Interaction of Foundations and Foundation Soil

Interaction d'une Fondation avec Sous-Sol

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SYNOPSIS Bored piles situated in a row or in a group influence one another, their load-bearing capacity increasing or decreasing in accordance with their spacing in plan or arrangement. A method of calculation of the load-bearing capacity of a group of piles was deduced according to which the load-bearing capacity of a pile group usually varies between 70% and 150% of the sum of the load-bearing capacities of the individual piles considered separately. The calculation was in good accordance with test results.

In model tests the interaction of a group of piles subjected to vertical centric and excentric loads and to horizontal loads was investigated by means of photoelasticimetry, and the isostatic and the isoclinic lines in the subbase of the pile group were determined.

In shallow foundations the influence of the rigidity of the structure, its foundation and the compressibility of the foundation soil expressed by the compressibility coefficient on the distribution of the contact stresses, on the relative deflection of the foundation and the effect of the maximum bending moment were investigated.

The load-bearing capacity of a group of piles may be higher or lower than the sum of the load-bearing capacities of the individual piles; this has been proved by model tests as well as actual measurements in the field. The piles influence one another in accordance with their mutual distance; this influence may be positive or negative and may be calculated.

When the ultimate load of the pile is exceeded, sliding surfaces originate below the pile which pass about the pile at a distance of x and the soil is pressed along the sliding surface upwards. The distance of the sliding surface x from the pile axis was determineed experimentally in dependence on the angle of friction of the soil Ø and is shown in Table 1 below.

Table 1. The radius x of the Influence Zone and Values

Ø		0^o	10^o	20^o	30^o	35^o
x/B		1.5	2.7	3.7	4.5	4.8
Coefficient of cooperation α						
1/B	1.5	1.0	1.0	1.0	1.25	1.35
	2	1.0	1.0	1.1	1.3	1.5
	> 6 or > 2x	1.0	1.0	1.0	1.0	1.0

If the sliding surfaces about two piles do not touch, the piles do not influence each other, act separately and the load-bearing capacity of a pile foundation is the sum of the load-bearing capacities of the individual piles.

If the sliding surfaces intersect and overlap (Fig.1), the soil in the overlapping zone is pressed upwards by both adjoining piles; the load-bearing capacity of both piles is, consequently, lower than the sum of their individual load-bearing capacities applied, when the piles do not influence each other. The sliding surfaces appearing about every pile, may reach beyond the adjoining pile. In the case that the sliding surface of the neighbouring pile reaches in the vicinity of the first pile or beyond it, the soil between the two piles is not pressed upwards, but - due to the skin friction of both piles - downwards; it cooperates with both piles and increases their load-bearing capacity.

In the determination of the magnitude of the influence of this cooperation between the individual piles in a group it was assumed that the soil was homogeneous as far as the depth equal 1.5 times the width of the pile foundation, that the piles were bored piles and that the foundation mounted on the piles did not contribute to the load-bearing capacity of the piles below it.

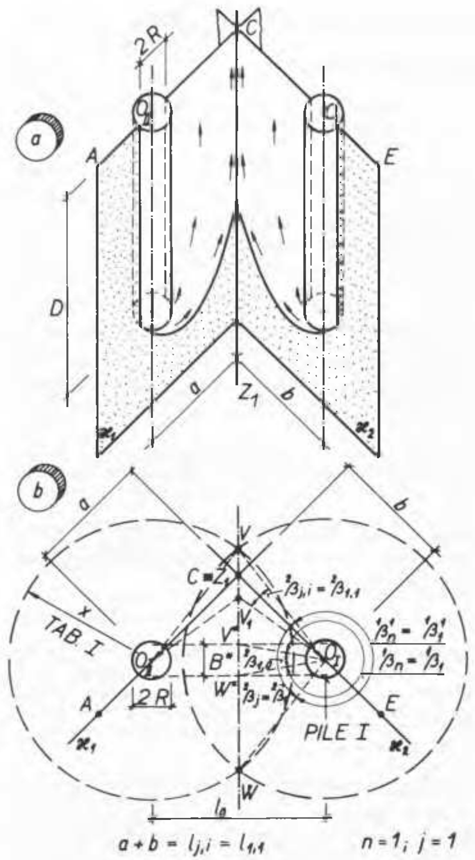

Fig. 1 Three-dimensional sketch (a) and plan (b) of two cooperating piles. ($B^* = \bar{B} = R\sqrt{\pi}$ for $l_o \le x$, $B^* = \bar{B}(2 - l_o/x)$ for $x < l_o < 2x$, $B^* = 0$ for $l_o > 2x$

The calculation of the ultimate load of a group of piles was based on the general equation used for the calculation of the ultimate load of a foundation strip, which was supplemented with the coefficients α_γ, α_q, α_c, expressing the influence of the coöperation of foundation strips, if situated near each other, with which the authors had dealt earlier.

The initial equation of the load-bearing capacity of cooperating foundation strips has the form of

$$q_{mI} = 0.5\,\gamma_1 B_I N_\gamma s_\gamma \alpha_\gamma + \gamma_2 D N_q s_q d_q \alpha_q + c\,N_c s_c d_c \alpha_c \quad \dots \dots \dots (1)$$

in which it was deduced from Brinch Hansen equation (1961). The quantities N_γ, N_q, N_c denote the coefficients of load-bearing capacity, the index I referring to the foundation considered in the calculation; α_γ, α_q, α_c are the coefficients expressing the influence of the cooperation of two foundations. The values of these coefficients which depend on the angle of friction of the soil ϕ, on the width of the foundation strips, their depth and mutual distance of the foundation strips are given in the book by Myslivec and Kysela (1975). When the depth of the foundation base $D > 5B$ (B being the width of the foundation strip or the diameter of the pile), the first term of Eq.1 may be neglected, so that the ultimate load of the foundation strip I is

$$q_{mI} = \alpha\, q^1_{mI} = \alpha\,(\gamma_2 D N_q s_q d_q + c\,N_c s_c d_c) \quad \dots \dots \dots \dots \dots (2)$$

when $\alpha = \alpha_q \doteq \alpha_c$. The values of the factor α are given in Table I for the case of $\delta \doteq 0.66\,\phi$. If δ is lower, the values of α for $\phi > 0$ are also lower, the minimum values ($\alpha < 1$) being form $l/B \doteq 7$. Eq. 2 holds for foundation strips and is taken as a basis for the calculation of the load-bearing capacity of a pile foundation.

If the cooperation of two piles (see Fig.1) is considered, the sliding surfaces situated at the distances of x_I and x_{II} about the piles respectively intersect in the points of V and W. Since the diameters of both piles are equal, $x_I = x_{II}$. The influence zone of every pile is divided into sectors. In the sector whose vertex angle is ${}^1\beta^1$ the sliding surfaces of the two neighbouring piles do not intersect, the piles do not influence each other and the respective part of the load-bearing capacity is

$${}^1q_{mI}{}^1 = \frac{{}^1\beta_1{}^1}{2\pi}\; q_{m1}{}^1 \quad \dots \dots \dots (3)$$

where $q_{mI}{}^1$ is the ultimate load-bearing capacity of an independent pile, $\alpha = 1.0$.

The sliding surfaces intersect in the points of V and W corresponding with the vertex angle ${}^2\beta_1$. The line segment VW is divided into minor sectors ${}^2\beta_{j,i}$ so that ${}^2\beta_j = {}^2\beta_1 = \Sigma\, {}^2\beta_{j,i}$. The sector ${}^2\beta_{1,0}$ corresponds with the line sector V^* W^* defined on the line VW by the stripe of the width B^* . In this sector the respective part of the load-bearing capacity due to the cooperation of 2 neighbouring piles is calculated from Eq. 2 like for parallel stripes spaced at l_o of the width B. Therefore, in this secto $s_\gamma = s_q = s_c = 1$ and the coefficient α is determined from Table 1. Fig. 1 shows also the partial sector i = 1 with the vertex angle ${}^2\beta_{j,i} = {}^2\beta_{1,1}$. In the middle of the line sector VV_1 , defined on the line VW by the arms of the angle ${}^2\beta_{1,1}$ there is the point Z1 which is the projection of the line of intersection Z1 of the planes

$\varkappa_1$ and $\varkappa_2$. The length of $O_{II}\ Z_1 O_I = a+b = l_{1,1}$ in relation to the width of the pile is decisive for the determination of the values of the coefficient α (according to Table 1), expressing the cooperation of piles, whose relative distance is $l_{1,1}/B$, B being equal 2R.

The sector with the vertex angle $^2\beta_{1,1}$ corresponds with the part of the ultimate load

$$^1q_{mI,1} = \frac{^2\beta_{1,1}}{2\pi}\ ^1\overline{q_{mI,1}} \quad \dots \quad (4)$$

when $^1\overline{q_{mI,1}}$ is the load-bearing capacity calculated according to Eq. 1 for the pile width B considering the coefficient α determined for the relative distance $l_{1,1}/B$. In the sectors $^2\beta_{j,i}$ for $i \geqslant 1$ the values of s_γ, s_q, s_c are considered as in the case of an independent pile. The ultimate load of every pile is (Fig.1) - for j = n = 1

$$\overline{q_{mI}} = {}^1q^1_{mI} + \sum_0^i {}^1q_{mI,i} = \frac{1}{2\pi}\left({}^1\beta^1_1\ q^1_{mI} + \sum_0^i {}^2\beta_{j,i}\ \overline{{}^1q_{mI,i}}\right) \quad \dots (5a)$$

When a major number of piles cooperates, the procedure is analogous. In such a case there may be several (j) sectors of cooperation with the neighbouring piles and several sectors (n), in which the neighbouring piles do not influence one another. The resulting equation may be written in the form of

$$\overline{q_{mI}} = \frac{1}{2}\left(q^1_{mI}\sum_1^m {}^1\beta^1_m + \sum_1^j\sum_0^i {}^2\beta_{j,i}\ \overline{{}^iq_{mI,i}}\right) \quad \dots (5b)$$

The load-bearing capacity of piles in a group according to Fig. 2 was investigates in a cohesive soil (a) and in loose soil(b).

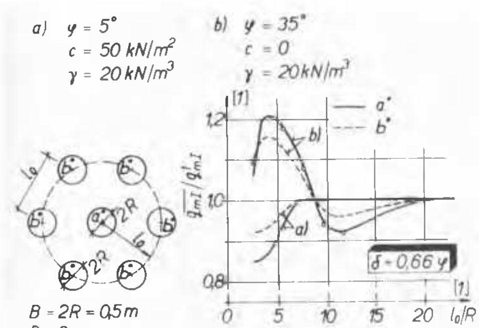

Fig. 2 Ultimate load $\overline{q_{mI}}$ of a pile in group plotted against the ultimate load q^1_{mI} of a single pile.

For various relative distances l/B between piles the ratio of $\overline{q_{mI}}/q^1_{mI}$ are represented in Fig. 2. From this and similar analyses it follows that for the distance of $l_0 < 2x$, when $\phi < 20°$, the load-bearing capacity of every pile is lower (Fig.2, curve a) than it would be, if the piles did not influence each other. Therefore, the distance of the piles in these soils should exceed 2x to prevent the piles from exercizing unfavourable influence on each other. In the soils with $\phi > 25°$ the load-bearing capacity of the piles is maximum, when their spacing at centres is $l_0 = 4R$ (Fig.2, curve b). Even in this case marked reduction of load-bearing capacity occurs, when $9 < l/R < 20$. The calculated ultimate load for bored piles in a group for the depth of the foundation base of D > 5B varies in various cases between 80% and 150% of q^1_{mI}, when the angle of friction of the soil and the pile skin $\delta \geqslant 0.66\ \phi$. The case in which $\overline{q_{mI}} > q_{mI}$ may arise in the soils whose angle of internal friction $\varphi > 15°$. If δ is lower, the load-bearing capacity of the piles is reduced by as much as 1/3 of the value calculated for coarse piles according to Eq. 5b. The values of the load-bearing capacity of the piles in a group calculated by the afore mentioned method agree well with the results of model loading tests carried out by many authors and with the results of in-situ loading tests carried out at Čížkovice.

The contemporary progress of boring techniques and the manner of production of cast-in-place piles made the problem of the structural analysis of these structures, particularly the problem of the overall interaction of the soil-pile-structure system come to the fore. The methods of analysis used so far are generally based on three theories, viz. the pile capacity theory, the theory of the stress functions of the shaft (skin) resistance and point resistance, the theory of the bearing capacity of strip footings at a great depth and on experimental or semiempirical theories. A problem apart is the system of loading acting in place and time; in the analysis this loading is idealized as static load, dynamic load, short term load or long term load; moreover it is difficult to compare the results of the loading tests with actual conditions. For this reason a pile group was subjected to considerable laboratory and theoretical investigation and the results were confronted with the pile loading tests in the field. The investigations were carried out by the Beggs-Blažek method (Šimek 1966), model tests on the scale of 1 : 15 (Šimek 1972) and the photoelasticimetric method (Nwelati 1973, Šimek 1975). The subject of the investigations was the basic system of a row of piles (see Fig.3); the overall results of the distribution of the normal and shearing forces for the vertical load can be observed in Fig. 4a for a pile group whose end piles are battered and in Fig.4b for a pile group of vertical piles only. The influence of horizontal forces on a group of piles is shown in Fig. 5, where also the influence of the horizontal force applied to the top of the pile and to the upper edge of the foundation structure may be observed. For the investigation of the interaction of the

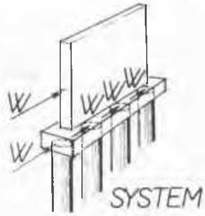

Fig. 3 System of a row of piles.

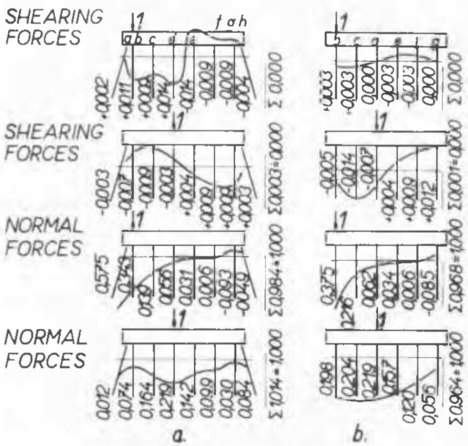

Fig. 4 Distribution of the normal and shearing forces for the decentric and the centric load.

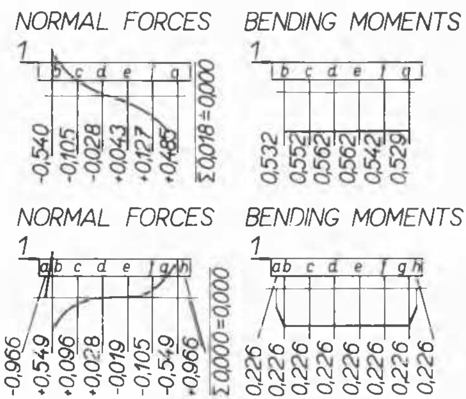

Fig. 5 Distribution of the normal forces and bending moments for the horizontal load.

pile group and the foundation soil the photoelasticimetric method was selected. The investigations were based on the ascertainment of isoclinics and isochromatics and the grouping of isoclinics in the vicinity of singular points. The resulting isochromatic and isoclinic curves were obtained from the photographs of the models in ring polarizability and supplemented by the drawing in an enlargement apparatus.

The conclusions of all four methods of investigation, incl. the loading tests in the field, of a group of two piles of dia. B=1, spaced at 1.8 m centres, afford the following conclusions for practical design:
- The assessment of the tests has shown that, in agreement with the formerly published reports, a thin layer of soil 1.0 - 3.0 cm thick moves along with the pile.
- The use of battered piles can be safely avoided, if permitted by geological conditions, even in the case of pile foundations loaded ba a major horizontal force. The influence of the battered piles on the stability can be felt only in a group of piles rammed only shallowly into the supporting soil or bearing on the rock base. If the piles are rammed to 50% of their length, the influence of battered piles is nil. Permissible horizontal pile capacity - provided the piles are fully immersed in the soil and their tops are connected by a foundation structure (foundation slab, foundation strip) - may be 200 kN for B=0.7 m, 300 kN for B=0.9 m, 400 kN for B=1 ÷ 1.1 m, and 500 kN for B > 1.20 m. A comparison of theoretical results reveals that the Davisson-Gill method (1963) is nearest the actual test results.
- The spacing of piles at centres may be safely selected at min. 1.5 - 1.7 B; the group efficiency equals one.
- Under eccentric load the theoretical load of a maximally loaded pile (row of piles) may exceed by as much as 50% the permissible pile capacity determined by the test or calculation.
- The permissible pile capacity may be determined from the equation

$$V_R = 1.3\ A\ q_f + \sum a_s D_i q_{si} \qquad (6)$$

where are: q_f - the permissible bearing capacity at pile point, according to the strip footing theory; a_s - area of pile surface in length D_i in contact with soil, A - area of pile point, D_i - increment of pile length $q_{si} = \gamma_i D_i \operatorname{tg} (3/4\ \phi'^R) + c'^R$ = unit shaft resistance and ϕ'^R - reduced effective friction angle, reduction factor 0.9, c'^R - reduced effective cohesion, reduction factor 0.5.

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