PERFORMANCE OF GROUPS OF CAST-IN PLACE PILES SUBJECT TO HORIZONTAL LOADING

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Together with vertical loads, significant horizontal loads are also transmitted to the foundations of a majority of industrial buildings and structures. At the present time, however, these loads are analyzed separately in design, and their interaction is virtually disregarded in connection with the fact that the problem concerning the performance of pile groups with caps subject to the combined action of vertical and horizontal loads is not well understood. We conducted studies, therefore, to:

1) study the performance of a low-profile pile-foundation cap subject to the action of horizontal loads and its effect on the bearing capacity;

2) ascertain what effect a vertical load would have on the bearing capacity of horizontally loaded pile foundations.

The studies were conducted on an experimental proving ground located at one of the construction sites of the Karaganda Metallurgical Combine.

To establish the geologic–engineering profile and determine the physicomechanical properties of the soils of the experimental site prior to the start of testing, we drilled holes 11 m deep from which soil monoliths were removed every 1 m beginning at a depth of 0.5 m.

The physicomechanical characteristics obtained for the soils at the site are presented in Table 1. We prepared eight pile groups for testing: two with high-, and six with low-profile caps. Cast-in-place piles with shaft diameters of 600 mm and embedment depths of 3 m were employed in the foundations. The piles were reinforced with three-dimensional cages of circular cross section with four effective Class A-II steel rods 18 mm in diameter. The caps were formed from monolithic concrete and reinforced with a mesh. Grade 200 concrete was used for the piles and caps. The piles within the group were spaced 3d on centers (d is the pile diameter); with four piles in a group, therefore, the cap took on dimensions of 2800 × 2800 mm. To provide for rigid attachment of the heads, the height of the cap was set equal to 500 mm, while the clearance between the ground and the high-profile cap was 400 mm. To compare the performance of piles standing individually and in a group, we fabricated and tested solitary cast-in-place piles with the same dimensions at the same testing ground.

The method of testing pile groups under the combined action of vertical and horizontal loads required that a constant vertical load and a horizontal load that increases in steps be transmitted to the foundation. A force-application scheme, which provides for a centrally applied vertical load and the free movement of the pile group with a horizontal load acting on the cap, was adopted in this case. The vertical load was applied using metallic slabs weighing 60-90 kN and was set equal to 0.25, 0.5, 0.75, and 1 P_{des}. The design load P_{des} for the given soil conditions amounted to 800 kN.

The horizontal load was applied to the low-profile pile caps using a hydraulic DG-100 type jack and braces, while a special support beam, which ensured the central application of the horizontal force on the geometric axis of the cap, was used in testing the high-profile caps. To reduce the frictional forces that develop along the lower surface of the support beam, the latter was mounted on two wooden strips. After conditional stabilization of the settlement due to the vertical load, the pile foundation was subjected to a horizontal load that was increased in steps of 100 kN.

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TABLE 1

Indicator	Brown clays of Quaternary deposit	Grayish-green clays of Neogenic deposit
Layer thickness, mm	1.4	9.6
Volumetric mass γ, g/cm^3	1.84	2.02
Natural moisture content W	0.29	0.26
Plasticity index W_p	0.33	0.39
Void ratio ε_0	0.92	0.89
Consistency index B	0.1	0
Angle of internal friction φ, deg	7	12
Unit cohesion c, MPa	0.085	0.093

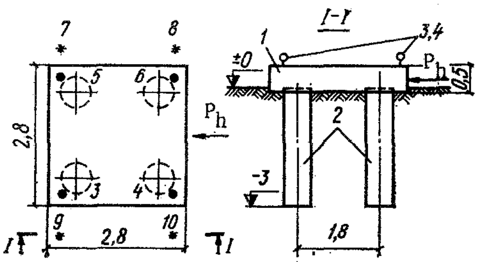


Fig. 1

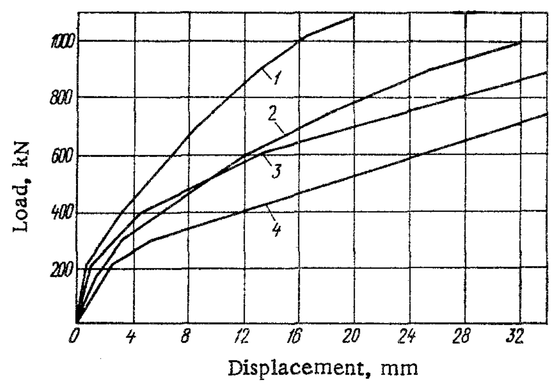


Fig. 2

Fig. 1. Diagrams showing installation of instruments for testing of pile group with low-profile cap. 1) Cap of pile foundation; 2) cast-in-place piles; 3-6) clock-type indicators; 7-10) Maksimov deflectometers.

Fig. 2. Curves showing dependence of horizontal displacement of pile groups due to horizontal, and the combined action of vertical and horizontal loads. 1) Group of four piles with low-profile cap, $P_v = P_{des}$; 2) with high-profile cap, $P_v = P_{des}$; 3) with low-profile cap, $P_v = 0$; 4) with high-profile cap, $P_v = 0$.

The vertical deformations of the cap due to the action of the vertical and horizontal loads were measured by clock-type indicators. Horizontal displacements were recorded by Maksimov deflectometers, mounted at the level of force application. Schematic diagrams of the testing and instrumentation are presented in Fig. 1.

For each load increment, the horizontal displacements of the cap were brought to its "conditional" stabilization, which is characterized by displacements of 0.1 mm during the last 2 h of the observation. A cap displacement of 10 mm at the level of force application was adopted as a criterion indicating the ability of pile groups to resist horizontal loading.

Data on cap displacement and the duration of loading for each increment are presented in Table 2, from which it is apparent that the increase in the deformations of the No. 1 cap are significant for each horizontal-load increment. With cap deformations exceeding 15-20 mm, the rate of its displacements and the time required for conditional stabilization increase significantly.

The results of static tests are presented in Fig. 2 from which it is apparent that a pile foundation with a low-profile cap possesses a significantly greater bearing capacity than one with a cap raised above the ground. This was observed both with the pile group subjected to a horizontal load only (curves 3 and 4 in Fig. 2), and to the combined action of a vertical and horizontal loading (curves 1 and 2 in Fig. 2); this demonstrates the need to consider resting the pile cap on the ground when designing a foundation for a horizontal loading.

TABLE 2

Increment No.	Horizontal load, kN	Pile group No. 1 with $P_v = 0$			Pile group No. 2 with $P_v = P_{des}$		
		horizontal cap displacements, mm	inc. in displacements for increment, mm	increment duration, h	horizontal cap displacements, mm	inc. in displacements for increment, mm	increment duration, h
1	100	0,60	0,60	4	0,30	0,30	4
2	200	1,45	0,85	4	0,85	0,55	4
3	300	3,50	2,05	4,5	1,75	0,90	4,5
4	400	7,35	3,85	7	3,60	1,85	7
5	500	11,40	4,05	10	5,50	1,90	8
6	550	12,80	—	10	6,15	—	8
7	600	16,60	5,55	14	7,71	2,71	14
8	650	23,80	—	23	10,22	—	19
9	700	32,40	15,80	26	12,27	4,56	20
10	750	40,13	—	22	14,54	—	21
11	800	64,53	32,13	24	17,52	5,25	24

TABLE 3

Increment No.	Horizontal load P_h, kN	Cap displacements at points, mm							
		pile group No. 1 with $P_v = 0$				pile group No. 2 with $P_v = P_{des}$			
		horizontal		vertical		horizontal		vertical	
		A	B	A	B	C	D	C	D
1	100	0,60	0,40	+1,16	−0,67	0,30	0,75	+0,17	−0,32
2	200	1,45	0,80	+2,23	−0,72	0,85	1,50	+0,31	−1,03
3	300	3,50	2,50	+3,67	−1,07	1,75	2,40	+0,54	−1,42
4	400	7,35	6,50	+5,75	−1,42	3,60	3,60	+1,02	−2,07
5	500	10,05	8,70	+8,04	−1,46	5,00	5,19	+1,39	−3,25
6	550	12,80	11,15	+8,59	−1,60	6,15	6,30	+1,70	−3,97
7	600	16,60	15,10	+10,90	−2,18	7,71	8,15	+1,97	−4,91
8	650	23,80	23,00	+17,49	−3,30	10,22	10,10	+2,02	−6,73
9	700	32,40	30,20	+23,31	−4,19	12,27	12,17	+2,17	−7,29
10	750	40,13	40,29	+27,96	−4,29	14,54	14,69	+2,99	−8,32
11	800	64,53	54,35	+38,48	−5,15	17,52	17,89	+4,15	−10,37

Note. The minus sign refers to cap settlement, while the plus sign implies its uplift.

To determine the performance of the horizontally loaded pile groups, we measured the horizontal and vertical cap displacements during their testing; the results of these measurements are listed in Table 3.

The displacements of points A and B of the No. 1 cap on which the horizontal loading acts, and the displacements of points C and D of the No. 2 cap subjected to the combined action of a vertical and horizontal load were constructed according to the data in Table 3 (Fig. 3a and b). The center of cap rotation (CR) was found on the basis of a geometric construction, while the pile displacements for the loads under consideration were given, proceeding from the conditions of absolute pile rigidity and their embedment in the cap.

It is apparent from Fig. 3a that with only a horizontal force acting on the foundation, the CR is located near the inside face of the outer row of piles. This position of the CR indicates that foundation stability is lost as a result of overcoming the pull-out resistance offered by the piles located on the side where the horizontal force is applied. In this case, the inner-row piles receive the pull-out and horizontal loads, and the outer-row piles exhibit negligible vertical displacements and come under horizontal forces only.

The significant uplift of the cap (A, Fig. 3) controls the small contact area between it and the ground. The area of the cap to the right of the geometric axis of the outer row of piles is virtually alone in this endeavor, since the center of rotation of the cap itself does not fall outside this axis. This is also confirmed by the readings of instruments installed along the lower surface of the cap.

Considering the performance of a pile foundation subjected to vertical and horizontal loads, we developed similar geometric constructions, and determined the CR of a foundation, which is situated at the level of the lower surface of the piles and is displaced from the geometric axis of the foundation toward the inner row of piles. In this case, the piles in

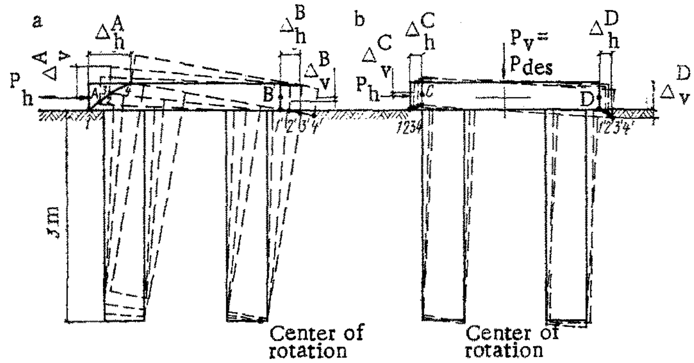
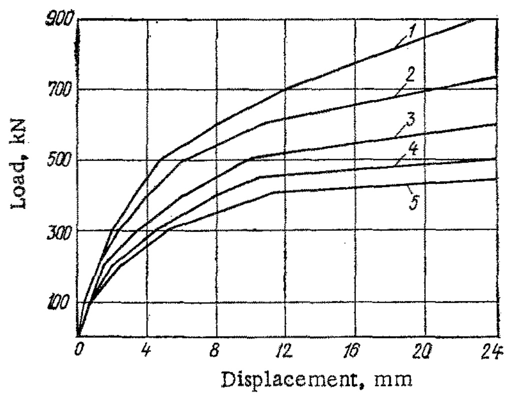


Fig. 3. Displacements of pile group. a) Subjected to horizontal load; b) subjected to combined action of vertical and horizontal loads. 1, 2, 3, 4 (1', 2', 3', 4') are points showing position of cap under horizontal loads of 0, 600, 700, and 800 kN, respectively Δ_h and Δ_v) are, respectively, horizontal and vertical cap displacements at corresponding points.



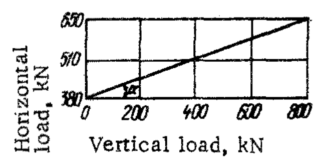


Fig. 4 Fig. 5

Fig. 4. Curves of relationship between pile-foundation displacements and horizontal load for different vertical forces. 1, 2, 3, 4, 5) Vertical load of 800, 600, 400, 200, and 0 kN, respectively.

Fig. 5. Dependence of bearing capacity of horizontally loaded foundation on vertical force.

the inner row exhibit a negligible uplift as a result of the fact that a portion of the pull-out forces exerted on this row of piles is compensated by the vertical loading. At the same time, the piles in the outer row, besides the horizontal load, receive additional compressive forces (due to the vertical load); this is characterized by the significant settlement of the cap at point D. Thus, the increase in the ability of the No. 2 pile group to resist the horizontal load when subjected to a combined loading action is explained primarily by the development of frictional forces along the lower surface of the slab of the cap and by the character of the performance of the piles in the group.

After completion of the static tests, the No. 1 pile group was unearthed and examined; in this case, we observed the displacement and uplift of the front piles, which are characterized by the presence of a gap between the pile shaft and the soil both along its leading edge, and also beneath its base.

The vertical-load effect is one of the important factors influencing the horizontal supporting capacity of pile foundations. Figure 4 presents diagrams of the horizontal displacement of a pile group subjected to various vertical and horizontal loads, while Fig. 5

shows a diagram of the relationship between vertical loads and the bearing capacity of a horizontally loaded pile foundation with a low-profile cap.

The results of tests conducted on pile groups subjected to a combination of loads suggest that the vertical load exerts a significant effect on the bearing capacity of horizontally loaded pile foundations. With a vertical load equal to the design load, for example, the ability of pile foundations to resist horizontal loadings increases by a factor of 1.5-1.7.

The ability of a pile foundation to support a horizontal load P_h with consideration given to the effect of vertical forces can be determined from the equation

$$P_h = P_h^0 \left(1 + \alpha \frac{P_v^a}{P_v^d}\right),$$

where P_h^o is the ability of the pile foundation to support a horizontal load with consideration given to the effect of vertical forces, p_v^a is the actual vertical force acting on the foundation, P_v^d is the vertical design load determined in accordance with the Construction Norms and Specifications, and α is a coefficient equal to 0.70 for rigid piles.

The equation can be used to determine the ability of a pile foundation to resist horizontal loads in clayey soils of hard and semihard consistency.

COLUMN FOUNDATIONS IN TAMPED PITS FOR AGRICULTURAL STRUCTURES SUPPORTED BY BENTS

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In recent years, buildings with frames consisting of three-hinge wooden and reinforced-concrete bents have come into widespread use in agricultural construction. Large horizontal loads (up to 250 kN with bays of 18-24 m), which are commensurate with the vertical loads, are transmitted onto the foundations of these buildings. The resultant inclines at an angle of 30-40°. Because the methodology employed to design foundations subject to inclined loads is not well developed, significant overexpenditure for materials is permitted in foundation design and construction. In this case, the labor cost incurred in site development and substructure installation amounts to 30% of the overall labor outlays for the building. Similar cases have also been reported in foreign practice.

Considering that column foundations placed in tamped pits come under considerable loads [1], the Scientific Research Institute of Foundations and Underground Structures (NIIosnovanii) has recommended that these foundations be used in soils prone to slump-type settlement for buildings with supporting structures consisting of three-hinge bents. Use of these foundations has been limited, however, due to the insufficiency of available data on experimental studies. In this connection, the NIIosnovanii in cooperation with the Ministry of Agricultural Construction of the Moldavian SSR investigated the bearing capacity of foundations in tamped pits under the combined action of vertical and horizontal loads at the construction site of a pig-fattening complex in the small village of Bul'boki, Moldavian SSR in 1974.

The experimental site was built up with Quaternary deposits of alluvial origin. Loess-like clayey soils of hard consistency, which exhibit slump-type-settlement properties are referred to type I soil conditions with respect to this kind of settlement, underlie a 0.4-

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Scientific-Research Institute of Foundations and Underground Structures Ministry of Agricultural Construction of the Moldavian SSR. Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 3, pp. 11-13, May-June, 1976.