Behaviour of Pile Foundations Submitted to Lateral Loads

Le Comportement des Fondations sur Pieux Soumises aux Charges Transversaux

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SYNOPSIS. Investigations carried out in connection with the foundation of some quay walls in Romanian harbours on the left bank of Danube river, have included also a program of field tests on single piles and pile foundations. The paper presents the results of tests on reinforced concrete, 16 m long, noninstrumented, driven piles, loaded individually or in groups of 2 or 3 vertical or batter piles.

INTRODUCTION

The behaviour of pile groups submitted to lateral loads has been the object of many publications. Most authors concentrated on the analytical side of the matter. Experimental checks have been fewer and, in most cases, on small scale.

In order to obtain design data for quay walls in Romanian harbours on the left bank of the Danube river, feild tests have been carried out on individual piles and on group of piles.

SOIL CONDITIONS ON THE SITE

Several 8½" borings on the site have shown the presence of recent alluvium deposits, as follows: 1: sandy silts, silty and clayey silts; 2: silty clays and clayey silts, stiff on the upper part of the layer, with lower consistency on the bottom; porosities are around 50%, natural moisture content 45%; 3: a thin layer of peat; 4: fine sands and fine silty sands; 5: a new thin layer of peat; 6: sandy and clayey silts of low consistency; 7: medium sands and sands with gravel.

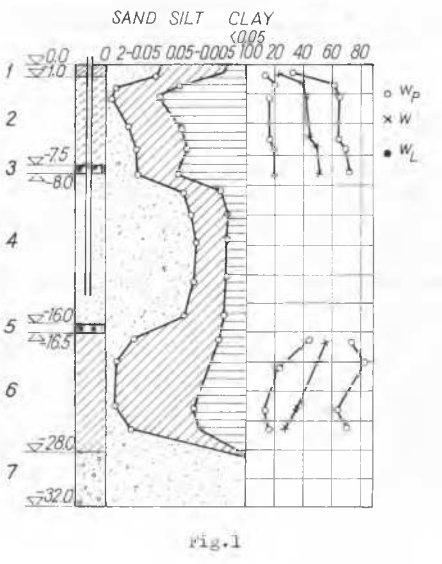

Fig.1

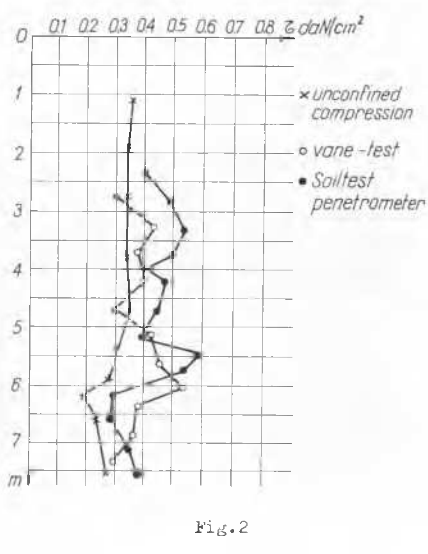

Fig.2

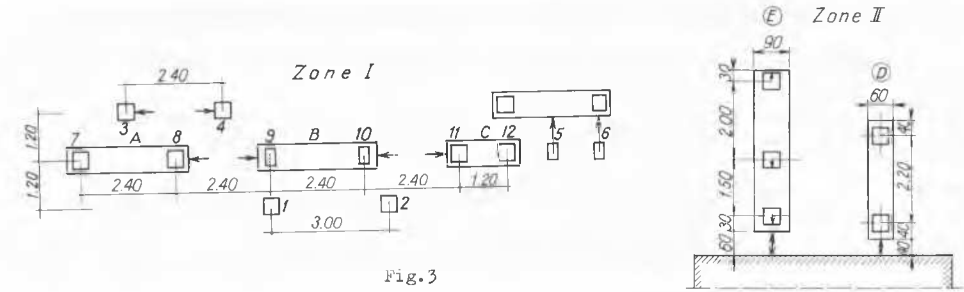

Fig.3

Fig.1 shows a soil profile, together with the variation with depth of the grain size, of Atterberg limits and of the natural moisture content. Fig.2 shows the variation with depth of the undrained cohesion of the layer 2, obtained by means of field vane tests and by unconfined compression and by a Soiltest pocket penetrometer in the laboratory.

TEST PROGRAM AND RESULTS

Test piles have been located in two zones (fig.3). In zone I have been tested single piles 1...6 and groups of vertical piles A, B,C; in zone II, groups of batter piles D and E. Precast driven noninstrumented piles, reinforced with 8 bars of 25 mm diameter and 3,800 daN/sqcm. yield limit steel, have been tested. Young modulus of the reinforced concrete was 250,000 daN/sqcm. Length of the piles was 17.0 m, embedment length 16.0 m. All piles have been square, 40 cm side, except piles No.5,6,9,10 which have been rectangular 35x45 cm.

All piles have been tested to lateral loads, except piles 1 and 2 tested to axial load. Both axial and lateral loads were applied by hydraulic jacks. Displacements have been recorded by dial gages, with 0.01 mm precision. Displacements x in horizontal direction and settlements , y, in 6 points (3 sections) have been recorded for the groups of piles, thus indicating the behaviour of the pile cap as an absolute rigid element and allowing the computation of the cap rotation.

Details of the pile groups are given in fig. 4 and 6. The results of the tests are summarized in tab.1 to 5.

COMMENTS ON THE TESTS RESULTS

In tab.6 are given some significant results. In order to compare single piles with piles from various groups, values of the lateral loads for a 10 mm deflection were established from the load-deflection diagram; dividing them to the number of piles in the group, a

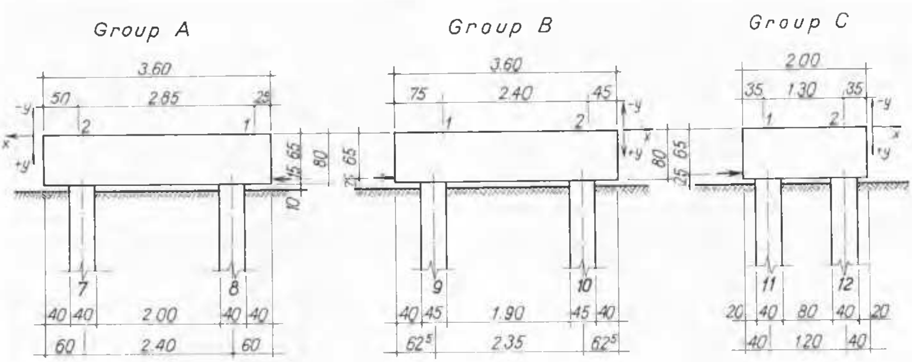

Fig.4

"transverse stiffness" of the pile, single or in group, was defined. Fig.6 shows the diagram"load per pile-deflection" for single piles and piles from various groups. As expected, the results show the favorable effect of the pile cap and of the batter on the bearing capacity of the piles in group. Larger deflections for equal loads exhibited by the group C, having an inter-axis distance between piles of 3d (d=pile width), compared to those of the group A, having 6d inter-axis, is seen as an expression of the "group effect" for transverse loads. Data given in tab.1 to 5 as well as the diagrams in fig.6 show the nonlinear character of the load-deflection relationship.

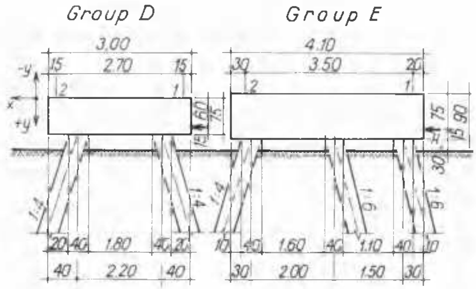

Fig.5

Tab.1

P, kN	Pile 1 y, mm	Pile 2 y, mm
200	0,58	0,44
300	0,99	0,69
400	1,47	0,92
500	2,18	1,24
600	3,15	1,72
700	4,30	2,34
800	6,35	3,13
900	12,47	3,88
950	44,44	-
1000	-	6,59
1050	-	10,46
1100	-	33,52
1000	-	33,70
900	44,50	-
800	44,52	33,76
600	44,13	32,53
400	43,40	32,83
200	42,27	31,80
0	40,16	29,84

Tab.2

H, kN	Pile 3		Pile 4	
	x, mm	$\theta.10^{-3}$	x, mm	$\theta.10^{-3}$
20	1,19	1,129	1,57	1,129
40	4,53	3,386	6,07	3,514
60	11,30	6,786	14,32	7,586
70	13,49	7,129	16,71	8,629
80	18,52	9,714	22,90	11,686
90	32,52	15,086	43,72	21,400
70	31,07	13,829	40,92	21,186
50	28,91	12,543	38,49	18,429
30	22,67	9,443	31,11	14,686
0	10,96	4,514	15,71	7,814

Tab.3

H, kN	Pile 5 x, mm	Pile 6 x, mm
20	2,32	1,11
40	5,61	3,10
60	9,63	6,54
80	17,24	10,95
100	30,06	18,35
120	-	27,44

Tab.4

H kN	Group A			Group B			Group C		
	x, mm	y_1 mm	y_2, mm	x, mm	y_1, mm	y_2, mm	x, mm	y_1, mm	y_2, mm
40	0,57	-0,05	0,04	0,55	-0,07	-0,02	1,15	-0,09	0
80	1,71	-0,13	0,10	1,47	-0,15	-0,05	2,45	-0,26	-0,09
120	3,55	-0,25	0,14	2,89	-0,36	-0,06	7,47	-0,52	-0,12
140	4,42	-0,33	0,28	3,54	-0,39	-0,06	12,21	-0,77	-0,14
160	-	-	-	-	-	-	17,26	-0,97	-0,16
180	6,78	-0,63	0,42	6,24	-0,52	-0,02	-	-	-
200	11,57	-0,84	0,42	7,71	-0,64	-0,05	-	-	-
220	15,55	-1,09	0,60	9,88	-0,70	-0,12	-	-	-
240	19,70	-1,29	0,63	12,17	-0,89	-0,22	-	-	-
260	23,19	-1,50	0,89	13,89	-0,96	-0,24	-	-	-
220	23,18	-1,50	-	13,86	-0,94	-0,24	-	-	-
160	22,43	-1,38	-	12,95	-0,86	-0,19	-	-	-
120	20,54	-1,14	-	11,32	-0,71	-0,14	16,85	-0,91	-0,14
80	17,87	-0,89	-	9,28	-0,55	-0,08	14,72	-0,65	-0,04
40	15,00	-0,62	-	7,24	-0,38	-0,06	10,96	-0,30	+0,12
0	10,82	-0,24	-	4,31	-0,24	-0,02	6,10	-0,02	+0,25

Tab.5

H, kN	Group D x, mm	Group D y_1, mm	Group D y_2, mm	Group E x, mm	Group E y_1, mm	Group E y_2, mm
40	0,22	-0,02	0,05	0,25	0,08	0
80	0,58	-0,17	0,19	0,56	0,17	0,02
120	1,20	-0,30	0,41	1,02	0,14	0,05
160	2,25	-0,60	0,76	1,70	-0,06	0,21
200	3,86	-0,85	1,45	2,56	-0,25	0,39
240	7,20	-1,25	3,07	3,68	-0,41	0,60
260	10,19	-2,17	4,41	-	-	-
280	15,34	-3,19	5,39	5,60	-0,43	0,84
300	21.02	-4,27	7,32	-	-	-
320	25,67	-4,32	10,13	9,62	-1,00	2,00
280	25,68	-4,63	10,12			
240	25,31	-4,62	10,10			
200	25,07	-4,68	10,06			
160	23,81	-4,57	9,77			
120	22,60	-4,37	9,40			
80	21,11	-4,13	8,85			
40	18,55	-3,69	8,00			
0	13,84	-3,50	6,47			

A thorough presentation of the results of the analytical checks of the results of field tests on pile groups is beyond the scope of this paper. However, some observations can be made on the computations performed which have taken into account the pile-soil interaction, considering piles as fixed in a rigid cap and embedded in a Winkler-type soil, characterized by a modulus of subgrade reaction varying linearly with depth $K_h = n_h \cdot z$. For various pile groups, values of n_h leading to a computed deflection equal to the measured one, for each load, have been sought. Diagrams n_h function of x, in good agreement to the ones given elsewhere (Manoliu, 1975) have been obtained. Thus, for a 10 mm deflection, n_h values were of order of 0.6...0.7 daN/cu.cm for groups A,B,D,E, with widely spaced piles and 0.3 daN/cu.cm for group C with closely spaced piles. For 5 mm deflection, n_h values were in the range of 0.8... 1.2 daN/cu.cm. Thus, it appears that by an appropriate selection of the parameter n_h in function of the deflection, a non-linear load-deflection relationship could be predicted analytically, at least in the domain of deflections up to 10 mm, considered as being tolerable for the structure.

Tab.6

Loaded element		Pile characteristics		No.of piles	H_{max}, kN	x_{max}, mm	H for x=10 mm	H for 1 pile
Single piles		40x40		1	90	32,5-43,7	49...56	49...56
		35x45		1	100-120	30,0-27,4	61...76	61...76
Groups of vertical piles	A	40x40, d=2,40		2	260	23,2	188	94
	B	35x45, d=2,40		2	260	13,9	203	102
	C	40x40, d=1,20		2	160	17,3	131	66
Groups of batter piles	D	40x40	1 batter -4:1 / 1 batter +4:1	2	320	25,7	258	129
	E	40x40	1 batter -4:1 / 2 batter +6:1	3	320	9,6	320	108

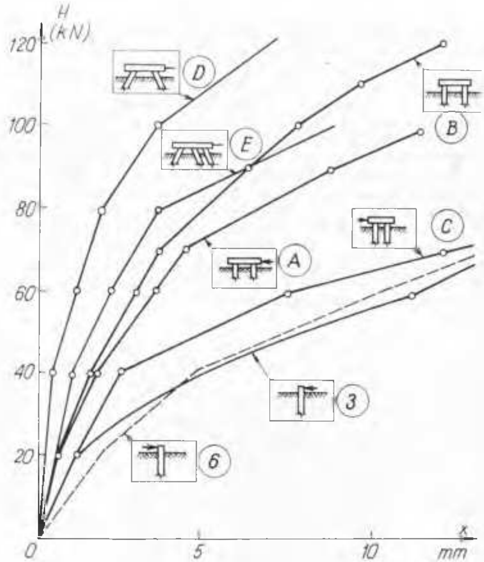

Fig.6

CONCLUSIONS

Field tests on 5 pile groups have furnished interesting data on the behaviour of pile foundations submitted to lateral loads. Usual methods for the analysis of pile groups, as for instance those which consider the soil as a Winkler-type medium, can lead to results in good agreement with experiments, provided appropriate parameters of the pile-soil interaction are accounted for.

REFERENCES

Manoliu, I. (1975) "Lateral Bearing Capacity of Precast Driven Piles". Proceedings of the VI-th European Conference on Soil Mechanics and Foundation Engineering, Vol.2, Vienna, 1975, p.515-518.