Group of piles in sand: interaction effects from centrifuge modelling tests

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ABSTRACT: The behavior of piles within a group is influenced by complex soil–structure interactions between the elements of the foundation and the subsoil. Two main interactions may take place in a group of pile in sand: (i) the decrease in the pile reaction modulus (i.e. the load–settlement ratio), (ii) the change in the pile bearing capacity. The increase in settlement of an individual pile in a group is due to the superimposition of the deformation fields of the neighboring piles (i.e. group effect). The variation in the ultimate capacity of a pile in a group can be ascribed to the overlapping of the stress field around the pile. These effects depend on installation method, on the sand state, on the load level, on the group dimensions and on the location of the pile within the group. This paper presents and analyses the results of centrifuge tests on groups of non–displacement piles in loose saturated sand, carried out to compare the load–settlement behavior and the bearing capacity of the piles in a group with that of an isolated single pile. The testing program included the models of the isolated single pile and groups of 3 and 7 piles with variable spacing. The adopted geometrical scaling factor was N = 100, the piles were close–ended and free headed. Some of them were instrumented with load cells to measure the axial load transmitted to each pile and to estimate the load transmitted through the shaft and the base.

KEYWORDS: Bored piles, pile groups, sand, centrifuge.

1 INTRODUCTION

Pile groups are widely used in geotechnical engineering to support heavy structural loads where shallow foundations are inadequate. However, the behavior of a pile group is not simply the sum of its parts: when piles are placed in proximity to one another, the interaction between them can significantly affect their performance. Specifically, their individual stress and strain zones in the surrounding soil can overlap, modifying the way loads are transferred to the soil and leading to increased settlements and/or change in efficiency compared to the behavior of isolated piles. Pile group interaction is a well–known phenomenon, but the existing analytical or empirical models may oversimplify the problem.

Most of the earlier studies on pile groups focused on fine grained soils. In their seminal work on pile foundations, Poulos and Davis (1980) proposed an analytical method for studying the behaviour of pile groups, introducing the concept of pile–to–pile interaction factors to account for the influence of one pile on another within a group and, using linear elastic theory, they applied the principle of superposition to determine the overall response of the pile group. They observed that, in certain soil conditions, especially in clays, the bearing capacity of a pile group can be less than the sum of the capacities of the individual piles due to overlapping stress zones in the soil, leading to efficiency factors less than 1. In contrast, granular soils like sand present more complex behaviour. They respond differently under load, due to factors like particle rearrangement, dilatancy and variations in relative density. Several authors have followed Poulos and Davis studies, among the others Mandolini and Viggiani (1997) and Randolph (1994) developed the use of interaction factors and "efficiency coefficients" to adjust the expected capacity of a pile group based on spacing, pile number and soil type. However, the mechanisms of load sharing and settlement in pile groups embedded in sand remain less well understood and documented in literature. E.g. test conducted by Chow (1995) on two adjacent piles driven in dense sand evidenced that the installation of a neighboring pile produced a large increase in shaft capacity and a reduction in base capacity and stiffness.

Lee and Choong (2005) carried out 1g model tests on isolated single pile and pile groups driven in sand and found that pile–soil–pile interaction favorably affects pile capacity at wide spacing of 4 and 5 times the pile diameter, while at narrow pile spacing the pile capacity was unchanged or decreased. Foglia et al. (2020) carried out large–scale experiments which involved single piles and two pile group systems on a scale of 1:10, driven in dense sand, and found that the group efficiency changes throughout the test with increasing pile head displacement. At very small displacement the group effect amounts to values smaller than 1, whereas it is larger than 1 for most of the load path until failure. Pratana et al. (2023) simulated axial loading tests on pile groups and single piles using a three–dimensional finite element program to obtain the load–settlement curve and the ultimate bearing capacity of the piles. The piles were embedded both in fine–grained and coarse–grained soils. They found group efficiency less than, or equal to one in fine soils, more than, or equal to one in coarse–grained soils, especially at pile spacing more than three times the pile diameter. Increasing the number of piles and pile spacing in granular soil resulted in increased the pile group efficiency. In this context, mall scale centrifuge tests are a valuable tool to investigate how factors like pile spacing, number of piles, and arrangement influence load–settlement behavior, group efficiency and load sharing, as they allow to reproduce on a model the stress field of the reference prototype and the results can be extrapolated to the real scale using well established scaling laws [Schoffield (1980)].

This paper presents some of the results of a centrifuge modelling test campaign on groups of non–displacement piles performed to analyse the effects of interaction between piles. The free–headed and close ended piles were embedded in saturated homogeneous, very fine silica sand; some of them were instrumented with loading cells to evaluate the base and the shaft resistance independently. The isolated pile was tested as well and assumed as reference test. From the results of the tests, the interaction effects were quantified with respect to the isolated pile, and the influence of the pile number, spacing and position was investigated.

2 TEST PROGRAMME AND SET–UP

2.1 *Soil models*

The model tests were carried out in the Geotechnical Centrifuge of the research institute ISMGeo of Seriate (Bergamo).

The geometrical scaling factor of the models was N=100 and the acceleration of 100g was imposed at the soil surface; the acceleration field distortion was accounted for in the computation of stress distribution with depth. The tests were performed using FF sand (FFS), a uniform very fine sand consisting of sub–angular particles made of 98.2% quartz, 1.3% feldspar and 0.5% mica. The main physical properties of FFS are: $\gamma_{d,min}$=11.58 kN/m^3, $\gamma_{d,max}$=14.78 kN/m^3, ϕ'_{cv}=33°, G_s=2.61, D_{50}=0.093 mm, C_U=1.89 [Giretti (2009)]

FS has critical stress ratio M equal to 1.35, that gives a shearing resistance angle at critical state $\varphi'_{cv} \approx 33°$.

The soil models were reconstituted into a cylindrical strong box, whose height and inside diameter are 440 mm and 400 mm, respectively. The sand was dry pluviated at a small, constant height of fall, to obtain very loose specimens ($D_R \approx$ 15% ÷ 20%). After deposition, the specimens were saturated by means of an upward water flow, with a hydraulic gradient sufficiently small to prevent hydraulic failure. As a model was subjected to the acceleration field in the centrifuge, the soil surface settled due to the self–weight re–equilibration; the surface settlement was measured with a displacement transducer mounted on a rigid frame fixed to the container rim. The test reference soil density is the average value attained at the end of the in–flight consolidation, and it is $D_R \sim$ 35%. A scheme of a model and the testing layouts are shown in Figures 1 and 2. They consisted in:

- model IP: isolated single pile;
- model P3: group of 3 piles, spacing s = 8.66D_p;
- model P7: group of 7 piles, spacing s = 5D_p.

Tables 1 and 2 summarize the details of the tests presented in this paper.

2.2 *Model piles*

The model piles employed in the centrifuge tests were close–ended and free headed and they had external diameter D_p and length L_p of 8 mm and 160 mm, respectively (slenderness ratio of 20). The ratio of the model pile diameter to the mean particle size was D_p/D_{50} = 86 and it was considered high enough to minimize the effects of grain size on the interface behavior [Garnier and Konig (1998), Foray et al. (1998), Fioravante (2002), Garnier (2002)].

The piles were made with an aluminum alloy, hollow pipe and had an external relative roughness R_n ≈ 1.3 > 0.1, which ensures that shear failure occurs in the soil surrounding the pile and produces an interface friction angle equal to the shearing resistance angle at the critical state, ϕ'_{cv}, so that the ultimate value of the shear resistance does not depend on the pile roughness [Yoshimi and Kishida (1981), Kishida and Uesugi (1987), Jardine et al. (1993), Foray et al. (1995), Garnier and Konig (1998)]

Table 1. Main characteristics of the performed tests.

Test No.	Scheme	No. of piles n	Load cell layout	D_R (%)
4	IP	1	L0	36
8	P3	3	L2	32
9	P7	7	L3	35

Table 2. Foundation dimensions (model and prototype scale).

Dimensions		Model (mm)	Prototype (m)
Pile diameter D_p		8	0.8
Pile length L_p		160	16
Pile spacing s	P3	69.3	6.93
	P7	40	4

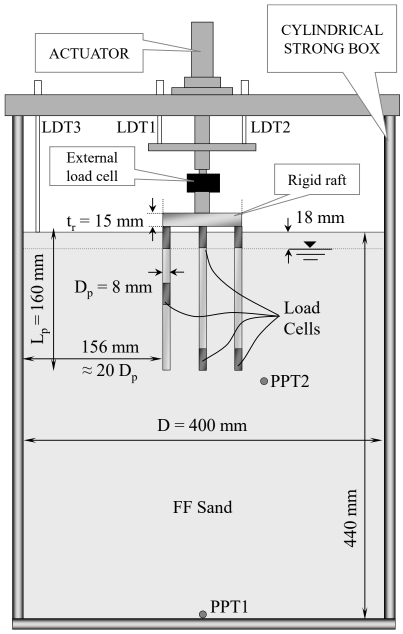

Figure 1. Model layout.

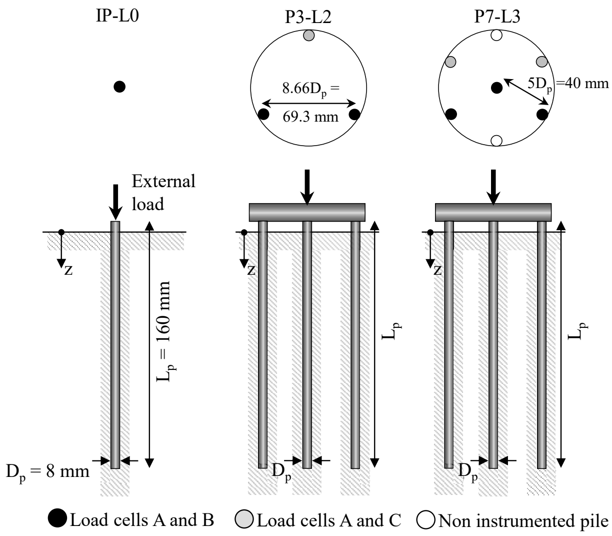

Figure 2. Model schemes.

Some of the model piles were instrumented with load cells, at the pile head and base (load cells A and B, respectively), or at the pile head and mid–pile (load cells A and C, respectively) as shown in Figures 1 and 2 and summarized in Table 1. The adopted instrumentation allowed the axial loads transmitted to each instrumented pile to be measured and the load transmitted through the shaft to be estimated.

2.3 *Test procedure*

At the end of the 1g soil saturation, the piles were inserted into pre–bored holes for a length of 130 mm (embedded length = 0.8L_p). A very rigid frame, which held a hydraulic actuator, an external load cell to measure the applied load, an 88 mm diameter circular rigid plate to load the pile heads (or an 8 mm diameter piston for the isolate pile test), two linear displacement transducers to monitor the displacement of the plate (LDTs 1 and 2 in Figure 1), was mounted onto the container top.

The container was loaded onto the centrifuge and accelerated to 100*g*. The accelerated soil was allowed to consolidate, and the water level was monitored through two miniaturised pore pressure transducers inserted into the soil mass, one at the bottom of the container and one near the pile tips (see Figure 1), and it was kept constant at 18 mm (1.8 m at the prototype scale) of depth from soil surface.

At the end of the self–weight equilibrium, the loading plate (or the piston for the isolated pile) was slowly lowered until contact with the pile heads was achieved and the model piles were loaded at a constant loading rate of 50 N/min. The total load, applied by the servo–controlled hydraulic actuator, was measured by the external load cell. The forces on the piles, the displacements of the loading plate and of the sand surface, the pore pressure were continuously recorded at an acquisition frequency of 0.1 Hz.

The pore pressure measured by PPT2 showed constant values during the tests, i.e. the loading conditions were drained. The foundation settlement, w, was obtained by averaging the measurement values of LDTs 1 and 2, which were placed in diametrically opposite positions from the actuator, as shown in Figure 1. The high stiffness of the loading plate ensured equal displacements of the pile heads in the groups.

3 RESULTS

In the test interpretation, all the forces have been assumed to act parallel to the vertical axis of the piles. With reference to Figure 3, Q_A is the pile total capacity and is directed downward (negative sign), while the shaft resistance, Q_S, the load acting at mid–pile, Q_C, and at the pile base, Q_B (i.e. base capacity), have an upward positive sign. Q_A, Q_C and Q_B, were directly measured during the tests by load cells A, C and B, respectively. The shaft resistance acting between load cells A–B, $Q_{S,AB}$ and between load cells A–C, $Q_{S,AC}$ were computed from the cell readings by means of the equilibrium equation:

$$Q_{S,AB}(w) = Q_A(w) + W_{AB} - Q_B(w) \tag{1a}$$

$$Q_{S,AC}(w) = Q_A(w) + W_{AC} - Q_C(w) \tag{1b}$$

where W_{AB} = dead weight of the pile between A and B; W_{AC} = dead weight of the pile between A and C; w = measured settlement.

The total load Q_T acting on the foundation was directly measured by the external load cell.

Due to their high axial stiffness, the piles were considered rigid in the test interpretation, and their displacement were assumed constant with depth.

Thanks to the axial–symmetry of the load and geometry, the piles placed at the same radial distance from the group centre, in P3 and P7 models, experienced the very similar load distribution with depth (as measured by the load cells) therefore, their measurements have been averaged to obtain an equivalent edge pile.

It's worth noting that even though the weight of the model piles was close to that of the substituted soil, differential settlements occurred between the piles and the surrounding soil during the in–flight consolidation and the soil surface settled 1–1.5 mm more than the piles, giving rise to negative skin friction in the upper pile shaft and mobilising positive skin friction in the lower shaft and the pile base resistance. Therefore, both Q_B and $Q_{S,AB}$ have non–zero values at the beginning of the loading phase.

3.1 *Isolated pile*

The results of the IP test are shown in Figure 4, where Q_A, Q_B, $Q_{S,AB}$ are plotted at the model scale and represented as a function of the measured settlement normalised over the pile diameter, w/D_p. The measured base and shaft resistance have mobilization curves typical of non–displacements piles: the base load gradually increases as the pile settles, without reaching a limit load, $Q_{S,AB}$ reaches a peak at $w/D_p \approx 10\%$, and then it only slightly increases with depth. IP is the reference test to evaluate the group behaviour in P3 and P7 models.

3.2 *Groups of 3 and 7 piles*

The results of test P3 are shown in Figure 5, in terms of Q_A, Q_B, $Q_{S,AB}$ vs. the normalised settlement. The values given in the Figure are averaged from the measures obtained from 3 instrumented piles (the measures from the piles of the group were very similar). Figure 6 shows the results of test P7. In the figure, the central pile is compared with the average–edge pile (obtained averaging the measures of 4 instrumented piles, which had very similar load settlement curves). Figures 7 and 8 report the base and shaft resistance of the average P3 pile and of the P7 average–edge and centre pile, normalized over Q_B and $Q_{S,AB}$ of IP, the settlement being equal. These ratios remind to the concept of group efficiency, originally used to compare the ultimate bearing capacity of a free–standing pile group with that of an isolated single pile, under equal soil conditions, in order to highlight the effect of the pile–soil–pile interactions on the group ultimate capacity. Figures 7 and 8 focalize the attention on the individual shaft and base components of the overall bearing capacity.

Despite the large spacing $s = 8.66D_p$, the average pile of the P3 group experienced a group effect in terms of shaft capacity, which, at peak was 40% higher than the isolated pile. However, at relative settlement lower than 0.05, the load efficiency was lower than 1, indicating negative interaction effects.

The base capacity efficiency was slightly lower than one all the test long, but this is interpreted more as an effect of a local lower density of the model than as a group effect.

In the P7 group (pile spacing s = 5Dp) the load efficiency was slightly lower than 1 at w/Dp = 0.05 – 1, afterword both the centre and the average–edge piles developed a shaft friction 80% higher than the isolated pile, at peak as well as at large settlement. The average–edge pile developed a base capacity 30% greater than IP at $w/D_p = 1$; the group effect on the base load was particularly marked for the central pile, which reached a load 60% larger than IP.

The results discussed so far evidenced that the load efficiency depended on the relative displacement. This is highlighted also in Figures 9, 10 and 11, where the load distribution with depth is plotted for three values of w/D_p, namely 0.05, 0.1, 0.2.

While at the initial loading stage ($w/D_p \leq 0.05$) the piles in the P3 and P7 groups had slightly lower or similar shaft and base resistance than IP, at larger settlement an increase in the shaft resistance was evident and remarkable, especially in the upper pile shaft and in the more confined P7 group. The increase in the base capacity was not relevant for $w/D_p < 0.2$, instead.

Similar considerations apply to the rate at which the pile base and shaft capacity developed, as highlighted by the load–settlement ratio (k) curves in Figures 12 and 13. The base stiffness, k_B, is very similar for IP, P3 and P7 piles, and it progressively decreased as the displacement increased.

The stiffness of the shaft, k_s, apart from an experimental scatter, was similar and almost constant for IP, P3 and P7 piles up to $w/D_p = 0.1$, then it remarkable decreased, the final stiffness of the piles in the group being larger than IP.

The overall effect of pile interaction on the total capacity is shown in Figure 14, where the total load applied to the piled foundations is normalised over 3 and 7 times the load carried by IP.

A load efficiency higher than 1 can be observed for relative settlement larger than 5%. Interaction between piles caused an increase in the total capacity from 15% up to 50%, in P3 and P7, respectively.

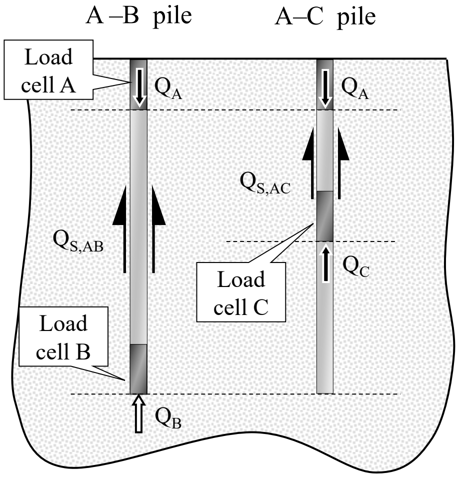

Figure 3. Model schemes.

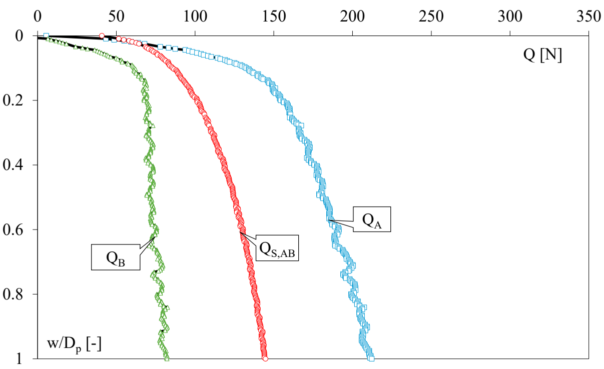

Figure 4. Isolate pile loads–settlement curves. Model scale.

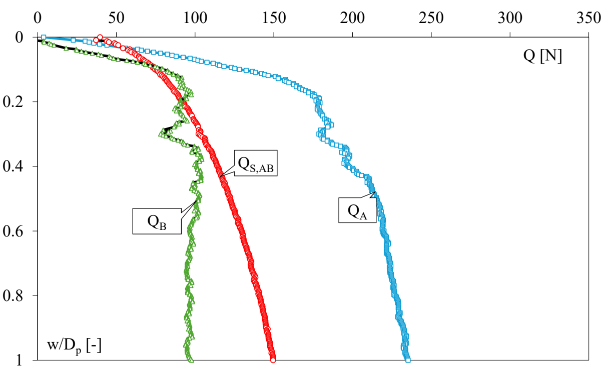

Figure 5. Average P3 pile load–settlement curves. Model scale.

4 DISCUSSION

The centrifuge tests carried out on groups of non–displacement piles embedded in loose, saturated sand have highlighted evidence of pile–soil–pile interaction effects, offering valuable insights into their implications for geotechnical design and performance evaluation.

Even in the case of the three–pile group (P3), where the spacing between the piles was relatively large (8.66 times the pile diameter), interaction effects were evident, especially in the shaft resistance component. Compared to the isolated pile (IP), the maximum shaft friction in the P3 group increased by up to 40%, despite the generous spacing. Conversely, base resistance showed negligible variation, indicating that shaft friction is more sensitive to pile group effects in looser sand configurations and at moderate spacing.

In the seven–pile group (P7), with a reduced spacing of 5 pile diameters, the effects of pile interaction became significantly more pronounced. Both shaft and base limit resistances were substantially enhanced, particularly for the central pile, which experienced a base resistance up to 60% higher than that of the isolated pile. The average edge piles also demonstrated increased capacities, with base resistance enhancements around 30% and shaft resistance improvements reaching approximately 80%. These findings suggest a pronounced confinement effect generated by the adjacent piles in a dense arrangement, which increases intergranular stresses and improves load transfer efficiency. These results are broadly consistent with previously reported pile–soil–pile interaction mechanisms in sandy soils [Chow (1995), Lee and Chung (2005), Foglia et al. (2021), Pratama et al. (2023)] with a distinctive feature which is the magnitude of capacity increase in loose sand at relatively large spacing (e.g. >40–80% shaft increases). However, interaction effects are influenced by the level of relative settlement. For both group configurations, interaction–induced increase in capacity became significant only after relative settlements exceeded 5% of the pile diameter ($w/Dp > 0.05$). At lower displacements, the behavior of grouped piles followed that of the isolated pile, with negligible changes in stiffness or capacity. This threshold behavior implies that, while pile groups may not offer substantial benefits under small–strain loading conditions, they can outperform isolated piles significantly under greater displacements.

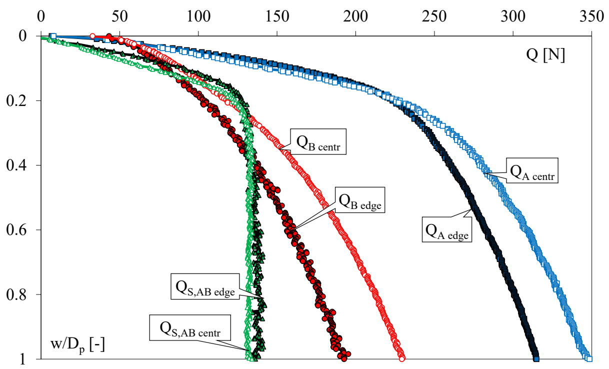

Figure 6. Central and average P7 pile load–settlement curves. Model scale.

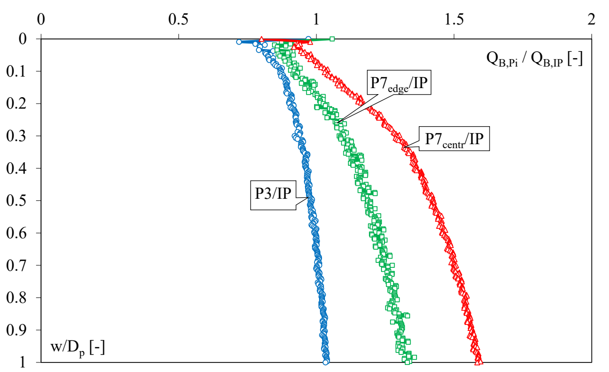

Figure 7. Base resistance of piles in groups normalized over the base resistance of IP.

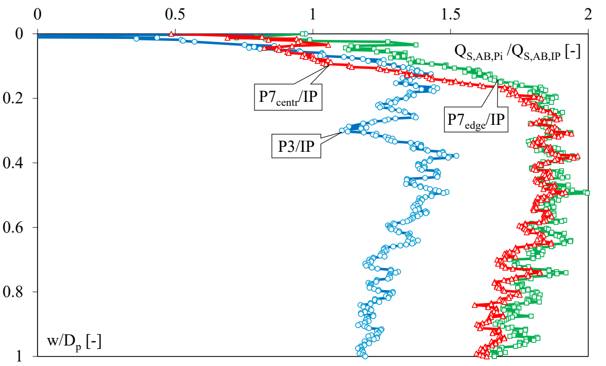

Figure 8. Shaft resistance of piles in groups normalized over the shaft resistance of IP.

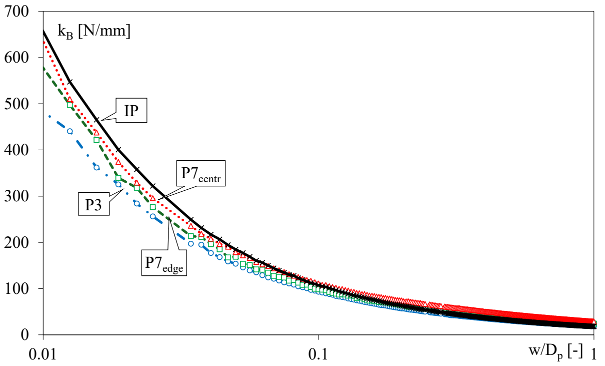

Figure 12. Base load–settlement ratio k_B vs. the normalized pile settlement w/D_p. Model scale.

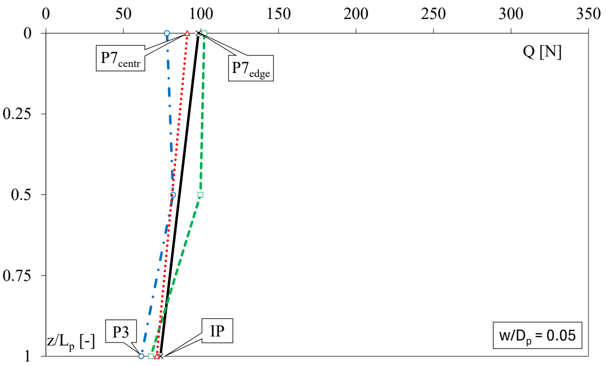

Figure 9. Axial load distribution along the pile shaft at $w/D_p = 0.05$. Model scale.

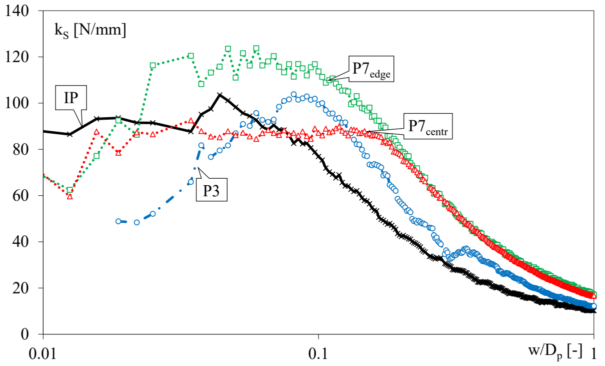

Figure 13. Pile shaft stiffness k_S vs. the normalized pile settlement w/D_p. Model scale.

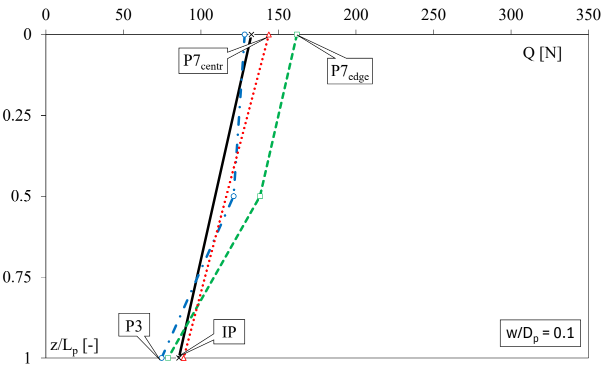

Figure 10. Axial load distribution along the pile shaft at $w/Dp = 0.1$. Model scale.

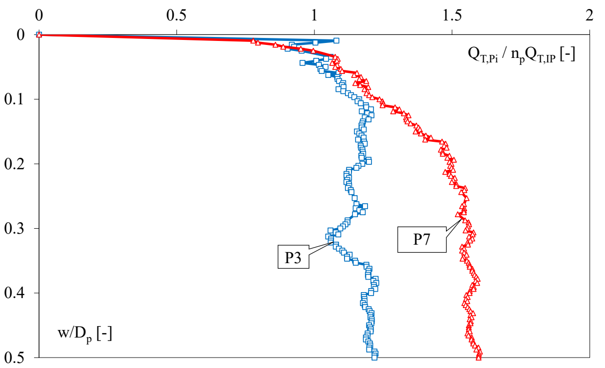

Figure 14. Piled foundation normalized resistance. Model scale.

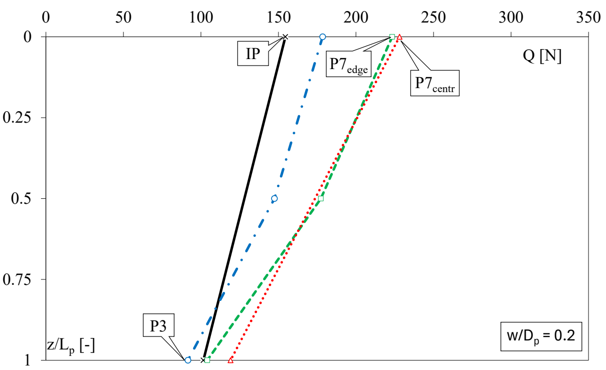

Figure 11. Axial load distribution along the pile shaft at $w/D_p = 0.2$. Model scale.

Load–settlement stiffness trends further support this observation. The initial stiffness, especially for shaft resistance, remained largely similar between isolated and grouped piles for relative settlements up to 10%. Beyond this point, however, the stiffness of piles in groups decreased less sharply than that of the isolated pile, indicating a more robust load transfer mechanism at higher displacements.

Overall, these results underline the dual nature of group effects in sandy soils. Positive effects: enhanced capacity due to increased confinement and intergranular stress redistribution, especially at high settlements and in tightly spaced configurations. Potential limitations: reduced stiffness and delayed mobilization of capacity at low settlements, which may be critical for serviceability–driven designs.

These findings underscore the necessity of incorporating pile–soil–pile interaction considerations into both ultimate limit state (ULS) and serviceability limit state (SLS) design frameworks. The application of centrifuge modeling has proven to be an effective method to isolate and quantify these effects under well–controlled conditions, bridging the gap between theoretical assumptions and real–world behaviour.

5 CONCLUSION

The centrifuge test results presented provided interesting results on the interaction mechanism which take place among piles in a free–standing group. Despite the loose state of the sand and the relatively large pile spacings, significant increases in shaft resistance and, to a lesser extent, base resistance were observed, indicating strong confinement and stress redistribution effects within the groups. While the magnitude of the interaction effects lies at the upper bound of values reported in the literature, the trends—reduced efficiency at small settlements and enhanced performance at larger displacements—are coherent with established experimental and numerical evidence. Overall, the study reinforces the need to explicitly account for settlement–dependent group effects when evaluating the performance of pile foundations in sand.

6 AKNOWLEDGEMENT

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