et la densité du sol. Pour la réalisation, des tests sur des groupes de pieux de 9 pieux, installés comme pieux forés et comme pieux à déplacement complet, sont effectués à la Centrifugeuse Deltares, pour quantifier l'impact des effets d'installation sur les performances des groupes de pieux. Par conséquent, la pression horizontale des terres a été mesurée directement sur la surface du pieu par de petites cellules de pression des terres. L'installation des pieux et le chargement ont été exécutés pendant le filage, grâce à un système innovant. Dans l'article, le concept et les résultats des essais de centrifugation sont analysés.

Keywords: Pile groups; centrifuge testing; earth pressure cells; bored piles; displacement piles.

1 INTRODUCTION

Regarding the basic concept of laterally loaded pile groups, 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.

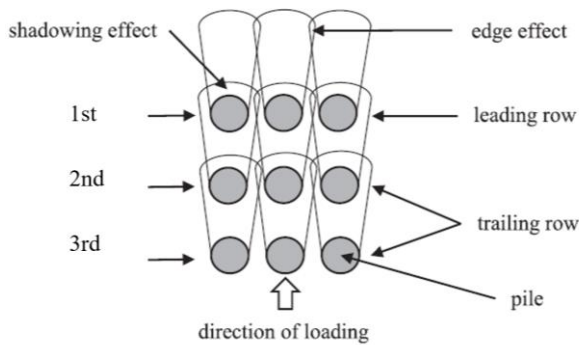


Figure 1. Scheme of a laterally loaded 3x3 pile group.

In Table 1 a selection of often cited research is documented. For driven piles, no tests were done at 1g gravity and for driven piles in the centrifuge, no pile-installation effects were considered. The values for the p-multipliers, an empirical reduction factor for p-y curves (Brown et al. (1988)), mentioned by Huang et al. (2001) for driven piles does not consider the impact of the installation method. 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.

Table 1. List of p-multipliers from frequently cited research sorted by installation method.

Author	Testing	p-Multiplier			
Bored piles		1st	2nd	3rd	4th
Klüber*	1g	1.0	0.625	0.625	-
Kotthaus 1992	1g	1.0	0.72	0.64	-
Kotthaus 1992	ng	1.0	0.685	0.685	-
Huang 2001	In situ	0.93	0.7	0.74	-
Brown 1988	In situ	0.8	0.4	0.3	-
Driven piles		1st	2nd	3rd	4th
McVay 1994	ng	0.8	0.4	0.3	-
McVay 1995	ng	0.8	0.4	0.3	-
McVay 1998	ng	0.8	0.4	0.3	-
Rollins 2005	In situ	0.8	0.4	0.4	-
Huang 2001	In situ	0.89	0.61	0.61	0.66

Table 2 shows the p-multipliers from Huang et al. (2001) again, mentioned here as f_m -values for bored piles and for driven piles. The columns on the right-hand side show the installation-factors, called p_m -values, for both types of piles. The p_m -values can be regarded as extended p-multipliers, where the installation effects are already considered.

Table 2. P-multiplier by Huang et al. (2001) - with and without considering installation effects.

Row	Bored group piles		Driven group piles	
	f_m	p_m	f_m	p_m
1st (Leading)	0,93	0,88	0,89	1,57
2nd	0,7	0,66	0,61	1,08
3rd	0,74	0,7	0,61	1,08
4th	-	-	0,66	1,16

Objective of the proposed tests is to quantify the impact of pile group installation effects on the performance of laterally loaded pile groups covering replacement piles (bored piles) and full displacement piles (driven prefabricated piles) As shown before in Table 2, Huang et al. (2001) observed a potential of 76% higher load-factors (p-multiplier) for full displacement piles and in addition higher lateral pile resistances for piles in a group, compared to a single pile. Opposite to those findings, the load capacity of driven piles in a group must be currently reduced, recommended by official guidelines, e.g. EA-Pfähle (2013). By transferring Huang’s findings from in-situ tests to centrifuge tests, the aim is to confirm the positive effects of a displacement pile installation for laboratory conditions, where boundary conditions can be controlled to generate reproducible tests and to isolate the impact of the installation method.

2 EXPERIMENTAL METHODOLOGY

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

Centrifuge modeling is indeed a technique used in geotechnical engineering to replicate the stress state experienced by full-scale prototypes in a scaled-down model. This technique allows to simulate the stresses and behaviors experienced by full-scale structures more accurately than traditional physical modeling methods.

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 driven, fixed-headed piles in a centrifuge without stopping means that the piles have to be driven, rigidly fixed and loaded laterally in flight, without stopping the centrifuge in between. If the centrifuge would have 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 driven 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 Experimental layout

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.



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

The intended gravity for the tests is 50g. Therefore, the planned 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.

As pictured in Figure 3, 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 is 1,5 m, 4,5 m and 7,5 m.

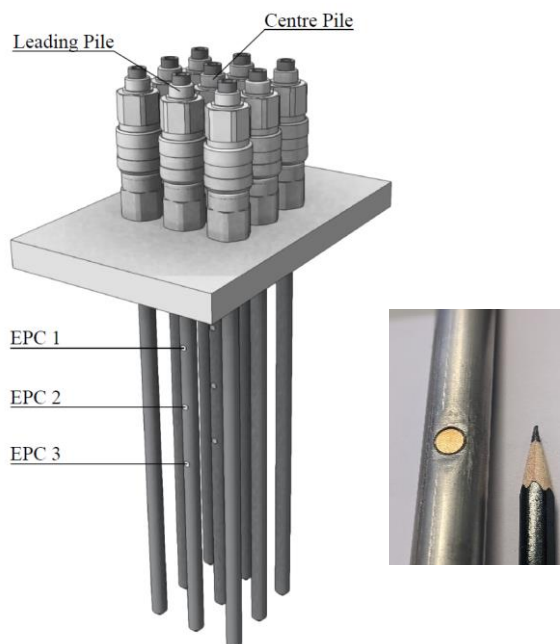


Figure 3. Model of fixed-headed pile group with applied Earth pressure cells (EPC) in 3 levels at the centre pile (CP) and the leading pile (LP).

2.2 Test soil and sample preparation

The centrifuge tests take place in dry, Bascarp Sand No. 15 (Figure 4 & Table 3). The relative density of the sand was about $I_D = 55\%$ and $I_D = 30\%$. For sample preparation, the sand raining method was used.

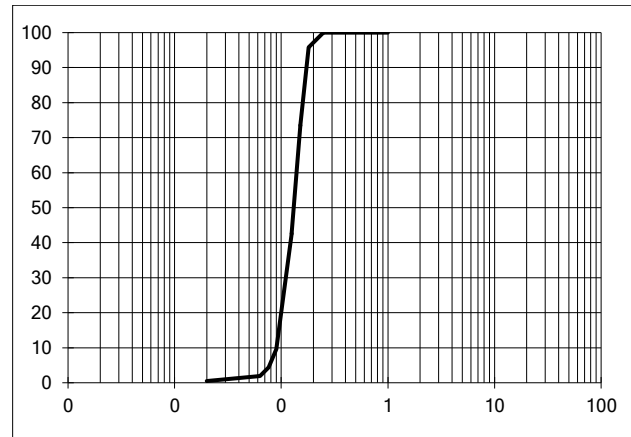


Figure 4. Grain size distribution Bascarp Sand No. 15.

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 ratio (-)	e_{min}	0,56
Angle of repose ($^{\circ}$)	φ	30,1
Critical state friction angle ($^{\circ}$)	φ_c	34
Specific gravity (-)	G_s	2,63
Coefficient of uniformity (-)	U	1,53

2.3 Loading of pile group

The lateral load was applied path controlled with 0,1 mm/s. Kotthaus (1992) captured, that the load distribution is 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 following piles takes place. With a diameter of 15 mm, this would mean 1.5 mm horizontal deflection at the pile-head. For these tests, the horizontal deflection was chosen with $0,1 \cdot D$, $0,2 \cdot D$ and $0,3 \cdot D$. The deflection was applied successively starting with the lowest deflection and was kept for 40 to 70 seconds until the measured earth pressure showed almost a constant value (Figure 7, Figure 8). After every load step the piles were unloaded to the starting position.

2.4 Test program

Six tests were performed at Deltares Centrifuge. Therefore, a cylindrical container was filled in two steps, once with medium-dense and once with loose sand. For each density, three tests were performed. One single pile test and two tests with a pile group of 9 piles in a 3x3 arrangement.

Table 4. Test program centrifuge tests.

Test	Pile installation	Type of pile	I_b [%]
1	re- & displacement	single pile	0,58
2	re- & displacement	single pile	0,29
3	replacement	pile group 3x3	0,32
4	replacement	pile group 3x3	0,56
5	displacement	pile group 3x3	0,32
6	displacement	pile group 3x3	0,54

Figure 5 shows the 3x3 arrangement of the pile-head-plate. The spacing of the pile axes is three times the diameter (3D) in load direction and particular to that. Following the recommendations of 'EA Pfähle' (2013), there should be no interaction effects out of the axis of load direction where no influences are expected with at least 3D spacing. In axes of the load direction the spacing is as well 3D. Here the crucial distance is assumed to be about 6D, therefore interaction effects can be expected. The two additional slots on the left and on the right side were made for the single pile tests, to enable four single piles to be tested simultaneously, see Figure 5 red marked dots. With a spacing of the pile axes of 8D in load direction, all overlapping effects can be ruled out.

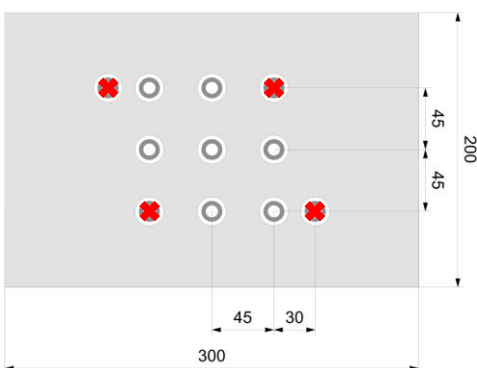


Figure 5. Top view of pile-head plate - values in [mm].

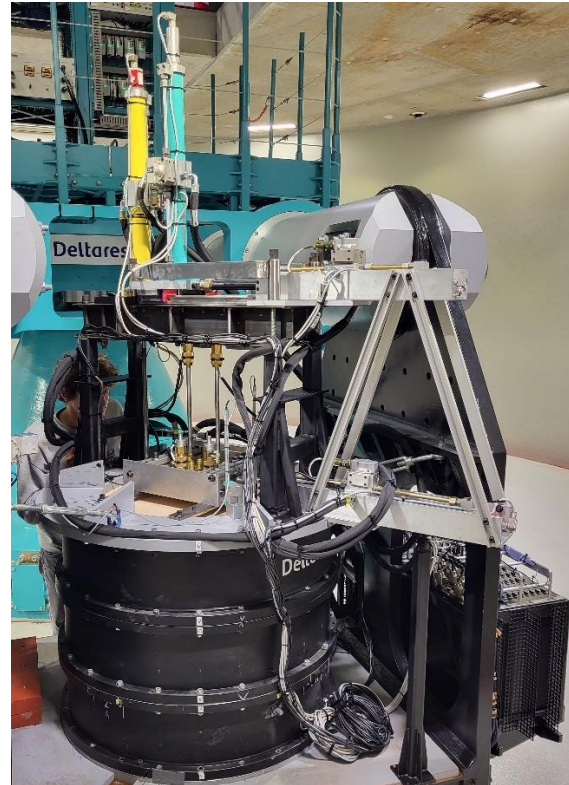


Figure 6. Full test set-up - Deltares Centrifuge.

3 TEST RESULTS

Five out of six tests were conducted successfully. A pile remained stuck in the precisely fitting holes of the pile-head-plate during installation and was thereby destroyed. Subsequently, the entrances of the holes were modified and round shaped to prevent any further complications during installation under high g-forces. The invented coupling system with a plug-in method to enable in-flight installation and loading of the pile group construction allowed 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.

Figure 7 and Figure 8 is an idealized plot of the earth pressure of the interaction of the soil and the pile. The three peaks show the successively applied deflection of $0,1 \cdot D$, $0,2 \cdot D$ and $0,3 \cdot D$ with an unloading to the starting position inbetween.

In Figure 7 for Test 3, where a group of replacement piles in loose sand was investigated, the measured horizontal pressures at pile surface are evaluated. It is evident, that the measured earth pressure values for the leading pile (LP) are significantly higher for each depth than the values for the centre pile (CP).

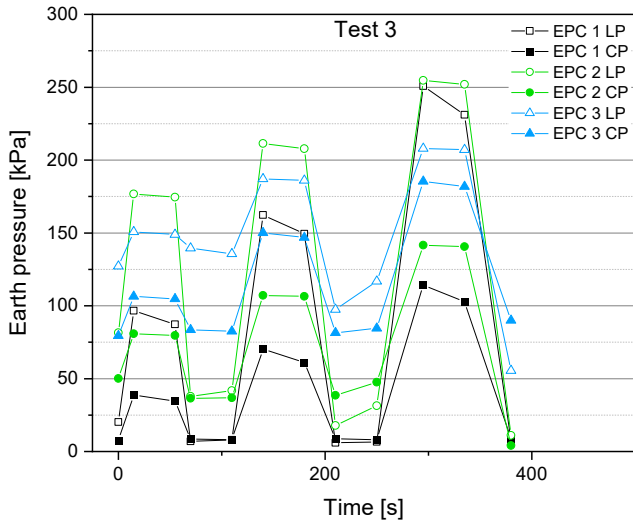


Figure 7. Data Test 3 - Earth pressure acting on Leading pile (LP) and on Centre pile (CP).

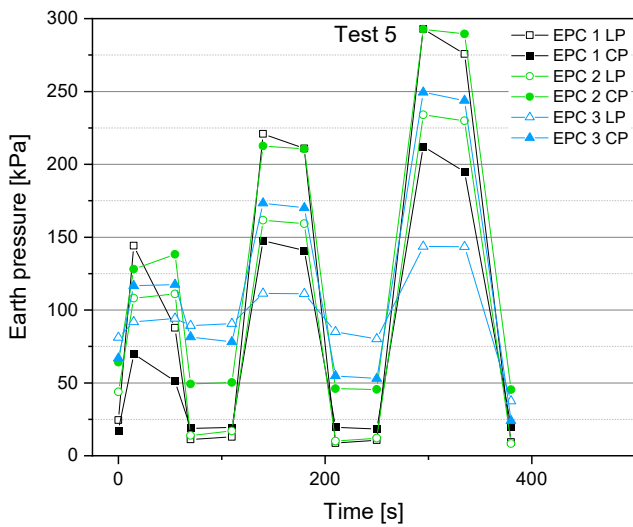


Figure 8. Data Test 5 - Earth pressure acting on Leading pile (LP) and on Centre pile (CP).

Figure 8 documents results of Test 5, where displacement piles in loose sand were modelled. With exception of the upper level EPC1, the distribution of the acting earth pressure on the piles is different for displacement piles. The measured values for EPC 2 and EPC 3 are significantly higher for the centre pile compared to the leading pile, if the installation effects are considered.

The ratio of the acting earth pressure between the leading pile and the centre pile is plotted in Figure 9 (Test 3 - replacement piles) and Figure 10 (Test 5 - displacement piles). For Test 3, higher values for the leading pile were detected at each applied deflection, especially in the two upper layers of EPC1 and EPC2. For Test 5, EPC1 shows still higher values for the leading pile, even if the ratio of acting earth pressure is significantly diminished. For EPC2 and EPC3 a ratio lower than 1.0 is observed, that indicate a higher acting

earth pressure on the centre pile, than on the leading pile.

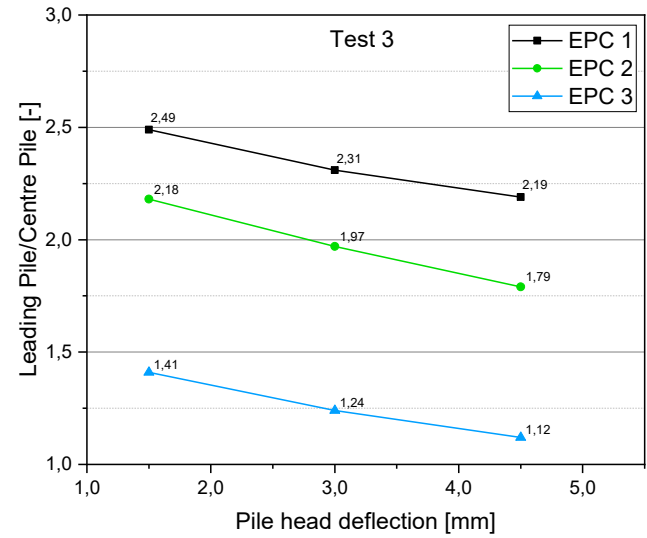


Figure 9. Test 3 - Replacement piles - Ratio of effective pressure for Leading Pile/Centre Pile.

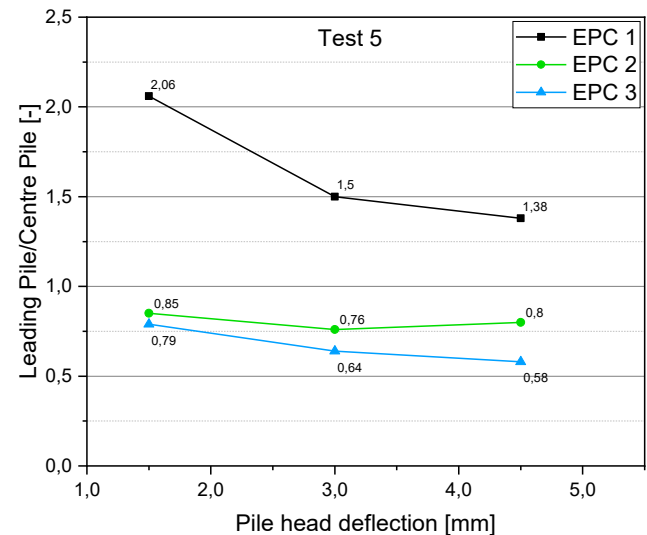


Figure 10. Test 5 - Displacement piles - Ratio of effective pressure for Leading Pile/Centre Pile.

The results indicate that installation effects exert a significant influence, with interaction effects being significantly attenuated. Soil compaction occurs in the mobilizable soil around the trailing piles, leading to increased soil-structure interaction and particularly affecting the central pile.

4 CONCLUSIONS

Through centrifuge testing conducted on a laterally loaded 3x3 pile group, this study examines the influence of installation effects on the load-displacement behavior of pile groups within dry sand.

Initial analysis of the data obtained from earth pressure cells reveals that these installation effects markedly affect both the load-bearing behavior and load distribution within the pile group. Specifically, displacement piles situated at the center of the 3x3 pile group exhibit notably higher earth pressure values on their embedded surfaces compared to bored piles.

These findings underscore the significant impact of pile installation methods on the load-bearing characteristics of pile groups. Consequently, it is evident that such installation techniques must be carefully considered in the design process. Further research is warranted to comprehensively investigate these effects and their implications for design methodologies.

ACKNOWLEDGEMENTS

The GeoLab project was a co-operation between Deltares and the University of Stuttgart.

The overall project is funded by the European Union's Horizon 2020 Research and Innovation programme.

REFERENCES

- Brown, D. A., Morrison, C., & Reese, L. C. (1988). Lateral load behavior of pile group in sand. *Journal of Geotechnical Engineering*, 114(11), 1261-1276. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1988\)114:11\(1261\)](https://doi.org/10.1061/(ASCE)0733-9410(1988)114:11(1261)).
- Deutsche Gesellschaft für Geotechnik Arbeitskreis Pfähle. (2013). *Recommendations on Piling (EA Pfähle)*. John Wiley & Sons.
- Huang, A.B., Hsueh, C.K., O'Neill, M. W., Chern, S., & Chen, C. (2001). Effects of construction on laterally loaded pile groups. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(5), 385-397. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2001\)127:5\(385\)](https://doi.org/10.1061/(ASCE)1090-0241(2001)127:5(385)).
- Klüber E. (1988) Tragverhalten von Pfahlgruppen unter Horizontalbelastung. *PhD Dissertation*, Mitteilungen des Instituts für Grundbau, Boden- und Felsmechanik der TH Darmstadt; Heft 25.
- Kotthaus M. (1992). Zum Tragverhalten von horizontal belasteten Pfahlreihen aus langen Pfählen in Sand. *PhD Dissertation*, Schriftenreihe des Instituts für Grundbau, Ruhr-Universität Bochum, Heft 18 (in German).
- McVay, M., Bloomquist, D., Vanderlinde, D., & Clausen, J. (1994). Centrifuge modeling of laterally loaded pile groups in sands. *Geotechnical Testing Journal*, 17(2), 129-137. <https://doi.org/10.1520/GTJ10085J>.
- McVay, M., Casper, R., & Shang, T. I. (1995). Lateral response of three-row groups in loose to dense sands at 3D and 5D pile spacing. *Journal of Geotechnical Engineering*, 121(5), 436-441. [https://doi.org/10.1061/\(ASCE\)0733-9410\(1995\)121:5\(436\)](https://doi.org/10.1061/(ASCE)0733-9410(1995)121:5(436)).
- McVay, M., Zhang, L., Molnit, T., & Lai, P. (1998). Centrifuge testing of large laterally loaded pile groups in sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(10), 1016-1026. [https://doi.org/10.1061/\(ASCE\)1090-0241\(1998\)124:10\(1016\)](https://doi.org/10.1061/(ASCE)1090-0241(1998)124:10(1016)).
- Nielsen, S.D., & Nielsen, B.N. Data report on Baskarp Sand No. 15 2018 Delivery.
- Rollins, K. M., Lane, J. D., & Gerber, T. M. (2005). Measured and computed lateral response of a pile group in sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(1), 103-114. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2005\)131:1\(103\)](https://doi.org/10.1061/(ASCE)1090-0241(2005)131:1(103)).

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The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.