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Pile groups subjected to lateral cyclic loading – a comparison of 1g and centrifuge model tests

Groupes de pieux soumis à une charge latérale cyclique – une comparaison des essais de modèles 1g et de centrifugeuses

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ABSTRACT: As part of a research project to develop a framework for quantifying cyclic effects on piles, centrifuge model tests on single piles and pile groups in dry silica sand were carried out at the Centre for Offshore Foundation Systems (COFS) in Perth, Australia. In addition, small-scale model tests (1g model tests) were undertaken at the University of Kassel, Germany. The pile groups were subjected to one-way lateral cyclic loading, with variations on the cyclic load magnitude and the pile group configuration. This paper studies the influence of these variations on the lateral load-displacement behaviour and the load distribution within the pile group.

RÉSUMÉ: Dans le cadre d'un projet de recherche visant à élaborer un cadre de quantification des effets cycliques sur pieux, la modélisation en centrifugeuse du comportement de pieux individuels et en groupes en sable siliceux sec fut effectuée au Centre for Offshore Foundation Systems (COFS) de Perth, en Australie. De plus, des essais en modèle réduit à 1g furent effectués à l'Université de Kassel, en Allemagne. Les groupes de pieux furent soumis à une charge cyclique latérale unidirectionnelle, avec variations de l'amplitude de la charge cyclique et pour plusieurs configurations de groupes de pieux. Cet article examine l'influence de ces variations sur le comportement latéral charge-déplacement ainsi que l'influence de la répartition des charges au sein du groupe de pieux.

Keywords: Pile groups; physical modelling; cyclic loading

1 INTRODUCTION

Understanding the response of pile foundations to cyclic loading is of importance in civil engineering design including offshore and onshore wind turbines (BSH 2007) and structures for transport infrastructure (Berger et al. 2003). Cyclic loading may be caused by wind and waves (e.g. offshore wind turbines) or temperature induced constraints (e.g. integral bridges without joints and bearings). The behaviour of both fine and coarse grained soil under cyclic loading is complex (e.g. Wichtmann 2016). For example, lateral cyclic loading on piles in sand has been shown to lead to both densification and loosening of the surrounding soil depending on the relative density (e.g. Reese & van Impe 2011). Nevertheless, the design of pile foundations under cyclic loading is typically based on modifications of the more simplistic monotonic loading conditions. A better understanding of pile-soil interaction during lateral cyclic loading is therefore required to establish more efficient design strategies for these types of foundations.

As part of a research project to develop a framework for quantifying cyclic effects on piles and pile groups, centrifuge model tests on single piles and freestanding pile groups in dry silica sand have been carried out at the Centre for Offshore Foundation Systems (COFS) in Perth, Australia. In addition, small-scale model tests (1g model tests) were undertaken at the University of Kassel, Germany.

Cyclic loading can be characterised as either one-way or two-way, where one-way cyclic loading is uni-directional with no load reversal and two-way cyclic loading is bi-directional with load reversals in each cycle. To categorise cyclic loads relative to the ultimate lateral capacity of a single pile H_{ult}, LeBlanc et al. (2010) introduced the cyclic loading parameters ζ_b and ζ_c for single piles, which is extended in this paper for pile groups through inclusion of the parameter n_p (Eq. 1), which is the number of piles within the pile group.

$$\zeta_b = \frac{H_{max}}{n_p \cdot H_{ult}} \text{ and } \zeta_c = \frac{H_{min}}{H_{max}} \quad (1)$$

where H_{min} and H_{max} are the minimum and maximum loads during one cycle.

The aims of the pile group tests were to identify specific factors influencing the behaviour of pile groups under lateral loading and to establish phenomenological correlations for the displacement behaviour and the load distribution within the pile group.

2 EXPERIMENTAL DETAILS

2.1 General remarks

The centrifuge tests were carried out at an acceleration of 100g using the 40g-tonne, 1.8 m radius beam centrifuge located at The University of Western Australia (Randolph et al. 1991). The 1g tests were carried out at the University of Kassel. The test program in both the centrifuge tests and the 1g tests comprised monotonic and cyclic lateral loading on single piles and cyclic lateral loading on pile groups.

2.2 Centrifuge Tests: Experimental Setup

The model pile group consisted of five piles ($n_p = 5$); two in the leading row, two in the trailing row and one centre pile (see Figure 1). Three piles were instrumented with six pairs of strain gauges at the depths shown in Figure 1. The centrifuge tests used circular model piles that were fabricated from aluminium to have a diameter, D = 10 mm, a length, L = 130 mm and a wall thickness, t = 1 mm. A cap at the base of the piles prevented soil entering the interior of the piles during installation. The surfaces of the piles were sand-blasted, such that the roughness of the pile-soil interface was comparable to bored piles in-situ. The embedment length of the piles was L_p = 115 mm (L_p/D = 11.5).

The pile cap was a rigid cruciform plate, fabricated from stainless steel to have an edge length of 125 mm and a thickness of 10 mm (see Figure 1). Each pile was connected to the pile cap via a threaded connection, such that the connection between each pile and the pile cap could be considered as rigid. The pile cap had provisions for a number of pile connection locations, such that the same pile cap could be used in all tests with s/D varying between 3 and 5. A detailed description of the experimental setup is provided in Niemann et al. (2017, 2018a, 2018b).

2.3 1g Tests: Experimental Setup

The pile groups were connected to a hydraulic press that allows load and displacement control along the horizontal axis. As in the centrifuge tests, no additional vertical load was applied to the pile group, such that the vertical load was limited to the self weight of the pile group. Horizontal loading was applied via a hinge located at the centre of the pile group, 130 mm above the sample surface, ensuring that the top of the pile group was free to rotate in the direction of loading. Horizontal displacements and loads were measured using the LVDT of the hydraulic press and an axial load cell attached between the hydraulic press and the pile group.

Pile deflections, and subsequently bending moments and shear forces, were derived from the strain measurements on the piles assuming Bernoulli's beam theory (e.g. Reese & van Impe 2011).

Various pile group geometries were tested, namely pile rows with three piles in longitudinal (in-line, 1×3) and transverse (side-by-side, 3×1) directions, and a 2×2 square pile group. One pile of each position in the group was instrumented with six layers of strain gauges at the depths shown in Figure 1.

The 1g tests used circular model piles that were cut from PVC pipes to have a diameter, D = 40 mm, an overall length, L = 550 mm and a wall thickness, t = 1.9 mm. The same sand that was used in the 1g tests (see Table 1) was glued to the surfaces of the piles, such that, like the piles used in the centrifuge tests, the pile interface was comparable to bored piles in-situ. The embedment length of the piles was L_p = 513 mm (L_p/D = 12.8).

The pile caps were rigid plates, fabricated from stainless steel to have a thickness of 20 mm (see Figure 1). Each pile was rigidly connected to the pile cap.

2.4 Test soil and sample preparation

The centrifuge tests were conducted in a fine to medium sub-angular silica sand. For the 1g tests a medium grained sand was used. The properties of the two model soils are summarized in Table 1. In both test programs the air pluviation technique was used for sample preparation to achieve repeatable medium dense samples.

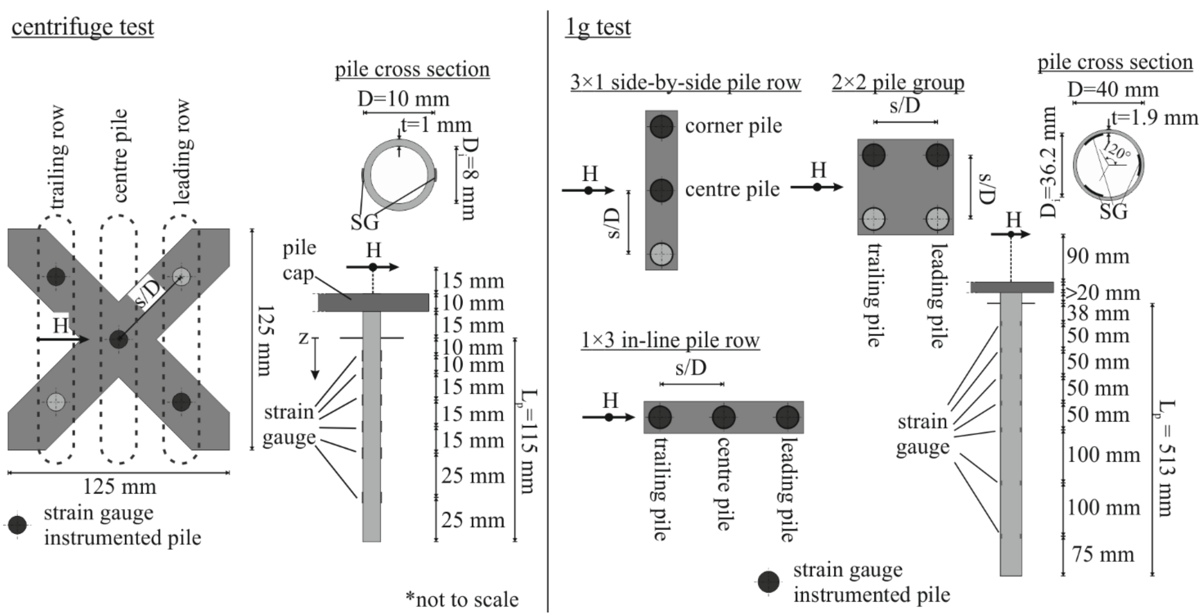

Figure 1. Pile geometry and instrumentation for the centrifuge and 1g tests

The sample density of the centrifuge samples was derived from measurements of the sample mass and volume. These measurements resulted in a relative density I_D = 45% for both samples.

Before any testing was undertaken, each centrifuge sample was spun to 100g and back a number of times to 'shakedown' the relative density to a steady value. Two cone penetration tests (CPTs) were conducted in the first sample in advance of the cyclic tests using a 7 mm diameter model cone penetrometer (Niemann et al. 2017, 2018a).

In the 1g tests the sample density was measured from calibrated sample tubes placed at different locations and layers in the testing container. These measurements resulted in an average relative density of I_D = 50%.

Table 1. Properties of the model sands for the centrifuge tests (Bienen et al. 2012) and the 1g tests

Parameter		**centrifuge tests**	**1g tests**
Mean grain size (mm)	d_{50}	0.19	0.50
Maximum void ratio (-)	e_{max}	0.79	0.84
Minimum void ratio (-)	e_{min}	0.49	0.53
Critical state friction angle (°)	φ_c	30.0	32.2
Specific gravity (-)	G_s	2.65	2.65
Minimum unit weight (kN/m³)	γ_{min}	14.9	14.4
Maximum unit weight (kN/m³)	γ_{max}	18.0	17.3
Coefficient of uniformity (-)	U	1.9	2.9

2.5 Test program

The test program is summarized in Table 2. In both the centrifuge and 1g tests, monotonic load tests were conducted to determine the ultimate capacity of a single pile prior to the cyclic tests. The monotonic tests were conducted by loading the pile head in displacement control at a velocity of 0.2 mm/s (centrifuge) and 0.25 mm/s (1g tests), respectively. The tests were carried out to derive the ultimate lateral load H_{ult} at the pile head, from which the load amplitude in the cyclic tests was scaled (see Eq. 1). The cyclic tests were carried out under load control.

A total of six cyclic pile group tests were conducted in the centrifuge, with varying amplitudes for 1-way cyclic loading. The piles were jacked into the soil at 1g rather than in flight, as the in-flight installation resistance would have exceeded the 7 kN vertical capacity of the actuator. According to Li et al. (2010) the behaviour of 'pre-jacked' model piles is comparable to that of field scale bored piles. After pile installation, the centrifuge was accelerated to 100g and the pile was loaded.

The intention of the 1g tests was to extend the results obtained from the centrifuge tests by investigating various pile group geometries and different load magnitudes. In the 1g tests, the piles were already in place during sample preparation, as an installation of the group after sample preparation would lead to significant changes of the initial stress state (for these 1g conditions).

A loading frequency of 0.1 Hz was selected in both series of tests. The data was acquired at a sampling frequency of 10 Hz.

Table 2. Test program for cyclic loading of pile groups

centrifuge tests		
No. of cycles	N	500
Pile spacing ratio	s/D	3, 4, 5
Cyclic load magnitude	ζ_b	0.2, 0.4
Cyclic load symmetry	ζ_c	0.0
1g tests		
No. of cycles	N	350 - 500
Pile group geometry	-	2×2, 3×1, 1×3
Pile spacing ratio	s/D	3, 5, 8
Cyclic load magnitude	ζ_b	0.15 - 0.5
Cyclic load symmetry	ζ_c	0.0

3 TEST RESULTS

Results from the displacement controlled monotonic load tests are provided in Figure 2 using the normalised groups suggested by LeBlanc et al. (2010). The horizontal displacement in Figure 2 is that of the pile head, which is L_h = 15 mm (L_h/D = 1.5) above the sample surface for the centrifuge tests and L_h = 20 mm (L_h/D = 0.5) above the sample surface for the 1g tests.

In this paper the ultimate lateral load for the single pile in the centrifuge test was defined as H_{ult} = 2 MN, which is within the range defined by several analytical approaches for the given soil properties and pile geometry (Niemann et al. 2018a). In the 1g test the same method was used, leading to H_{ult} = 210 N.

Example load displacement responses during cycling loading, for both centrifuge and 1g tests are shown in Figure 3. The load displacement responses exhibit the hysteretic behaviour that is characteristic of cyclic 1-way loading and deformation accumulation with number of cycles, N.

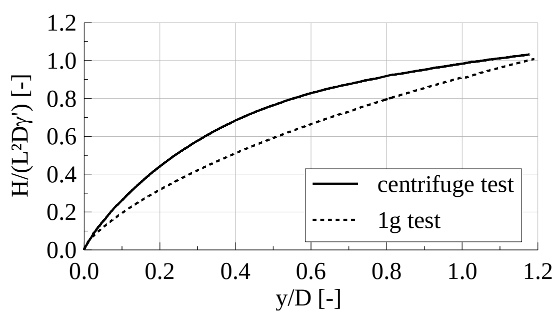

Figure 2. Monotonic loading of a single pile: Pile head load vs. displacement

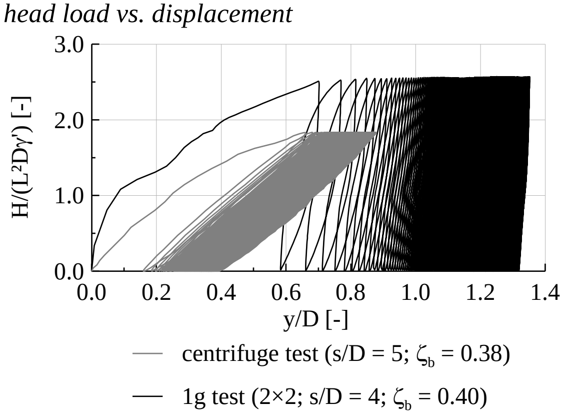

Figure 3. Typical cyclic load-displacement response measured in 1g and centrifuge tests

Figure 4 shows the normalised pile head displacements as a function of the number of cycles for the 1g tests (Figure 4a) and the centrifuge tests (Figure 4c).

The 1g test results indicate that the pile head displacements are dependent on the pile group geometry. The largest initial displacements at N = 1 are for the 3×1 'side-by-side' pile row with s/D = 3 (y/D = 0.63), whereas the smallest values are for the 1×3 'in-line' pile row with s/D = 5 (y/D = 0.13). During cyclic loading, the displacements increase to varying degrees, which is evident from Figure 4a, but also from the ratio of accumulation, $y_{N=n}/y_{N=1}$, where $y_{N=1}$ and $y_{N=n}$ are the maximum lateral displacement at the 1st and nth cycle, as shown in Figure 4b. The ratios indicate a dependency on the pile group geometry, the pile spacing and the load amplitude, with high ratios for the 1×3 pile row and the 2×2 pile group. For these geometries (1×3 pile row and the 2×2 pile group), after 500 cycles the displacement reached over twice that measured in the first cycle : $y_{N=500}/y_{N=1}$ = 2.60 for s/D = 5, $y_{N=500}/y_{N=1}$ = 2.04 for s/D = 3 (1×3 pile row), $y_{N=500}/y_{N=1}$ = 2.00 for s/D = 5 and $y_{N=500}/y_{N=1}$ = 3.20 for s/D = 3 (2×2 pile group).

These results are higher than from centrifuge tests on a 2×2 pile group (s/D = 3) in medium dense to dense soil samples reported by Rakotonindriana (2009), who used logarithmic functions to describe the accumulating displacements. An evaluation of these logarithmic functions for N = 500 leads to a ratio of $y_{N=500}/y_{N=1}$ = 1.43 for medium dense soil samples (I_D = 0.53).

Results from the centrifuge tests on Figure 4c show an obvious dependency of pile group displacement on the magnitude of cyclic loading and pile spacing. Smaller loads lead to smaller displacements and the highest displacements at a specific load amplitude occur at the lowest pile spacing, s/D = 3.

Figure 4d indicates that at small cyclic load amplitudes (ζ_b = 0.2) the pile groups with a pile spacing of s/D = 4 and s/D = 5 behave similarly. The relatively low displacement-ratio, $y_{N=n}/y_{N=1}$, evolves with cycle number to an almost stable state (shakedown, e.g. Poulos 1982) and accumulates to displacements of $y_{N=500}/y_{N=1}$ = 1.03 after a few cycles (ζ_b = 0.2, s/D = 4 and 5).

A higher displacement ratio of $y_{N=500}/y_{N=1}$ = 1.13 was measured in the test with the lowest pile spacing (ζ_b = 0.2, s/D = 3). Similar to the low cyclic load amplitude tests, at a higher amplitude (ζ_b = 0.4), displacements accumulated with shakedown, but higher incremental displacements, for each spacing ratio (s/D = 3, 4 and 5). The pile group displacement response is different for each pile spacing ratio, with an increase in displacement as s/D reduces: $y_{N=500}/y_{N=1}$ = 1.17 for s/D = 5, $y_{N=500}/y_{N=1}$ = 1.22 for s/D = 4 and $y_{N=500}/y_{N=1}$ = 1.33 for s/D = 3.

The distribution of bending moment along the pile length was derived from the measured strains at the locations indicated in Figure 1. From these results, the lateral load acting on each pile head can be determined by differentiating the measured bending moment distribution.

Small scale model tests reported by Klüber (1988) show that the contribution of the individual piles of a horizontally loaded pile group with a rigid cap (i.e. equal lateral pile head displacement) to the load transfer varies significantly. Klüber (1988) deduced load distribution factors, α_{Load} (Eq. 2) applicable to horizontally loaded double symmetric pile groups with uniform pile spacing:

$$\alpha_{Load} = \frac{H_i}{\Sigma H_i} \tag{2}$$

where H_i is the lateral force at the head of the individual pile i within the pile group and ΣH_i is the sum of the pile head forces for all piles in the pile group.

The factor α_{Load} quantifies the load distributed to a particular pile within a pile group under monotonic loading, with respect to their position within the pile group and to the distance to other surrounding piles.

To analyse the influence of cyclic loading on the load distribution factor α_{Load}, Figure 5 plots the cyclic load distribution factor, $\alpha_{Load(N)}$, against the logarithm of cycle number, log (N).

In the centrifuge tests, $\alpha_{Load(N)}$ (and hence the lateral force at the pile head) reduces with cycle number in the leading row, but increases for the centre pile and for piles in the trailing row.

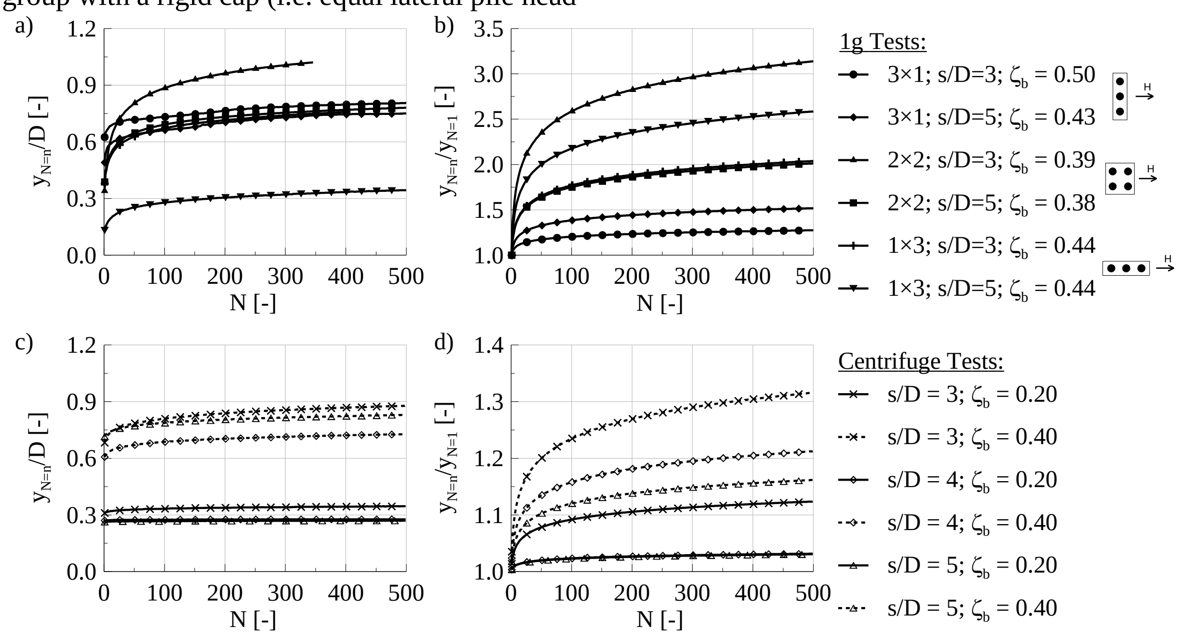

Figure 4. Evolution of horizontal displacement ratio with cycle number

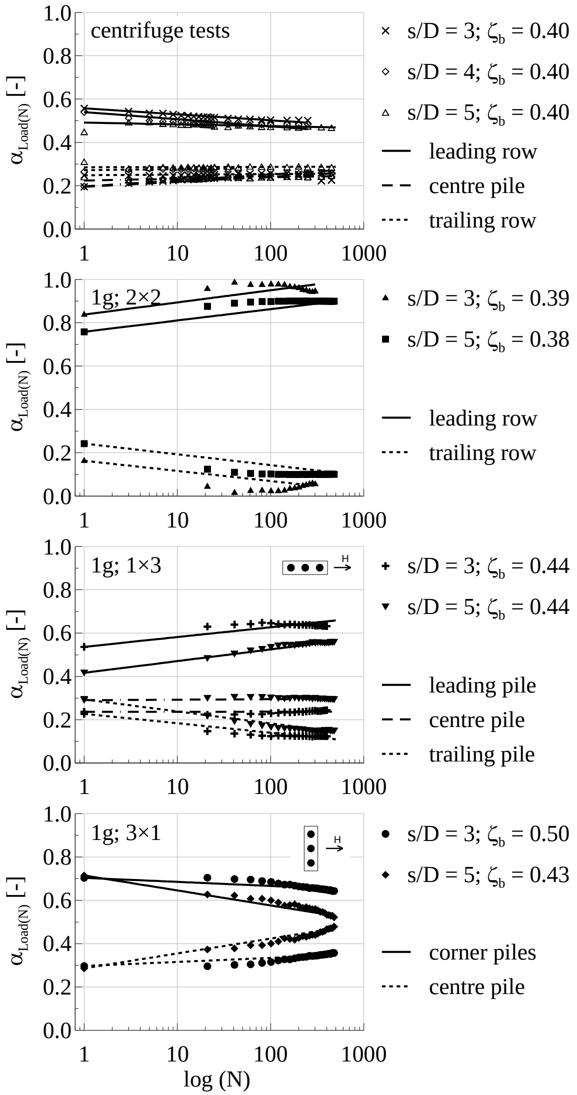

Figure 5. Evolution of load distribution factor with cycle number

This indicates that a shift in the load distribution within the pile group takes place during cyclic loading, which can be ascribed to densification and loosening effects in the soil around the piles.

Similar results were obtained for the 3×1 pile row in the 1g tests, with decreasing pile head loads for the corner piles and increasing loads for the centre pile. A partly different behaviour was observed in the remaining tests, where the load at pile head increases for the leading row piles (2×2 and 1×3) and reduces for the trailing row piles. The pile head load of the centre pile in the 1×3 pile row remains almost constant over the 500 cycles of applied load.

The load distribution factor $\alpha_{Load(N)}$ due to cyclic loading can then be described as a logarithmic function according to Eq. 3:

$$\frac{\alpha_{Load(N)}}{\alpha_{Load,1}} = t_\alpha \cdot log(N) + 1 \tag{3}$$

where $\alpha_{Load,1}$ is the load distribution factor for monotonic loading and t_α is a constant that describes the change in load distribution with cycle number. The data on Figure 5 are fitted by Eq. 3 using values of t_α as summarized in Table 3.

Table 3. Factor t_α to describe cyclic changes of load distribution

		t_α	
centrifuge test	**leading row**	**centre pile**	**trailing row**
ζ_b = 0.2; s/D = 3	-0.060	0.058	0.064
ζ_b = 0.2; s/D = 4	-0.013	0.076	-0.006
ζ_b = 0.2; s/D = 5	-0.094	-0.017	0.184
ζ_b = 0.4; s/D = 3	-0.050	0.119	0.011
ζ_b = 0.4; s/D = 4	-0.061	0.140	0.017
ζ_b = 0.4; s/D = 5	-0.017	0.033	0.003
1g-test: 2×2	**leading row**		**trailing row**
ζ_b = 0.39; s/D = 3	0.029		-0.125
ζ_b = 0.38; s/D = 5	0.030		-0.089
1g-test: 3×1	**corner piles**		**centre pile**
ζ_b = 0.50; s/D = 3	-0.012		0.027
ζ_b = 0.43; s/D = 5	-0.042		0.104
1g-test: 1×3	**leading pile**	**centre pile**	**trailing pile**
ζ_b = 0.44; s/D = 3	0.037	0.000	-0.083
ζ_b = 0.44; s/D = 5	0.056	0.003	-0.082

4 CONCLUSIONS

The results of the 1g tests and the centrifuge tests on cyclic loading show the influence of pile group geometry, pile spacing and load amplitude on the accumulation of pile group displacements. In general, displacements were higher in the 1g tests than in the centrifuge tests. The change in load distribution throughout the pile group was deduced from the measurements, and described well using a simple logarithmic function. The centrifuge tests indicate that, for the two pile group geometries considered, the loads redistribute from leading row to trailing row piles as cycle number increases. In contrast, the 1g tests show the opposite behaviour, with the leading piles (in the 2×2 and 1×3 pile groups) taking an increasing amount of the load with increasing cycle number. Additional 1g tests that more closely replicate the centrifuge tests are planned in an attempt to understand the origin of the behavioural differences.

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