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Combined Pile-Raft Foundation subjected to lateral loads

Fondation mixte semelle-pieux sous chargement horizontale

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ABSTRACT

Concerning the load bearing behaviour of vertically loaded Combined Pile-Raft Foundations many studies and publications are available whereas for Combined Pile-Raft Foundations subjected to lateral loads scientific results or case histories are very rare. But also for horizontal loading it is possible to obtain a very economic foundation design and to reduce displacements by using a Combined Pile-Raft Foundation (CPRF). In order to investigate the bearing behaviour of a CPRF subjected to horizontal loads a number of small scale model tests with CPRF, raft foundation and pile group at 1g-level were performed. The results show that e.g. the horizontal resistance of the CPRF is much higher than the resistance of a comparable pile group and a considerable part of the horizontal load applied is carried by the raft. Thus neglecting the horizontal resistance of the raft, as usually done for design purposes, leads to an underestimation of the total resistance of the foundation and to an overestimation of the horizontal displacements and of the shear forces as well as bending moments in the piles.

RÉSUMÉ

Au sujet fondations mixtes semelle-pieux sous chargement verticale beaucoup de publications sont disponibles. À l'opposé les publications au sujet du comportement des fondations mixtes sous chargement horizontale sont très rare. Dans cette recherche le comportement des fondations mixtes sous chargement horizontale est étudié à l'aide de modèles à petite échelle de fondation mixte, de fondation superficielle et de groupe de pieux traditionnel. Les résultats d'essais montrent que par exemple la résistance horizontale de la fondation mixte est plus grande que la résistance du groupe de pieux et une grande partie du chargement horizontal est porté par la semelle. Pour cette raison la négligence de la résistance horizontale de la semelle, comme elle est habituellement pratiqué pour le dimensionnement, cause une sous-estimation de la résistance total et une surestimation du déplacement horizontale, de la force horizontale et du moment des pieux.

1 INTRODUCTION

Compared to traditional pile foundations (pile groups) where building loads are assumed to be transferred to the soil only by piles, the Combined Pile-Raft Foundation (CPRF) is a new approach. A CPRF is consisting of the bearing elements piles, raft and subsoil (e.g. Katzenbach & Reul, 1997; Poulos, 2001). The load share between piles and raft is taken into consideration and the piles can be used up to a load level equal or greater than the bearing capacity of a comparable single pile. This design concept leads to a considerable cost reduction for foundations compared to the traditional pile foundations. Many publications concerning vertically loaded Combined Pile-Raft Foundations are available whereas for a CPRF subjected to lateral loads (bridge foundations, foundations subjected to earthquakes etc.) scientific results or case histories are very rare (Kulhawy & Prakoso, 1997).

Like for vertically loaded Combined Pile-Raft Foundations the horizontal loads acting on a CPRF are shared between piles and raft. The total horizontal resistance of a CPRF H_{tot} is given by the horizontal resistance of the raft H_{raft} and the sum of the horizontal resistances of the piles $\Sigma H_{pile,i}$.

$$H_{tot} = \sum H_{pile,i} + H_{raft} \quad (1)$$

H_{raft} is derived by integration of the shear stresses acting between the bottom side of the raft and the soil. The passive earth pressure developed by the soil in front of an embedded, laterally loaded raft and the shear forces developed by the soil along the sides of an embedded raft (Mokwa & Duncan, 2001) were neglected in the work described here. This assumption is applicable for rafts with a small thickness compared to their length. $H_{pile,i}$ is the horizontal resistance of pile *i*.

Undoubtedly a part of the horizontal load acting on a CPRF is carried by the raft and the load displacement behaviour of a horizontally loaded CPRF is different from the behaviour of traditional pile foundations but just a few results from load tests were published up to now (e.g. Horikoshi et al., 2003; Mokwa & Duncan, 2001; Pastsakorn et al., 2002; Watanabe et al., 2001). Therefore the behaviour of laterally loaded Combined Pile-Raft Foundations is still not clarified. In the present study horizontal loading tests with a small-scale model of a CPRF were performed. In addition tests with a pile group (no raft-soil contact, same pile geometry and pile positions as the CPRF) and with a raft foundation (same raft geometry as the CPRF) were carried out. The results of the tests with the raft foundation are not presented in this paper.

2 TEST APPARATUS

The geometry of the model components was determined based on typical dimensions of Combined Pile-Raft Foundations in Frankfurt am Main and a model scale of length of $\lambda = 1/50$. Other scales e.g. the scale of forces λ^3 could be derived from the scale of length using the commonly known scaling law relationships (Franke & Muth 1985). However the aim of the model tests described here was not to examine the behaviour of a specific prototype but to obtain some basic results concerning the bearing behaviour of laterally loaded Combined Pile-Raft Foundations.

Dry sand was used throughout the present study as model soil. The grain size distribution of the sand is shown in Fig. 1 and the soil properties are summarized in Tab. 1.

Half of the tests were carried out with loose sand and half of the tests with dense sand. The filling procedure of the test box is described in section 3 and the densities achieved are described in section 4.

Table 1. Properties of the sand used for the tests

water content	w	0.11	[%]
density of solid constituents	ρ_S	2.642	[g/cm³]
min. porosity	min n	0.309	[-]
max. porosity	max n	0.444	[-]
uniformity coefficient	C_U	3.0	[-]
coefficient of curvature	C_C	1.1	[-]
angle of internal friction	ϕ'	38.4	[°]

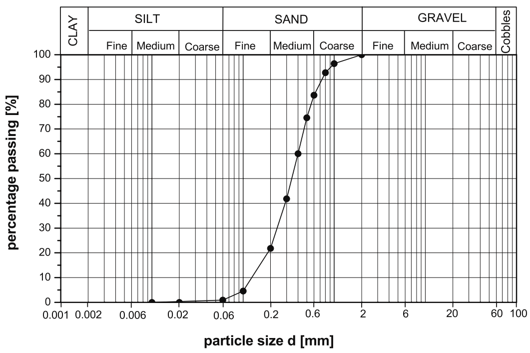

Figure 1. Particle size distribution of sand used for the tests

Plastic tubes made of polycarbonate with an outer diameter of 30 mm, an inner diameter of 27 mm and a length below soil surface of 640 mm were used as model piles for the tests with a pile group and a CPRF. The outer surface of the piles was sand-blasted and the tips of the tubes are closed. The tests were performed with a group of 5 piles.

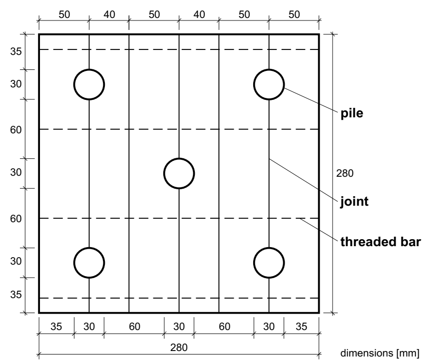

Figure 2. Plan view of model raft

A plan view of the model raft is given in Fig. 2. The quadratic raft with a length and width of 280 mm and a thickness of 40 mm is made of aluminium. It consists of 6 strips that are connected by 4 threaded bars. A separation of the raft was necessary to allow for a trouble free installation of the raft.

The piles were connected to the raft with a “fixed-head” constraint and distances of 180 mm between the corner piles and 127 mm between corner piles and centre pile. Tests with pile groups were carried out with a gap of 50 mm between raft and sand surface whereas the raft is in contact with the sand surface during tests with Combined Pile-Raft Foundations and raft foundations. In the pile group the load is transferred to the soil only by the piles, whereas for Combined Pile-Raft Foundations a load share between piles and raft occurs. During tests with raft foundations the 5 openings in the aluminium raft were closed with fitted pieces of plastic.

All tests were carried out in a steel test box with a length and width of 1000 mm (Fig. 3). With a wall thickness of 10 mm and several stiffening beams on the outer side, the box is considered to be rigid. A plexiglass lining is fitted to the inner surface of the walls. The box with a height of 1250 mm was filled with sand up to a level of 1180 mm. An opening is located in the bottom of the box, which is used to poor out the sand after finishing a test.

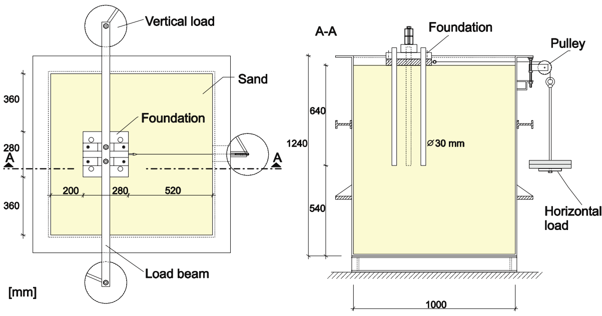

Figure 3. Plan view and section of test box with CPRF

The tests were carried out with vertical load levels of 1000 N, 3000 N and 5000 N. After the vertical load was applied a horizontal load with a maximum value of 1200 N was applied while the vertical load remained constant. The loading setup is shown in Fig. 3. The vertical loading setup consists of a load beam that is fixed to the raft and two vertical bars, which are connected to the load beam with a pendulum joint. The bars were loaded with steel weights. Horizontal loading was obtained by converting the vertical load of steel weights into horizontal load with the help of a steel cable fixed to the raft and a pulley (Fig. 3).

The raft settlements and horizontal displacements were measured with high-resolution displacement transducers. The vertical movement of the sand surface was also observed with displacement transducers. All piles were supplied with strain gauges in order to measure the axial forces at the top and the bottom, the lateral forces at the top and the bending moments in 10 levels of depth. The measurement devices were connected to an electronic data logging system, which provides an online visualization and storage of all measurement data.

3 TEST PROCEDURE

One factor with a strong influence on the load-settlement behaviour of the model foundations is the density of packing of the sand grains. The test series performed here covers tests with loose sand und tests with dense sand. Therefore a method of forming artificial beds of sand that are homogeneous and reproducible over a wide range of porosities was required (Walker & Whitaker, 1967). This requirement was met by pouring the sand into the test box with a “rainfall method” which was successfully applied for several model tests in Darmstadt (e.g. Heineke et al., 2001).

To prepare the test installation for pile groups and Combined Pile-Raft Foundations the test box was filled with sand up to the level of pile tips. Next the foundation was fixed to the test box with the help of a holding device and the box was filled nearly up to the final level. Thus the installation process did not disturb the sand surrounding the piles. This procedure is used to simulate the construction of a bored pile with casing where soil disturbance is usually small. Before pouring the last centimetres of sand the raft was removed. After the final height of the sand surface was reached a smooth and plane surface was obtained with screed plates and the raft was installed again.

Finally the measurement devices were set up and the vertical loading procedure was started with load increments of 200 or 400 N and a maximum final vertical load of 5000 N. After the final vertical load was applied the horizontal loading procedure started with increments of 100 N and a maximum final load of 1200 N.

For each foundation type except the pile group, horizontal load tests in loose and dense sand with vertical loads of 1000 N, 3000 N and 5000 N were carried out. The number of tests carried out for each boundary condition is displayed in Tab. 2. Each of the tests was repeated once or twice in order to check the repeatability of the tests. In the following some results of the tests carried out in dense sand are presented.

Table 2: Number of horizontal load tests carried out

Density of sand	Vertical load	Foundation type		
		Raft	Pile group	CPRF
Loose (1.534 g/cm³)	1000 N	2	2	3
	3000 N	2	-	2
	5000 N	2	-	3
Dense (1.712 g/cm³)	1000 N	2	2	3
	3000 N	2	3	2
	5000 N	2	2	3

4 TEST RESULTS

The results of the tests show that the application of the aforementioned rainfall method leads to reproducible densities of the sand beds and to reproducible test results. For the tests carried out in dense sand the mean value of dry densities achieved is $\rho_d = 1.712$ g/cm³ with a standard deviation of 0.013 g/cm³. In loose sand the mean value of dry densities is $\rho_d = 1.534$ g/cm³ with a standard deviation of 0.006 g/cm³. The results of the loading tests shown in the following figures are the mean values of first test and repeating test.

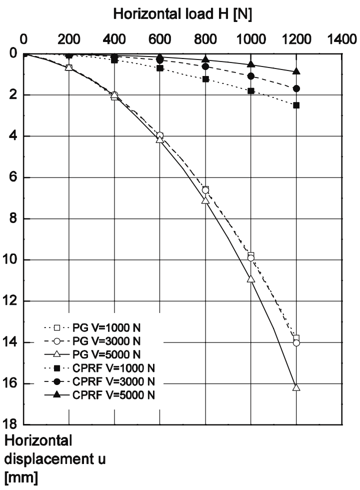

Figure 4. Horizontal displacement of CPRF and pile group (PG) in dense sand

Concerning the vertical load bearing behaviour of Combined Pile-Raft Foundations the results show good agreement with the results published by other authors (e.g. Horikoshi & Randolph, 1996) and several conclusions regarding load share between piles and raft and settlement reduction of a CPRF compared to traditional pile foundations are obtained (Turek & Katzenbach, 2003).

The relationship between horizontal displacement and load of CPRF and pile group (PG) for the different vertical load levels obtained from the tests in dense sand are summarised in Fig. 4. It can be seen from Fig. 4, that the horizontal displacements *u* of the CPRF are depending on the vertical load level. The displacements decrease with increasing vertical load. Whereas the load-displacement relationship of the pile group is not depending on the vertical load. For a vertical load level of 1000 N the horizontal resistance of the CPRF is about 2.5 times higher than the horizontal resistance of the pile group. For vertical load levels of 3000 N and 5000 N the horizontal resistance of the CPRF is even 4 respectively 6 times higher due to the resistance provided by the raft.

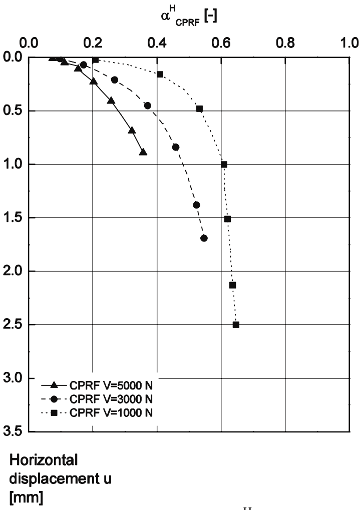

Figure 5. Horizontal CPRF coefficient α^H_{CPRF} derived from tests in dense sand

Analogous to the widely known CPRF coefficient α_{CPRF} for vertically loaded Combined Pile-Raft Foundations (Katzenbach & Moormann, 2003) the horizontal CPRF coefficient α^H_{CPRF} is defined by the ratio of horizontal pile resistances $\Sigma H_{pile,i}$ and the total horizontal resistance H_{tot}.

$$\alpha^H_{CPRF} = \frac{\sum H_{pile,i}}{H_{tot}} \tag{2}$$

α^H_{CPRF} describes the proportion of horizontal load carried by the piles. Thus the value of α^H_{CPRF} can range from 0 for a raft foundation to 1 for a pile group. The values of α^H_{CPRF} derived from the model tests in dense sand are plotted versus horizontal displacement in Fig. 5. With increasing horizontal displacements α^H_{CPRF} increases to values of 0.4 – 0.6. Higher vertical load levels are leading to a decrease of α^H_{CPRF}. Especially for small horizontal displacements and high vertical load levels the major part of the horizontal load is carried by the raft. The load share between piles and raft leads to smaller horizontal pile loads and smaller bending moments of the piles of the CPRF compared to the pile group. The measurements of the bending moments of the piles indicate, that the maximum bending moment of the pile group is more than 4 times higher than the maximum bending moment of the CPRF.

The relationship between the horizontal resistance of the piles and the horizontal displacement of the CPRF for the tests with vertical loads of 1000 N and 5000 N is shown in Fig. 6. The maximum horizontal load applied in both tests was 1200 N but as already shown in Fig. 4 the maximum horizontal displacement of the CPRF with a vertical load of 1000 N is more than twice as high as the displacement of the CPRF loaded with 5000 N in vertical direction. Even though the relationship between horizontal pile resistance and horizontal displacement seems to be quite similar for both vertical load levels there is a difference concerning the distribution of loads between the different pile locations. For a vertical load of 1000 N the distribution of lateral pile loads meets one's expectations concerning the shadowing effect, which is well known from several works on group behaviour of laterally loaded piles (Reese & Van Impe, 2001). The highest pile resistance was measured for the front piles while the soil resistance of the trailing rows (middle pile and back piles) was reduced because of the presence of the pile ahead. In contrast to this behaviour the results of the tests with a vertical load of 5000 N show that the resistance of the back piles is higher then the resistance of the middle and front piles. This effect is thought to be due to the increase of stresses and stiffness in the soil beneath the raft, which is caused by the high vertical load transferred by the raft. The highest increase of stresses and stiffness occurs in the soil beneath the centre of the raft while no increase occurs beneath the edges of the raft. Thus the reaction modulus of the soil in front of the back piles is increasing more than in front of the front piles, which leads to higher lateral resistance of the back piles.

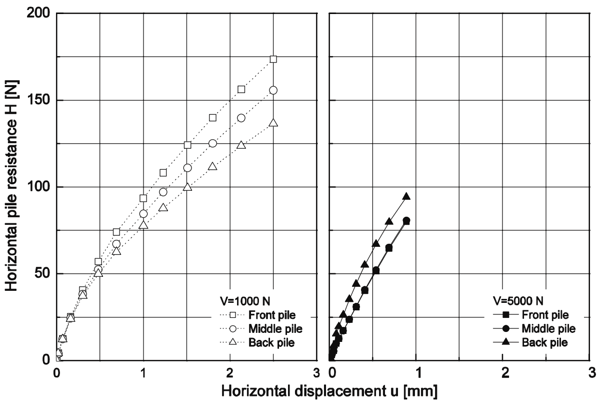

Figure 6. Horizontal resistance of piles of CPRF versus horizontal displacement in dense sand

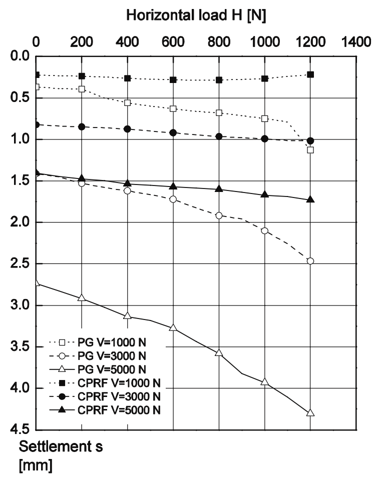

Figure 7. Settlement of pile group (PG) and CPRF versus horizontal load in dense sand

In Fig. 7 the settlements of pile group and CPRF are plotted versus horizontal load. The initial value of settlements (horizontal load H = 0) is the final value measured after applying the maximum vertical load V. The settlements of the CPRF loaded with 3000 N and 5000 N in vertical direction are increasing during horizontal loading. After the maximum horizontal load was applied a settlement increase of about 20 % compared to the settlement resulting from the vertical loading procedure was observed. For the CPRF loaded with 1000 N in vertical direction only minor changes of settlement due to the horizontal loading procedure were observed. It is obvious from the results in Fig. 7, that the horizontal load leads to a higher increase of settlements of the pile group than of the CPRF.

5 CONCLUSIONS

Small-scale horizontal load tests with a Combined Pile-Raft Foundation, a pile group and a raft foundation were carried out in order to investigate the lateral load bearing behaviour of a CPRF. Some of the conclusions that can be drawn from the results of the tests are listed in the following:

1. The horizontal resistance of the CPRF is depending on the vertical load acting on the CPRF during horizontal loading procedure. Higher vertical loading leads to a higher horizontal resistance of the CPRF. No significant increase of horizontal resistance due to increasing vertical loading was observed for the pile group.

2. The horizontal resistance of the CPRF is about 2.5-6 times higher than the horizontal resistance of the pile group.

3. For small horizontal displacements the major part of the horizontal load is carried by the raft. With increasing displacements the proportion of load carried by the raft decreases but even for the maximum displacements occurred in the tests about 40 % of the load were carried by the raft.

4. The Load share between piles and raft leads to significant smaller horizontal pile forces and bending moments of the piles of the CPRF compared to the pile group.

5. The distribution of horizontal loads between the piles of the CPRF depends on the vertical load level. For small vertical loads the highest lateral pile loads were measured for the front piles but for high vertical loads the highest lateral loads were carried by the back piles.

6. Due to horizontal loading a strong increase of settlements of the pile group was observed whereas only minor increase was observed for the CPRF.

It is evident that neglecting the horizontal resistance of the raft, as usually done for design purposes, leads to an underestimation of the total resistance of the foundation and to an overestimation of the horizontal displacements and of the shear forces and bending moments of the piles.

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