Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-106

Axial behaviour of displacement pile groups in sand based on model tests in a calibration chamber

Comportement axial des groupes de pieux de déplacement dans le sable sur la base d'essais modèles dans une chambre d'étalonnage

F. Mitlmeier*, Ch. Moormann
University of Stuttgart, Institute of Geotechnical Engineering, Stuttgart, Germany

**felix.mitlmeier@igs.uni-stuttgart.de*

ABSTRACT: This paper presents results of physical model tests with a 3 x 3 displacement pile group in sand. The test results are evaluated to investigate mainly the influence of spacing on the axial group bearing behaviour. Accordingly, the instrumentation of the model piles allows one to identify the effect of pile-pile interaction on skin friction and tip resistance of the group piles depending on their position inside the group. First results of this experimental study show that for a spacing of three pile diameters the resistance of a driven group pile in medium-dense sand is higher than the resistance of a comparable unaffected single pile. This insight substantiates that there is a great potential in an optimized design assessment of the axial resistance of displacement pile groups which is intended to be considered for a sustainable pile design in future.

RÉSUMÉ: Cet article présente les résultats d'essais sur modèle physique avec un groupe de pieux à déplacement 3 x 3 dans le sable. Les résultats des essais sont évalués pour étudier principalement l'influence de l'espacement sur le comportement axial du groupe de pieux. En conséquence, l'instrumentation des pieux modèles permet d'identifier l'effet de l'interaction pieu-pieu sur le frottement cutané et la résistance de pointe des pieux du groupe en fonction de leur position à l'intérieur du groupe de pieux. Les premiers résultats de cette étude expérimentale montrent que pour un espacement de trois diamètres de pieux, la résistance d'un groupe de pieux enfoncés dans du sable moyennement dense est plus élevée que la résistance d'un pieu unique comparable non affecté. Cette constatation montre qu'il existe un grand potentiel dans l'évaluation optimisée de la résistance axiale des groupes de pieux de déplacement, ce qui devrait être pris en compte pour une conception durable des pieux à l'avenir.

Keywords: Displacement pile group; pile-pile-interaction; group efficiency; axial behaviour; calibration chamber test.

1 INTRODUCTION

The pile-pile interaction of displacement piles in sand both due to installation and due to loading and the resulting impact on the axial pile bearing behaviour has so far not been intensively investigated and clarified. While for bored pile groups a reduction of skin friction due to pile group effects is already often considered in pile design (DGGT, 2013), for displacement pile groups it is not clear, whether installation effects and the resulting modifications of status variables as soil density and stress status compensate group effects due to axial loading resulting in a reduction of shaft resistance or even lead to a higher axial pile resistance in comparison to an unaffected single pile.

To investigate the static axial load-bearing behaviour of displacement pile groups, a new calibration chamber was designed at the Institute of Geotechnical Engineering (IGS) at the University of Stuttgart. The chamber allows single displacement piles as well as 2 x 2 and 3 x 3 displacement pile groups up to a pile center distance of 6·D to be investigated under real stress scenarios. In the following, the pile-pile interaction is quantified and the findings from existing literature are provided. Thereafter the experimental setup, testing program, pile installation results, and the test outcomes of a 3 x 3 displacement pile group with a pile spacing of 3·D and the corresponding single piles in medium dense sand are described in detail.

2 GROUP EFFICIENCY AND MODEL TESTS OF OTHER AUTHORS

To compare the ultimate axial resistance of a pile group with that of an aggregate of unaffected single piles, Vesić (1969) as well as Valsangkar and Meyerhof (1983), among others, use group efficiency η defined as:

$$\eta = \frac{Q_g}{n\,Q_s} \tag{1}$$

where Q_g is the ultimate load capacity of a pile group, n is the number of piles in a group and Q_s is defined as the ultimate resistance of a single pile.

Model tests on 3 x 3 jacked displacement pile groups in sand were performed e.g. by Hanna (1963), Vesić (1969), Tejchman (1973) and Le Kouby et al. (2006), see Figure 1. In loose non-cohesive soils, it is evident that the group efficiency η is always greater than 1.0, extending up to a 6·D pile spacing. Moreover, the highest group efficiency occurs within the range of 2·D to 3·D pile spacing. In medium-dense sands, conflicting results emerge regarding group effectiveness: Studies by Vesić (1969) and Tejchman (1973) demonstrated η-values greater than 1.0 up to 6·D, while Le Kouby et al. (2006) reported a significantly lower value with η = 0.64 in a pile group test with 2.8·D pile spacing. In dense sands, research by Hanna (1963) consistently indicated that the bearing capacity of the pile group is always less than that of an equivalent number of individual piles, irrespectively of the pile center distance.

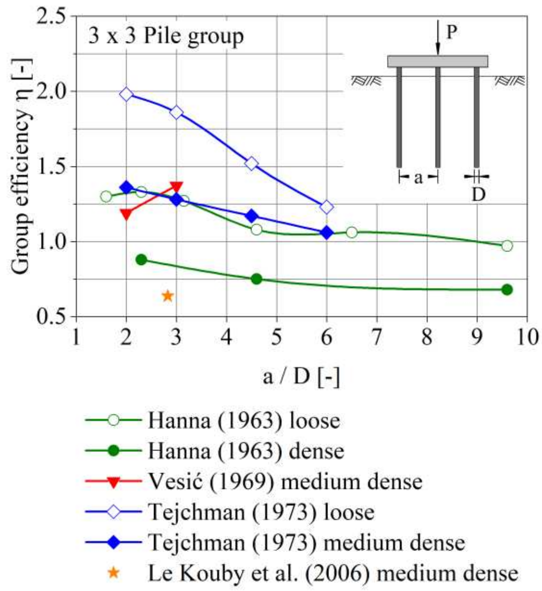

Figure 1. Group efficiency of 3 x 3 displacement pile groups in non-cohesive soils from model tests at a settlement s = 0.1·D.

3 EXPERIMENTAL SET-UP

Within the new calibration chamber developed at IGS (Figure 2), it is possible to regulate the vertical stress state. A categorization by Salgado et al. (1998) identifies this type of calibration chamber as 'BC3'. Application of the surface load is facilitated by a rigid 25 cm thick reinforced concrete slab, braced to the test tank with a system of preload beams, anchor rods and hydraulic presses. The new chamber accommodates a soil body measuring 1980 x 1980 x 1400 mm³. The results of the experiments shown herein correspond to using an air-dried, narrow-graded, medium-coarse sand known as *Berlin Sand* (Taşan, 2011, Le, 2015). The upright sand column method (Walz et al., 1975) is applied to create a homogenous medium-dense sand body of the specified dimensions.

The density of this sand body is determined directly by the volume of soil that has been poured. An indirect determination of the soil density is conducted through light dynamic probing (DPL-5) before and after pile installation. A distance of at least 9·D between the DPL-5 and installed piles is maintained to prevent any change in the soil density.

The model piles are driven vertically into the soil using a new designed model guide. The pile (group) test is controlled by force using a hydraulic control and regulation unit, transferring the force through a single press into a rigid pile head plate. Composed of aluminium, the model piles measure D = 40 mm in outer diameter and 1150 mm in length. After installation, they are embedded in the soil up to L = 750 mm (Figure 3), resulting in an L/D ratio of 18.75. These model piles are expected to represent a reinforced concrete displacement pile with a smooth pile surface and a flat pile tip, having an equivalent pile diameter (D_{eq}) of 0.5 m and an embedment depth of 10 m at a real scale. The ratio of chamber width B = 1980 mm to the diameter of a single pile, being 50, minimizes boundary effects. Additionally, a sufficient distance of 16·D from pile base to tank bottom is provided.

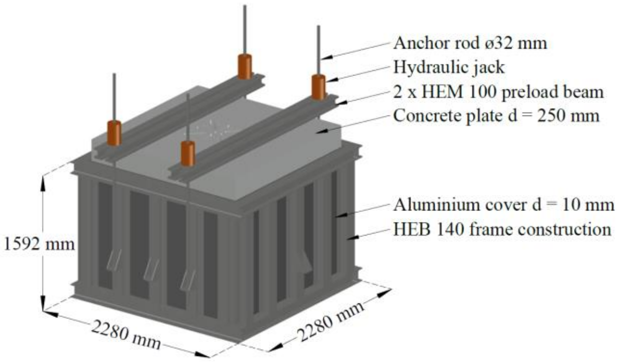

Figure 2. IGS calibration chamber – isometric view.

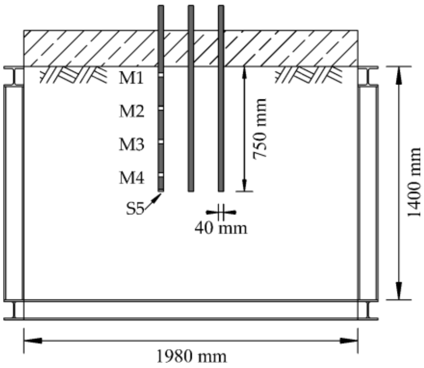

Figure 3. Cross section through IGS calibration chamber, model pile dimension and instrumentation.

In the 3 x 3 pile group test, one edge, one corner and one center pile (Figure 4 a) are instrumented with four measuring levels (M1 - M4) of strain gauges along the pile shaft and one at the pile base (S5), as shown in Figure 3, to determine the pile normal force as well as skin friction and tip resistance.

4 TEST PROGRAM

Following the preparation of the soil in a medium-dense packing with I_D = 37 %, it is consolidated under a vertical surface load of 200 kN/m². Afterwards either the group or individual piles are installed by hammering. The ratio of driving weight to pile weight is 2:1, providing a theoretical driving energy of 22.5 N·m per blow. In the pile group test, the piles (P1 - P9) are driven from left to right at a horizontal and vertical pile center distance of 3·D = 120 mm (Figure 4 b). During installation, the number of blows and the pile penetration are monitored to determine the theoretical driving energy per penetration depth. After completing the installation of all group piles, a load test of the pile group involving an initial loading, unloading and reloading phase is conducted, following the guidelines of DGGT (2013).

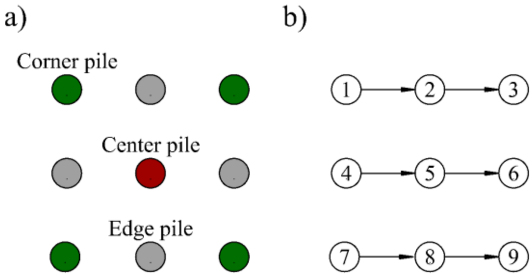

Figure 4. a) Group pile definition, b) installation order.

The corresponding individual pile tests (P10, P11 and P12) are conducted in a separate test for the same experimental conditions and soil density. The elapsed time of the single pile P10 after installation up to its test loading aligns with the elapsed time of the group piles (approx. 18 h to 24 h). Conversely, the single piles P11 and P12 were tested immediately after driving.

5 EXPERIMENTAL RESULTS

5.1 Pile installation data

Figure 5 displays the number of blows (N_5) and the theoretical driving energy per 5 cm of penetration, as well as the energy sum for both the group piles P1 to P9 (pile positions acc. to Figure 4 b) and the unaffected single piles P10 to P12. According to model tests conducted by Le Kouby et al. (2016) involving jacked displacement piles in sand, it was observed that the installation force increased with each additional group pile. Similarly, in a field test with medium-dense to dense gravel-sand mixtures (Garbers et al., 2022), there was a consistent rise in the pile energy sum for subsequently installed group piles within a 3 x 3 driven pile group. Briaud et al. (1989) also noted an increase in the number of blows for each sequentially installed pile in a driven 5-pile group in sand.

Regarding the current test, it can be stated initially that the energy sums of the group piles range from 2430 N·m (P3) to 3038 N·m (P1). It becomes apparent, starting from about half of the final penetration depth of 750 mm, that - except for the first pile installed (P1) - a greater driving energy per 5 cm of penetration is required compared to the group piles installed later.

The sum of energy of the single pile P10, with an elapsed time corresponding to that of the group piles, is 2745 N·m, falling within the range of the group piles.

5.2 Single pile and pile group tests

The results of the pile group test with a pile spacing of a = 3·D and a testing load of 50 kN are illustrated in Figure 6 (left). Following the guidelines from DGGT (2013), the resistance of the pile group, as well as that of the single or group piles in the ULS, corresponds to an average pile cap settlement or a pile head settlement of 0.1·D = 4 mm.

To assess the load-settlement behaviour under service load conditions, the resistances at a pile head settlement of 0.025·D = 1 mm were also evaluated. All measuring levels were reset to zero before the

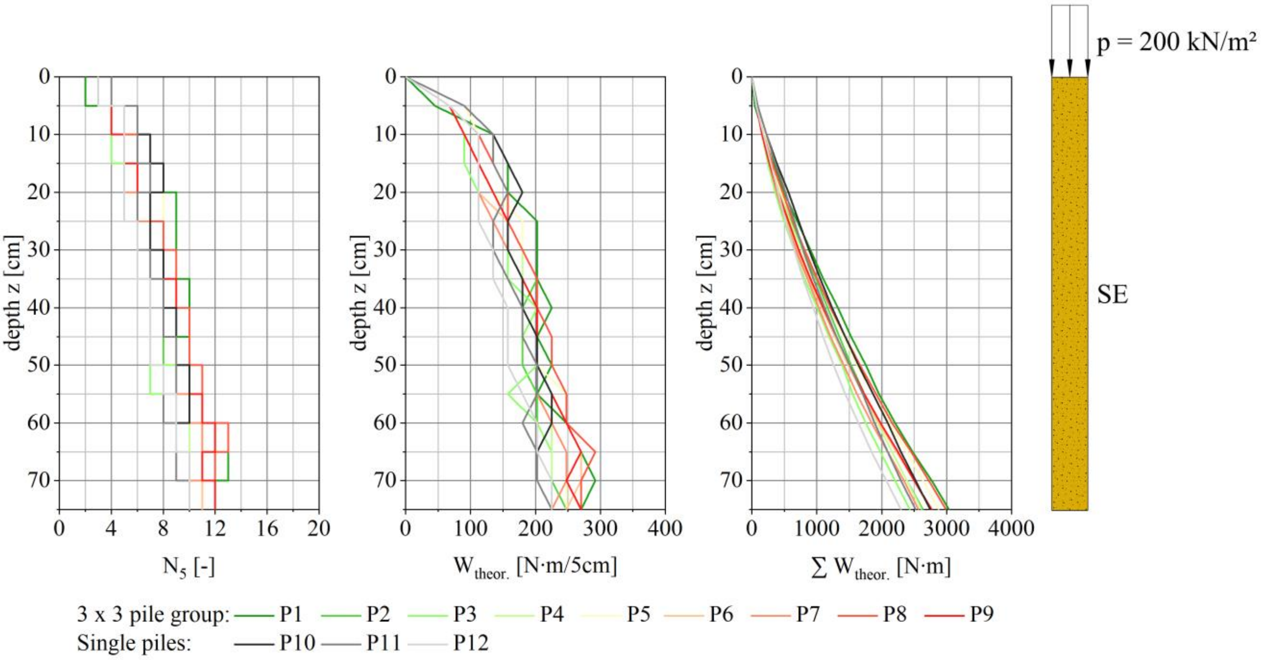

Figure 5. Number of blows N_5, theoretical driving energy per 5 cm of penetration $W_{theor.}$ and energy sum $\sum W_{theor.}$ for the group piles P1 - P9 (acc. to Figure 4 b) and the unaffected single piles P10 - P12.

tests, eliminating residual forces from pile driving. At a settlement of $s = 0.1\cdot D$, the resistance of the 9-pile group measures 42.47 kN, significantly exceeding that of $9 \cdot Q_s$. Comparison with 9 · P10 yields a group effectiveness $\eta_{s=0.1\cdot D} = 1.26$, while with 9 · P11 it reaches $\eta_{s=0.1\cdot D} = 1.36$. These results align closely with those of previous studies: Tejchman (1973) and Vesić (1969) found a group efficiency of $\eta = 1.26$ and $\eta = 1.37$ when the piles were spaced at 3·D. Hanna (1963) determined a group efficiency in loose sand with a 3.15·D pile spacing at $\eta = 1.27$, as shown in Figure 1.

A positive group effect is also apparent under service load conditions at a settlement of 1 mm: Compared with 9 · P10, it results in a group effectiveness of $\eta_{s=0.025\cdot D} = 1.20$.

Figure 6 (right) shows the axial resistance of the representative group piles under the pile group test load and the axial resistances of the unaffected individual piles. The efficiency of the group piles in SLS and ULS and are summarised in Tables 1 and 2.

Table 1. Axial resistance of the group piles and group pile efficiency at $s = 0.025\cdot D$ (SLS).

	Q (s=0.025·D)	**η (s=0.025·D)**
Center pile	2.56 kN	1.28
Corner pile	2.56 kN	1.28
Edge pile	2.64 kN	1.32
Single pile P10	2.00 kN	-

Table 2. Axial resistance of the group piles and group pile efficiency at $s = 0.1\cdot D$ (ULS).

	Q (s=0.1·D)	**η (s=0.1·D)**
Center pile	5.48 kN	1.46
Corner pile	4.42 kN	1.18
Edge pile	4.88 kN	1.30
Single pile P10	3.75 kN	-

The results in Table 1 confirm that a positive group effect is evident even under service load conditions. At this settlement, the resistances are evenly distributed among the center, edge and corner pile. As the load increases and reaches the limit settlement of 4 mm, it can be seen that the center pile bears increasingly more load compared to the other group piles. This can be attributed to the increased stress status in the pile group area. This effect decreases at the edges and is least noticeable at the corners, a trend also reflected in the efficiencies of the group piles (Table 2).

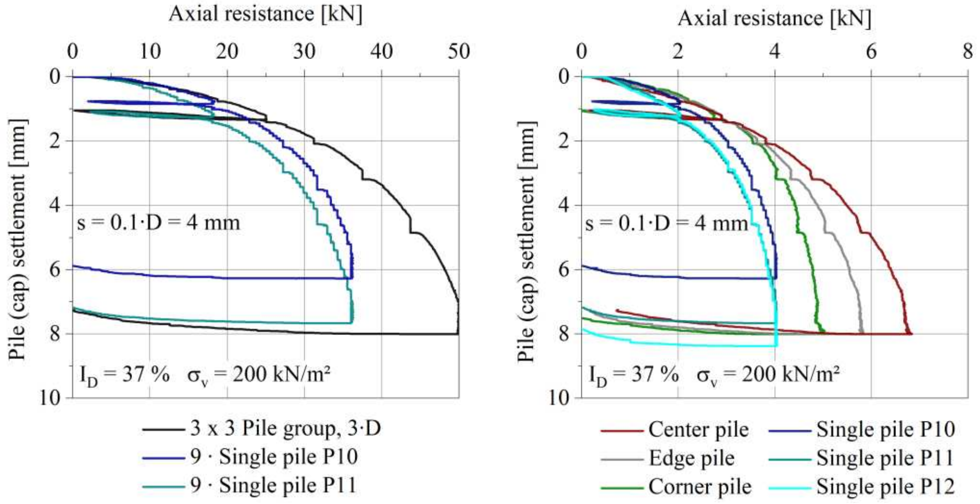

Figure 6. Pile group resistance and resistance of an equivalent amount of unaffected single piles (left) - group pile and single pile resistances (right) in medium dense Berlin Sand.

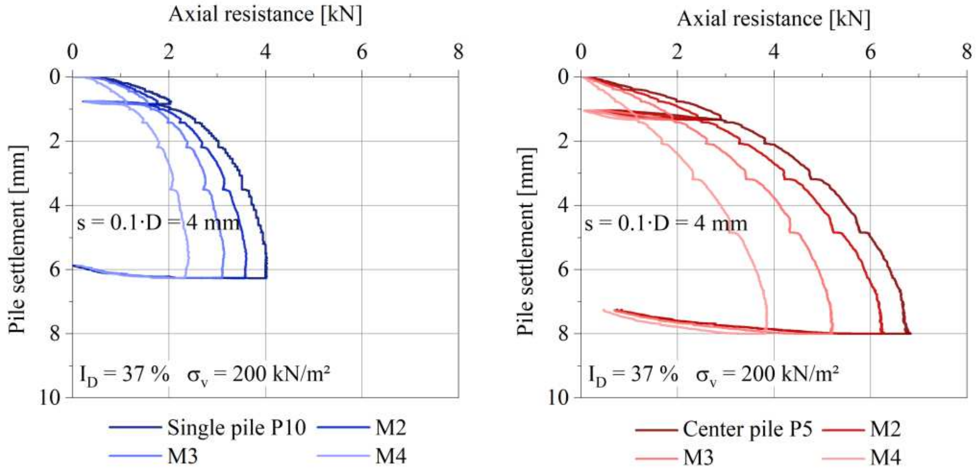

Figure 7. Single pile (P10) resistance, shaft distribution (left) and center pile resistance, shaft distribution (right) in medium dense Berlin Sand.

Unlike the individual piles, where no significant increase in load-bearing capacity is recognisable after the settlement s = 0.1·D, the elevated stress level in the pile group test leads to an increase in axial capacity, particularly noticeable for the center and edge piles, which clearly exceed the resistance determined at 4 mm.

Figure 7 illustrates the load-deformation curve of the single pile P10 (left) and that of the center pile (right), along with the distribution of the axial normal force over the measuring levels. The measuring level M4 at the lower pile shaft corresponds to level S5 at the pile base, enabling the determination of the proportion of the pile's normal force from base resistance Q_{base} and shaft resistance Q_{shaft}, see Table 3.

The results indicate that 41 % of the single pile's normal force is transferred through skin friction and 59 % via end bearing. For the center pile, on the other hand, 62 % of the axial resistance at a settlement of 1 mm is attributed to skin friction mobilisation. At a settlement of s = 0.1·D, the proportion of load transfer via skin friction is 0.47. These findings highlight that the increased axial resistance of the group piles, exemplified by the center pile, is due to an increased mobilisation of skin friction compared to the individual pile, as previously demonstrated by Vesić (1969).

Moreover, it is noticeable that the single pile exhibits no residual forces after the pile test when fully unloaded. However, for the center pile, a residual force of up to 0.74 kN is detected across the entire pile shaft after complete unloading of the pile cap. This residual force accounts for approximately 11 % of the maximum normal force of the center pile, which is 6.8 kN at a settlement of 8 mm.

Table 3. Ratio of pile normal force induced by skin friction to pile resistance of the respective piles at s = 0.025·D and s = 0.1·D.

	s=0.025·D: Q_{shaft} / Q	**s=0.1·D: Q_{shaft} / Q**
Single pile P 10	0.41	0.41
Center pile	0.62	0.47

6 CONCLUSIONS AND OUTLOOK

Model scale tests at the Institute of Geotechnical Engineering at the University of Stuttgart, assessing a displacement pile group in a calibration chamber in medium dense sand and a pile spacing of 3·D, illustrate a positive group efficiency of $\eta = 1.26$ aligning with findings by relevant researchers. It has also been demonstrated that the increase in axial resistance of the group piles is primarily attributed to increased skin friction.

Despite this potential, the current pile design does not consider these positive effects on the axial behaviour of displacement group piles. Therefore, an additional test series examines the influence of key aspects like the pile center distance, initial soil density, stress state within the calibration chamber, and the influence of the installation method.

REFERENCES

Briaud, J.L., Tucker, L.M., & Ng, E. (1989). Axially loaded 5 pile group and single pile in sand, In: *Proc. 12th Int. Conf. on Soil Mechanics and Foundation Engineering*, Rio de Janeiro, Brazil, pp. 1121-1124.

DGGT (2013). *Recommendations on Piling (EA-Pfähle)*. John Wiley & Sons.

Garbers, T., Mitlmeier, F., Moormann, Ch., Wardinghus, P. (2022). Zum Gruppentragverhalten von Verdrängungspfählen - Untersuchungen zu Interaktionseffekten bei Installation und axialer Beanspruchung, In: *Vorträge der 37. Baugrundtagung*, Wiesbaden, Germany, pp. 181-190.

Hanna, T.H. (1963). Model studies of foundation groups in sand. *Géotechnique*, 13(4), pp. 334-351. https://doi.org/10.1680/geot.1963.13.4.334

Le, V.H. (2015). *Zum Verhalten von Sand unter zyklischer Beanspruchung mit Polarisations-wechsel im Einfachscherversuch*, PhD thesis, Veröffentlichungen des Grundbauinstituts der Technischen Universität Berlin, Heft 66.

Le Kouby, A., Canou, J., Dupla, J.C. (2006). Group effect on model piles under axial monotonic load-ing, In: *Proc. 4th Int. Conf. on Soft Soil Engineering*, Vancouver, Canada, pp. 179-187.

Le Kouby, A., Dupla, J.C., Canou, J., Francis, R. (2016). The effects of installation order on the re-sponse of a pile group in silica sand. *Soils and Foundations*, 56(2), pp. 174-188. https://doi.org/10.1016/j.sandf.2016.02.002

Salgado, R., Mitchell, J. K., Jamiolkowski, M. (1998). Calibration chamber size effects on penetration resistance in sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(9), pp. 878-888. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:9(878)

Taşan, E. (2011). *Zur Dimensionierung der Monopile-gründungen von Offshore-Windenergieanlagen*, PhD thesis, Veröffentlichungen des Grundbauinstituts der Technischen Universität Berlin, Heft 52.

Tejchman, A.F. (1973). Model investigations of pile groups in sand. *Journal of the Soil Mechanics and Foundations Division*, 99(2), pp. 199-217. https://doi.org/10.1061/JSFEAQ.0001852

Valsangkar, A.J., Meyerhof, G.G. (1983). Model studies of the collapse behaviour of piles and pile groups, In: *Developments in Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 65-109.

Vesić, A.S. (1969). Experiments with instrumented pile groups in sand. *Performance of Deep Founda-tions, ASTM STP 444*, pp. 177-222. https://doi.org/10.1520/STP444-EB

Walz, B., Schober, H.-D., Diekmann, N. (1975). Untersuchungen zum lagenweisen Einbau von Sandvolumina für bodenmechanische Modell-versuche, In: *Aus Theorie und Praxis des Grundbaus und der Bodenmechanik, Festschrift zum 70. Geburtstag von Herrn Prof. Dr.-Ing. Hans Lorenz,* Berlin, Germany, pp. 219-247.