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AXIAL CYCLIC LOADING OF SMALL DIAMETER INJECTION PILES IN SAND

ABSTRACT

In a research program at the Institute for Soil Mechanics, Rock Mechanics and Foundation Engineering, Technical University of Munich (Director: Univ.-Prof. Dr.-Ing. R. Floss) ten small diameter injection piles, 5 m in length and 130 mm in diameter, were tested in unsaturated sand in the test pit of the institute. The boreholes were drilled with casing and a continuous flight auger. The concrete was poured and then pressurised to 5 bar. Alltogether, 3 static tests (compression and tension), 9 tests with various alternating (two-way) cyclic loads, and 3 tests with cyclic compression and cyclic tension (one-way) loads up to 200 000 cycles were performed. The results showed that failure depends on the number of cycles as well as on the span of load and can occur suddenly after a large number of cycles. A safety factor appropriate for static loading is likely too low for cyclic loading of small diameter injection piles in sand, especially when many cycles are to be expected. Consequently new safety factors are proposed.

The aim of current research project is to find correlations between laboratory tests (standard and cyclic tests) and the results of the large scale tests. Furthermore, it is to confirm and extend the findings by variation of parameters, such as density and water content.

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NF: using foreign results as benchmark

INTRODUCTION

Cyclic loads on piles can be caused by wind, traffic, ground water variations or waves on offshore structures. The expression "cyclic loading" used in this paper refers to quasi-static loading with no dynamic component. Cyclic loading can be two-way (alternating) as well as one-way (cyclic compression or cyclic tension).

This paper deals with 3 static and 12 cyclic tests on ten injection piles, which were tested in three series. Detailed descriptions of the first series are given by Gruber, Koreck, Schwarz (1985). The tests provide an indication of the behaviour of injection piles in a moist, medium-dense sand under various cyclic loads and show that the required factor of safety for structures under cyclic loading should be significantly higher than for those under static loading.

THE TEST PILES

The piles were executed in a test pit measuring 4 to 5 m wide and 8 m deep (Fig. 1), filled in layers with a fine- to medium-grained tertiary quartz sand, having a moisture content $w = 9.1\ \%$, dry density $\rho_d = 1.58\ \mathrm{t/m^3}$ and an average static cone penetrometer resistance $q_c = 5\ \mathrm{MN/m^2}$. A grain size curve and index properties of the sand are shown in Fig. 2.

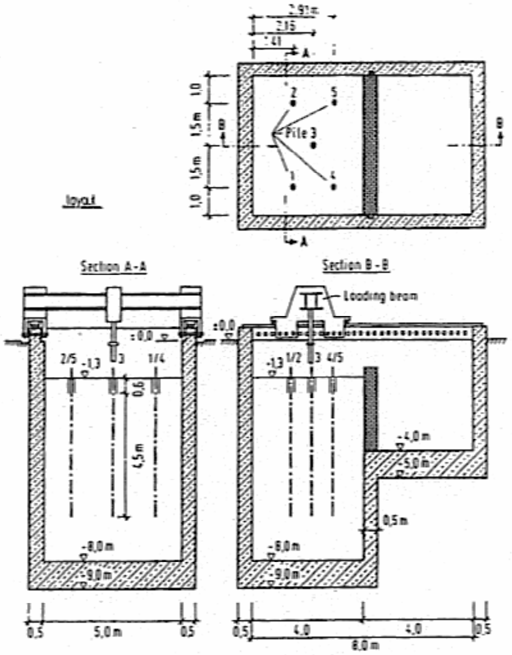


Fig. 1. Test pit and layout of test piles

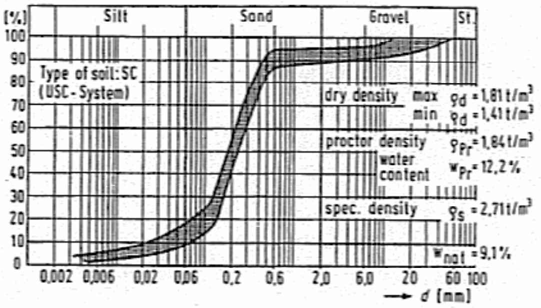


Fig. 2. Grain size distribution and soil parameters

The execution of the test piles was in accordance with German Standard DIN 4128 using a Bauer UBW 05-7 t double head boring machine. This device allows advancement of both the casing and the flight auger independently. The outer diameter of the casing was 108 mm, the diameter of the continuous flight auger 90 mm. After drilling, 50-mm diameter Dywidag steel reinforcement bars were inserted, cement grout poured in, and a pressure of 5 bar applied. In the first series, five piles were constructed and tested. After excavation, the sand was refilled and five additional piles were constructed in the same manner. In the following, the designation "3/1" indicates, for example, the first test on pile 3.

Excavation after the tests revealed that the piles of the first series (piles 1 to 5) and piles 7 and 8 of the second series had a average diameter of 130 mm, while the lower part of piles 9 and 10 had diameters to a maximum of 200 mm. Pile 6 had an expansion of 240 mm at a depth of 4.5 m below the surface.

TEST RESULTS

Static Tests. - To provide reference capacities for the cyclic test results, 3 piles were tested statically (piles 1 and 4 of the first series and pile 6 of the second series). Pile 1 was loaded first by compression, piles 4 and 6 were loaded first by tension in several steps and then unloaded after having reached the test limit load. After a short break, the piles were loaded the other way and again unloaded. The static load-displacement diagram for pile 4 for the first 2 complete tension-compression reversals is shown in Fig. 3.

From the static load-displacement diagrams in the two series, different ultimate loads Q_F for tension and compression have been evaluated according to German Standard DIN 1054 res. to a creep displacement rate of $k_s = 1.0$ mm according to DIN 4125. The ultimate loads were:

for the first series:	1. loading in compression	$Q_{F\ compression}$	= 290 kN
	1. loading in tension	$Q_{F\ tension}$	= 245 kN
for the second series:	1. loading in tension	$Q_{F\ tension}$	= 280 kN

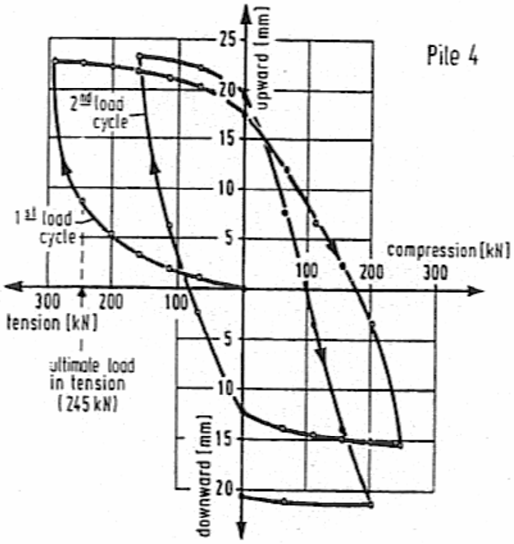


Fig. 3. Static load-displacement diagram for pile 4

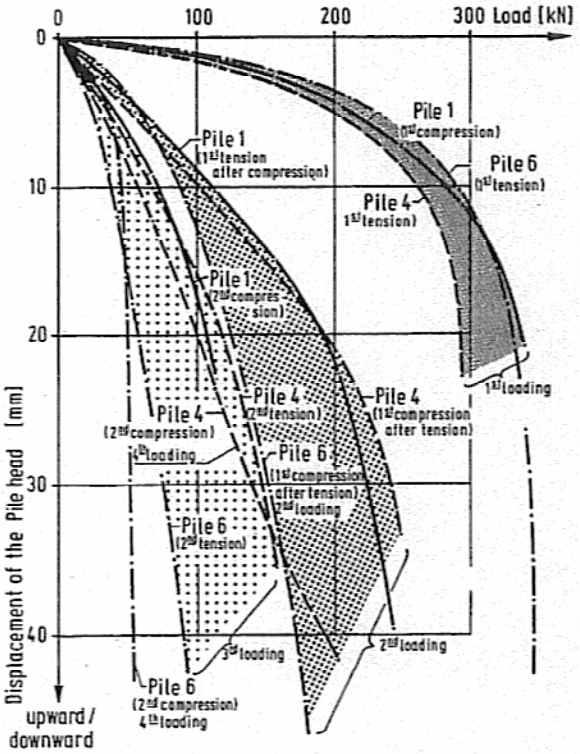


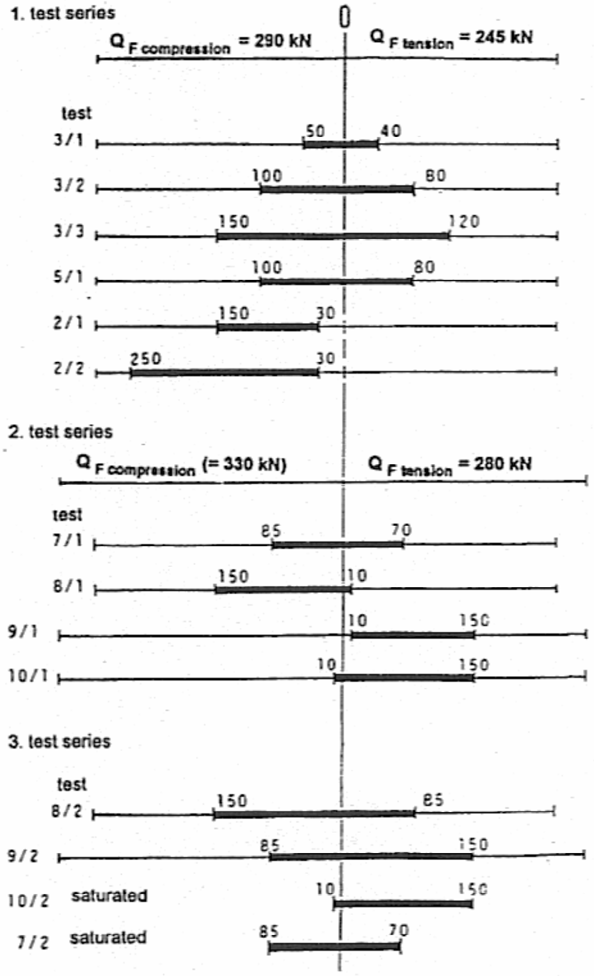
Fig. 4. Summarizing chart of all static tests (Piles 1, 4 and 6)

The tests show that there is relatively little difference in the load-displacement behaviour between tension and compression loading. In comparison with this effect, the decrease of the ultimate load capacity during the first three static load reversals was more significant (Fig. 4).

Cyclic Tests. - During the cyclic tests, all piles were loaded sinusoidal, starting with twenty 20-minute cycles, continuing with 1-minute cycles up to 100 000 cycles, and then continuing with 30-second cycles up to 200 000 cycles or until failure of the pile. The load was applied by a computer-controlled servo-hydraulic system, which included a 500 kN-load cell. The displacement of the pile top as well as the movement of five points on the soil surface were measured with dial gauges and displacement transducers. All data were simultaneously printed and plotted as well as stored for later evaluation.

The cyclic tests were carried out with various load spans, which included alternating (two-way) as well as one-way cyclic compression and tension loads. In Fig. 5 the load span (peak-to-peak) for all cyclic tests is shown together with the maximum number of cycles. The load span is also shown in percentage of the reference load Q_{ref}, which was defined as twice the ultimate tension capacity of the static tests: $Q_{ref} = 2 * Q_{F\ tension}$. Thus load spans of more than 100% in two-way loading are excluded.

The 6 cyclic tests of the first series were performed with load spans ranging between 18 and 55 percent of Q_{ref}. Two of these tests ended with failure, which was defined as a displacement of more than 10 mm. The others were terminated at 100 000 cycles.



Q_F	Q_{ref}	span of load		max. number of cycles	max. displacement	remarks
kN	kN	kN	%	max. N	mm	
245	490	90	18	12.017	0,24	
245	490	180	37	17.059	0,8	
245	490	270	55	24.059	10	failure
245	490	180	37	60.815	10	failure
245	490	120	24	100.017	2,82	
245	490	220	45	50.031	7,24	
245	490	155	32	208.160	2,03	
245	490	160	33	201.600	4,91	
280	560	140	25	203.534	4,5	
280	560	160	29	200.300	5,12	
245	490	235	48	148.180	10	failure
280	560	235	42	84.168	10	failure
		160		58	10	failure
		155		3	>80	failure

Fig. 5. Loading conditions for all cyclic tests, summarizing Q_F, Q_{ref}, span of load and number of cycles

In contrast with these tests, the first 4 tests (7/1, 8/1, 9/1 and 10/1) of the second series were carried out with a constant load span, equal to about 30 percent of Q_{ref}. These tests show the behaviour of piles under two-way cyclic loading as well as under one-way cyclic compression and tension loading. These tests were stopped after 200 000 cycles without failure. Two of these piles were loaded again with a cyclic load spans of 48 and 42 percent of Q_{ref} (tests 8/2 and 9/2) until failure occurred.

The displacement envelopes observed in tests 3/3, 5/1 and 7/1 with two-way cyclic loads are shown in Fig. 6 as a function of the number of cycles. Under a load span of 55 percent of Q_{ref} (test 3/3), failure occurred suddenly after 24 059 cycles. Fig. 7 shows the sudden end of test 3/3 in detail. Under a load span of 37 percent (test 5/1) failure occurred after 60 815 cycles. In contrast, under a load span of 32 percent of Q_{ref} (test 7/1) the total displacement after 200 000 cycles was 2.03 mm with a cyclic displacement during the last cycle of 1.50 mm.

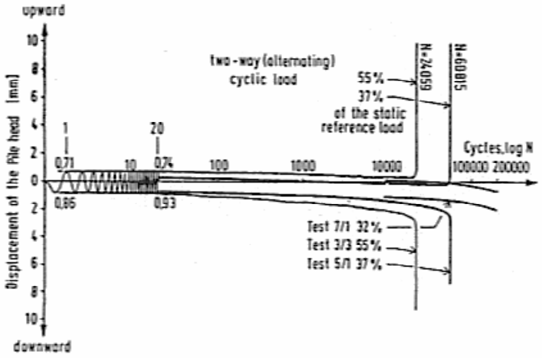


Fig. 6. Displacement envelopes observed in tests 3/3, 5/1 and 7/1

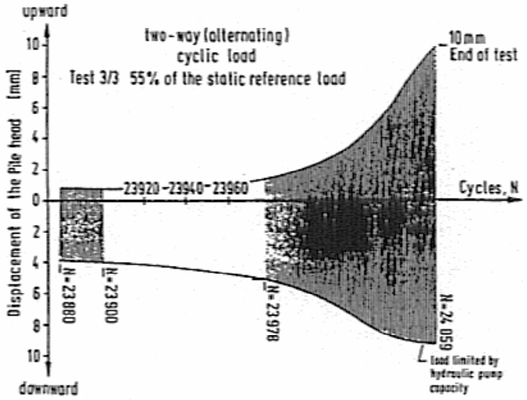
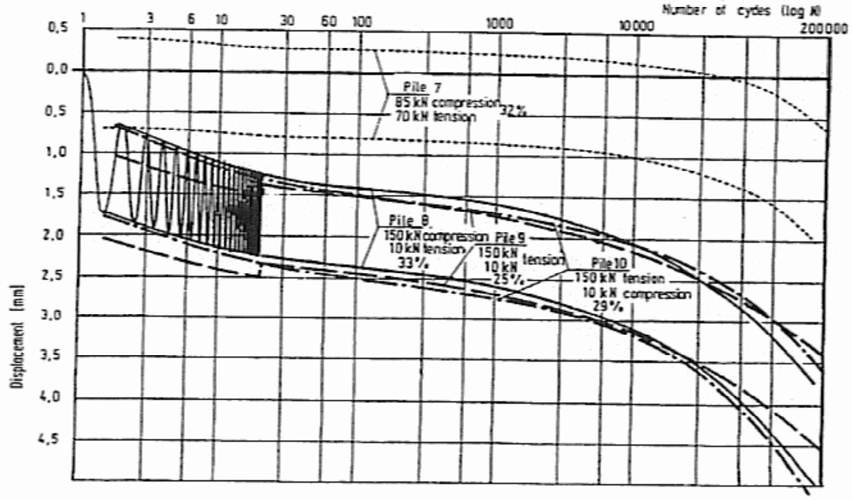


Fig. 7. End of test 3/3 in detail

Between cycles 120 000 and 200 000, the total displacement increased gradually from 1.58 mm to 2.03 mm, and the displacement per cycle increased from 1.36 mm to 1.50 mm.

The results of tests 8/1, 9/1 and 10/1, with load spans of 29 to 33 percent of Q_{ref} are shown in Fig. 8 in unidirected plotting. At this level of loading, there is no significant difference for one-way cyclic loading in tension and compression. The displacement envelopes are also similar to the two-way test 7/1 and show a gradually, non-log-linear displacement. The tests 8/2 and 9/2 were carried out with load spans of 42 and 48 percent of Q_{ref}. Failure occurred at 84 164 cycles for test 9/2 and at 148 281 cycles for test 8/2 after steadily increasing total displacement and displacement per cycle.



After the third series the test pit was filled with water and two additional tests were started under saturated conditions (Fig. 6). Failure of the piles 10/2 and 7/2 occurred already after 3 res. 58 numbers of cycles. The previous loadings as well as the saturated conditions may have caused the sudden failure.

CONCLUSIONS

The tests show that in a medium-dense, slightly silty sand at a water content below the optimum value, the bearing capacity of small diameter injection piles under two-way cyclic loads as well as under one-way cyclic tension or compression loads can decrease significantly in relation to bearing capacity under static loads. The capacity depends on the number of cycles as well as on the load span, i. e. the lower the load span, the higher the number of attainable cycles. Failure can occur both suddenly after a large number of cycles as well as gradually by increasing displacements.

From the curves of the rate of displacement vs. number of cycles in a log/log scaled chart (Fig. 9) up to 10.000 cycles no clear prognosis can be given at an early stage. Only after about 10.000 cycles different tendencies of the rate of displacement curves are evident and may be used for prediction of pile behaviour, as it is sometimes done in analogy to creep behavior.

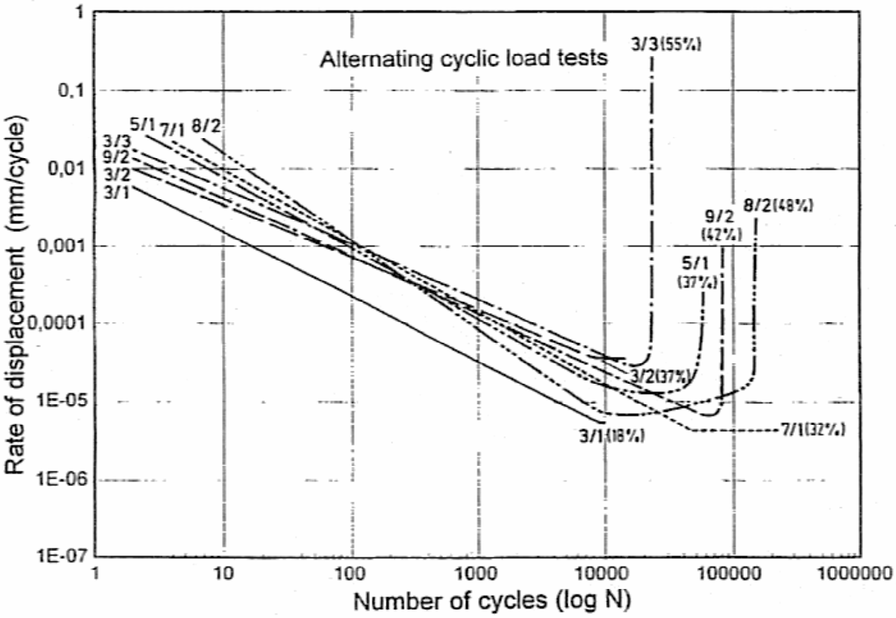


Fig. 9. Rate of displacement of alternating load tests

Normally it is not possible to simulate the actual pile behaviour since it is generally inpractical to apply the necessary number of cycles. A small number of cycles may lead to unsafe conclusions, as the extended cyclic tests reported here have shown. Therefore, until additional results (for example, more tests in dense sand or in other soils) are available, the following recommendations are proposed for small diameter injection piles in moist, medium-dense sand.

Depending on the expected number of cycles, the peak-to-peak cyclic load span shall not exceed the following values related to the allowable static design load Q_D:

Expected number of cycles	Allowable peak-to-peak cyclic load span
1	1.0 Q_D
100	0.8 Q_D
10 000	0.68 Q_D
100 000	0.56 Q_D
1 000 000 and more	0.40 Q_D

FURTHER INVESTIGATIONS

The aim of a current research project is to extend the knowledge of the behaviour of the used soil, the pile-soil interaction and the mechanisms which cause failure during cyclic loading. A wide range of the soil parameters water content and density is covered by laboratory tests such as direct shear tests, cyclic direct shear tests and triaxial shear tests. A model pile, which shall be tested in a small scale testing set-up is built with intent to confirm the findings of the large scale tests and also to extend the findings by variation of parameters. It is hoped that a more comprehensive formulation of design guidelines will be possible.

ACKNOWLEDGEMENTS

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REFERENCES

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