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Horizontal load tests on files of large diameter bored piles

Essais de chargement horizontal sur files des pieux moulés

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SYNOPSIS Piers for bridges are often founded on large diameter bored piles arranged in a single file. German codes of practice differ as to the group efficiency under lateral load. Some large-scale horizontal load tests were run, each on two or three piles simultaneously, situated one behind the other. The loading device as well as the test programme are described, and the load bearing behaviour of the test piles is discussed. Additional investigations are suggested.

INTRODUCTION

In the Federal Republic of Germany, piers for road or railway bridges are often founded on a single file of large diameter bored piles, see fig. 1. If pile groups are subjected to lateral loads, German Standard DIN 4014 Teil 2 yields that the modulus of horizontal subsoil reaction k_s must be reduced as a function of the interspace, and that to the same degree for each pile of the group, whereas the code of practice EBK recommends reductions that differ from pile to pile, depending on its position within the group, see fig. 2. There are no special rules for single files of piles.

The group action of laterally loaded piles has been investigated mostly by model tests and/or analyses, hence involving always some doubts as to their relevance for the prototype. Large-scale tests are scarce, yielding very often only the behaviour of the pile group related to that of a single pile, and results of load distribution and pile-soil interaction are missing. For this reason, some tests were run on files of two or three free-headed, large diameter bored piles located one behind the other.

HORIZONTAL LOAD TESTS

To facilitate the test procedure, a new loading device was designed (Schmidt 1981), see fig. 3. It may be

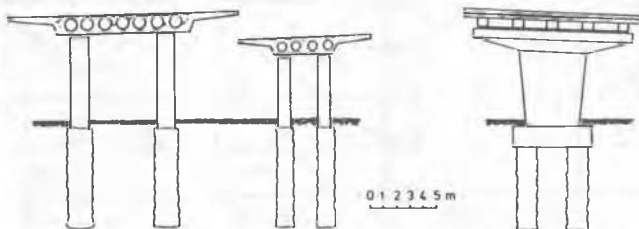


Fig. 1 Typical bridge piers founded on a single file of large diameter bored piles

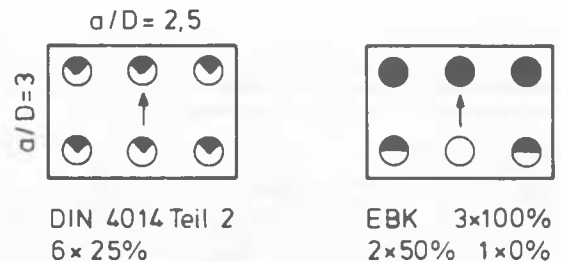


Fig. 2 German codes of practice concerning group action under horizontal load

adapted to pile diameters ranging from $D = 0.9$ m to 1.5 m, and to any distance of the test piles. Total loads up to 1.0 MN may be applied. The tensile rods are stressed by two double-acting hydraulic jacks, which are supported by working piles or by two sections of a pile casing embedded in the soil. The load is transferred to steel beams and induced in the test piles by two more hydraulic jacks, acting as load cells, and which may be used to correct the pile distance during the test, if necessary.

This paper concentrates on a test series run on 7 piles with lengths $L = 8.5$ metres and diameters $D = 1.2$ metres, embedded in uniform, medium dense sand above the ground water level. Two piles were constructed with a casing, 3 piles using a bentonite slurry, and for two piles the boreholes were excavated using a casing, but were filled with bentonite slurry for 7 hours before concreting. Three groups were tested: C 2/2, B 3/2.2, and CB 2/3. The letter denotes the construction procedure, the first number the number of piles, and the second number the pile spacing, related to the pile diameter. The following test procedure was adopted for each group:

- (1) Maintained load test of the pile group, 5 increments for both loading and unloading;
- (2) cyclic loading of the pile group, 10 cycles;
- (3) reloading and unloading of the pile group by steps as described above;
- (4) reloading and unloading of the individual piles one after the other by steps as described above.



Fig. 3 Loading device for two-pile files

The measuring device was described by Nowack and Gartung (1983).

TEST RESULTS

The test results proved the suppositions derived from the behaviour of single piles (Schmidt 1981).

Effect of interspace

The test results for the groups C 2/2 and CB 2/3 are plotted in fig. 4, showing that the load bearing behaviours of the piles with a distance $a = 3D$ are almost identical, whereas in the group C 2/2 with a distance $a = 2D$ the bearing capacity of the rear pile differs from that of the front pile more and more with increasing load and displacement, respectively. Results of incremental reloading corroborate that three of the four piles show the same behaviour as part of the group and as single piles, except the rear pile of group C 2/2. From these results may be concluded that

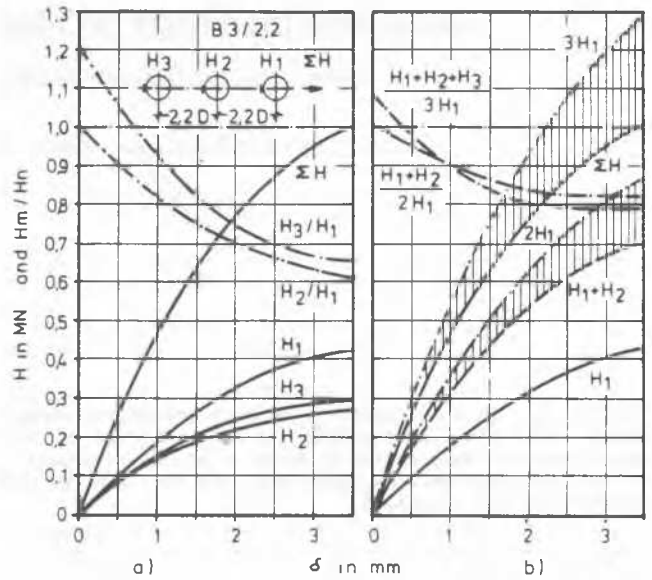


Fig. 5 Results of horizontal load test on three-pile file

the front piles of the files behave as single piles, and that the bearing capacity of pile files is not reduced by group action, if the pile distance equals or exceeds 3 pile diameters.

Load distribution

File no. B 3/2.2 consisted of 3 piles, see fig. 5 a). The load-deflection-curves of piles no. 2 and no. 3 coincide, but differ from that of the front pile. This pattern of the load distribution indicates that the behaviour of the center pile is influenced by the movement of the front pile, but not in addition by the

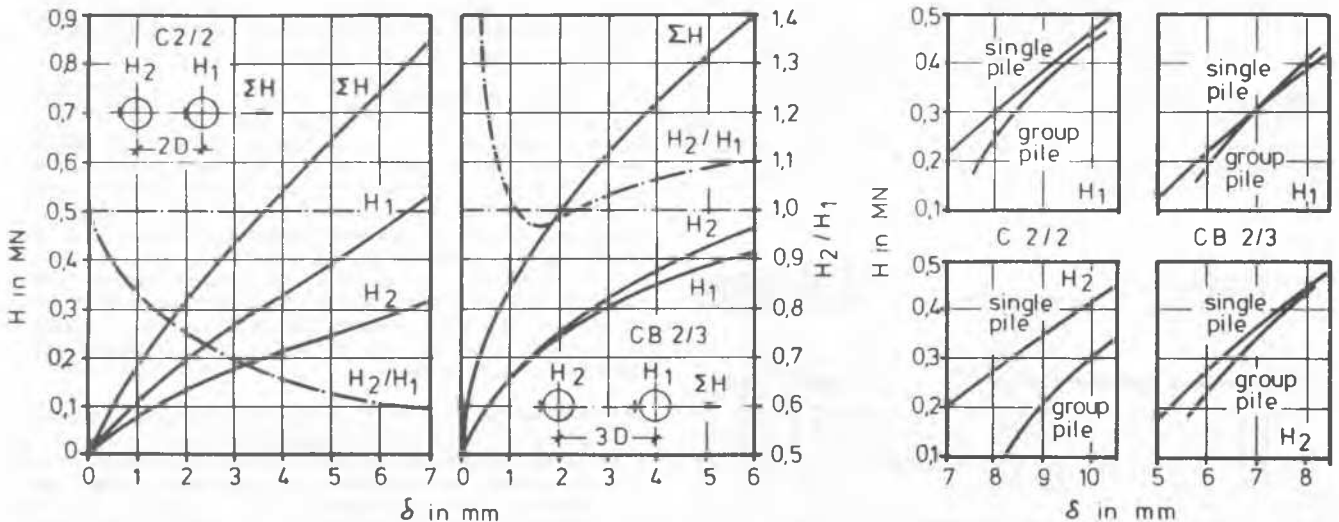
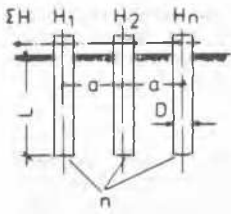


Fig. 4 Test results of two-pile groups C 2/2 and CB 2/3



no	n	D m	L m	a/D	Soil type
1	2	1,0	5,0	2,0	n
2	2	1,2	8,5	2,0	n
3	2	1,35	8,5	2,2	n
4	2	1,2	8,5	3,0	n
5	3	1,35	8,5	2,2	n
6	2	1,2	12,5	4,0	c, n
7	2	1,2	28,0	2,4	c, n
8	2	1,2	16,0	1,33	c
9	2	1,5	25,0	1,67	c

c = cohesive soil
n = non-cohesive soil

ring capacity of any pile file to that of the front pile, see fig. 5 b).

Group efficiency

In this way, the group efficiencies of all the pile files tested were evaluated and plotted in fig. 6. Files no. 4 and no. 6 with piles spaced at three or more pile diameters showed no group effect. Differential behaviour of the piles in file no. 6 resulting in $G_w = 0.9$ is due to non-homogeneous soil conditions, as it is often measured in tests on identical single piles. The curve for file no. 5 starts at $G_w = 1.1$, as the rear pile initially showed a better bearing behaviour than the front pile. Some differences in the geometries of the pile shafts were to be expected due to the production procedure (see above), affecting the behaviour under small loads. All the results yield that the group efficiency decreases with increasing displacements (and loads), down to values of $G_w = 0.75-0.8$ for the two-pile files. As test conditions differ, definite rules concerning the effect of the interspace or of the load on the group efficiency may not yet be derived from these results.

Bearing behaviour

In a number of tests, the bending moments of the pile shafts were measured, and the moduli of horizontal subsoil reaction were evaluated from the test results. The bending moments measured on the pile file C 2/2 are plotted in fig. 7, showing that the depth of the maximum bending moment does not vary very much with increasing loads. In spite of the fact, that the horizontal loads carried by piles no. 1 and no. 2 differ more and more with increasing load, the bending moments of both piles are approximately equal. Cyclic loading affects the bending moments of the rear pile to a greater degree than those of the front pile. In the lower section of the pile shafts, the residual moments after unloading are noteworthy. Measurement results corroborated the rule of thumb, saying that cracking of the concrete starts, if the tensile stresses exceed some 3 MN/m^2 . By this effect, the stiffness of the pile shafts was reduced to fifty percent of the initial value.

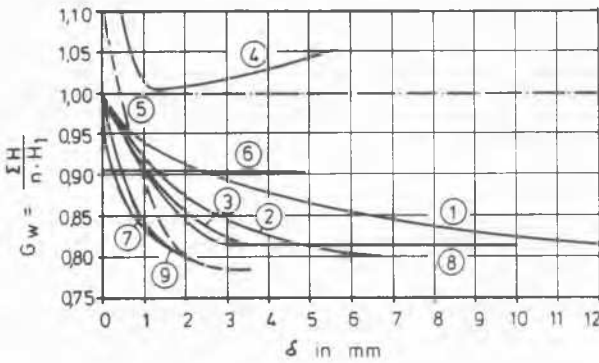
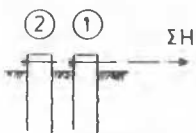


Fig. 6 Group efficiencies of laterally loaded pile files

displacement of the rear pile. This fact is in good agreement with suppositions made before (Schmidt 1981), and corroborates the above statement, that the front pile behaves as a single pile. Hence, piles no. 1 and no. 2 may be considered as a 2-pile file, and group efficiency may be evaluated by relating the bear-

File C 2/2



Nr	δ mm	H1 KN	H2 KN
1	0,46	58	52
2	1,55	154	120
3	3,17	271	187
4	5,17	408	249
5	6,68	510	307
6*)	10,32	463	337
7	∞	0	0

* after cyclic loading

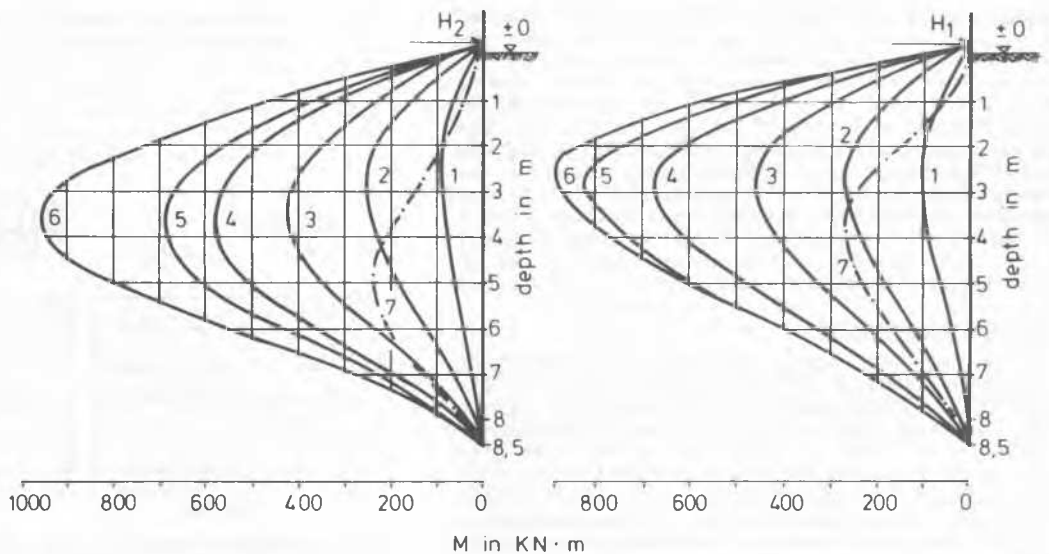


Fig. 7 Bending moments measured on file C 2/2

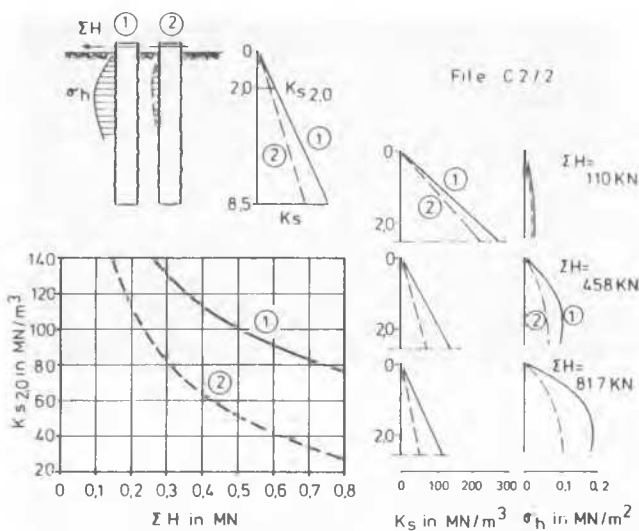


Fig. 8 Moduli of horizontal subsoil reaction and contact pressures evaluated for file C 2/2

Moduli of horizontal subgrade reaction were evaluated from the measurement results, see fig. 8. The common statement that the reaction modulus increases proportionally to the depth below the soil surface was proved. Various patterns were tried, yielding that good agreement was achieved in any case, if the values coincided approximately from the soil surface down to a depth of some two metres, whereas the values at the pile base showed ratios up to 6:1. As different patterns for the increase of the reaction modulus with depth are in common use in Germany, it is felt that the modulus of horizontal subsoil reaction should be defined at a depth of approximately two meters, see fig. 8. The investigations yielded that the maximum value of the contact pressures, too, was located approximately at that depth, for all the piles tested. Once more, the results illustrate the effects of group action on the modulus of horizontal subsoil reaction, and hence on the contact pressures.

Apparently, the displacement of the front pile reduces the soil resistance for the rear pile in the upper region, and this pile transfers a greater part of its load to lower sections, resulting in higher bending moments. Therefore, the ratio of loads carried is improved compared with that of the soil resistances, and bending moments are approximately equal, see fig. 9. Short piles behave in a different way. Comparing the bearing behaviour of the front pile with that of the rear pile in the two-pile group no. 1 in fig. 6 yielded that for approximately rigid piles the relations of the loads carried, of the bending moments, and of the soil moduli are almost equal.

"Induced displacements"

In a two-pile file, group efficiency is governed by the bearing behaviour of the rear pile, which is affected by the displacements of the front pile. It was felt, therefore, that on the other hand displacements induced in the front pile by loading the rear pile alone could be a means to judge group efficiency. Test results proved that such "induced settlements" indicate reliably, whether group action is to be expected or not. But there was no definite relation between group efficiency and the induced displacements, see fig. 10,

maybe due to the fact, that group efficiency was evaluated from the initial loading of the whole file, whereas the induced displacements were measured in the final reloading of the individual piles.

Effect of cyclic loading

File CB 2/3 was subjected to four cyclic loadings, see fig. 11. In each case, the number of cycles amounted to $n = 10$, and the loads applied ranged from some 150 kN per pile to some 450 kN per pile. Keeping the initial distance of the piles constant resulted in the fact, that the displacements and the total loads of the pile group differed to a small degree for each cycle. Hence, those loads were evaluated, that would have induced constant displacements. The results show that unloading and reloading did not affect the displacements up to a definite amount of the horizontal load, and that the ten cycles applied were not sufficient to reach stable, quasi-elastic conditions under higher loads. Results of files C 2/2 and B 3/2.2 yielded that the load distribution may be influenced by cyclic loading, but results do not allow for definite conclusions.

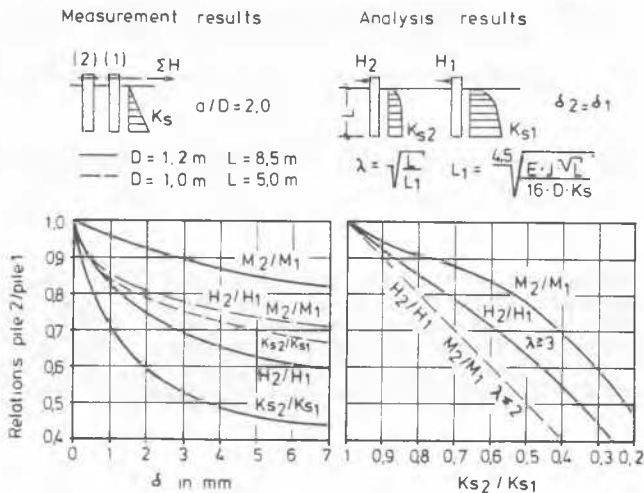


Fig. 9 Results of measurements and analyses on the effect of pile stiffness on the load bearing behaviour of pile files

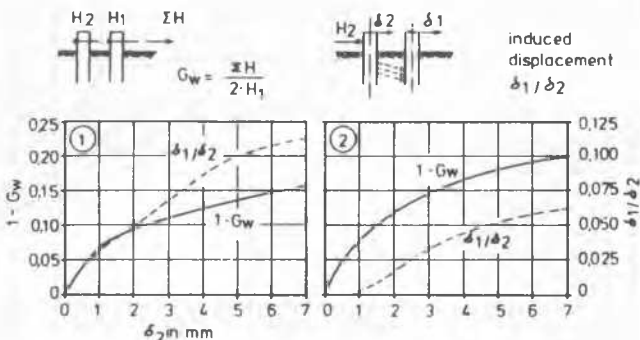


Fig. 10 Relation between group efficiency and ratio of induced displacement

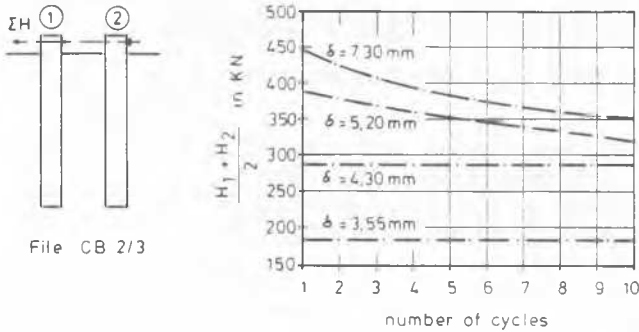


Fig. 11 Results of cyclic load tests run on file CB 2/3

Effect of bentonite slurry

It is often suspected that the bearing behaviour under horizontal loads is deteriorated, if bentonite slurry is used for the pile construction. The test series reported in this paper yielded the opposite result. Using bentonite slurry instead of a casing resulted in an enlarged pile diameter and hence improved the bearing behaviour, and even for piles showing the same diameter (file C compared with file CB, see above), those constructed with a slurry showed improved bearing behaviour under small loads. It is to be supposed that the sand above the ground water table was cemented to a short distance around the pile, and that the bentonite cake might have reacted with the pile concrete.

PILE-SOIL INTERACTION

Pile-soil interaction in a pile file is not yet fully understood. Two simplified models are plotted in fig. 12. As the soil in between the two piles is compressed, whereas the pile distance remains unchanged, a joint will develop around the backside of the front pile in the upper region. Hence, stresses transferred to the soil from the rear pile must be "diverted", resulting in a more intense compression of the soil, thus reducing the modulus of reaction. Shearing resistance along a soil slice between the piles may be supposed to govern the pile-soil interaction. In non-cohesive soils it depends on the lateral pressure, which might vary from earth pressure at rest to passive pressure. Substantially, these models are corroborated by the results of two tests, see fig. 13, showing the displacements of piles situated beside two test files

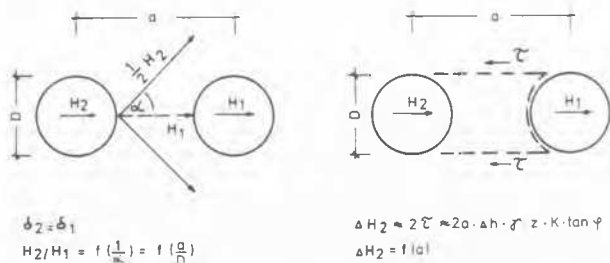


Fig. 12 Simple models for pile-soil interaction in pile files

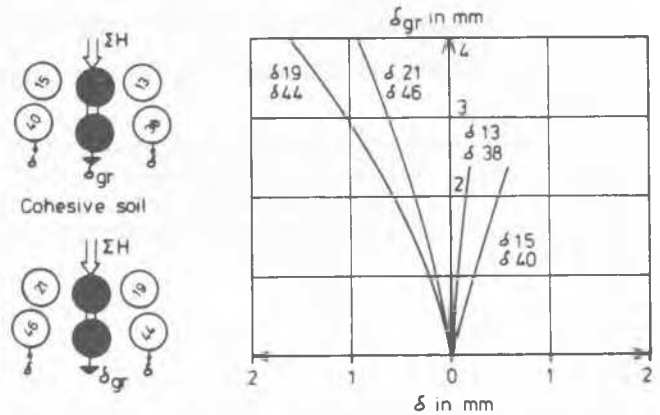


Fig. 13 Displacements of unloaded piles beside a laterally loaded pile file

(see no. 9 in fig. 6). Additional investigations are necessary on this subject, and it is felt that the FE method would be a powerful tool. It may be concluded as well, that pile-soil interaction in groups consisting of a definite number of pile files is more complicated, resulting in a smaller group efficiency than measured on pile files.

CONCLUSIONS

The behaviour of the pile files tested may be characterised as follows: Group action vanished at pile distances equal to or greater than three pile diameters; in pile files with smaller distances, the front pile behaved as a single pile, and group efficiency was governed by the bearing capacity losses of the rear piles, which were equal for each pile in a file; for long piles, bending moments were approximately the same for all the piles of the file, in spite of different load ratios of the front pile and of the rear piles, respectively; bentonite slurry did not deteriorate the horizontal bearing behaviour, and displacements induced in an unloaded, neighbouring pile indicated that group action must be taken into account. Additional investigations on the group action of pile groups that consist of a number of pile files are necessary.

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