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# Design of a piled raft foundation as a three-component system "Pile-soil-raft"

Le calcul du fondement en beton et au pilot comme systeme de trois parties "pilot-sol-dalle"

N.Gotman & A.Gotman – *BashNIIstroy, Ufa, Russia*  
D.Shapiro – *Mostengservis Ltd., Voronezh, Russia*

**ABSTRACT:** Based on experimental and theoretical investigations of large-sized pile groups and pile foundations, it was stated that their design should be realized taking account of the interaction of three components: pile, soil and raft. To develop a method of a piled raft foundation design taking the above interaction into account, a complex of experimental and theoretical investigations is carried out which includes in-situ and model tests, numerical simulation and parametrical investigations. A numerical simulation of a stressed-deformed state of a piled raft foundation base is carried out using an axisymmetrical version of a program of an elasto-plastic design of the geotechnical structures. A parametrical investigation of loads redistribution in a pile raft foundation is carried out by calculation a raft on an elastic foundation.

**RESUME:** En vertu des recherches experimentales et theoriques des pilots grands et fondements en beton et au pilot il faut faire leurs calcul etant donne l'interaction de trois parties : les pilots, le sol et la dalle. La serie de recherches experimentales et theoriques ( y compris les essais en nature, la simulation numerique et les recherches parametriques) a ete faite pour elaborer une methode de l'etude du fondement en beton et au pilot etant donne l'interaction des pilots, du sol et de la dalle. La simulation numerique de l'etat de deformation-contrainte du fondement en beton et au pilot a ete faite considerant la version axial-symetrique du programme du calcul elastique-plastique de constructions geotechniques. En outre la recherche parametrique de redistribution des charges dans le fondement a ete faite comme pour une construction sur la base elastique. L'article analyse les resultats des recherches experimentales et theoriques et donne les recommandations pratiques du calcul du fondement en beton et au pilot etant donne l'interaction des pilots, le sol et la dalle.

## 1 INTRODUCTION

In design practice the computation of a piled raft foundation is performed in two steps: computation of pile axial capacity and evaluation of pile group parameters (pile length and pile spacing) and computation of a raft as a structure on an elastic base. Despite some available experimental practice of piled raft investigation, group parameters are still evaluated in design practice by data of a single pile computation without accounting for interaction of piles in group. This is inadmissible by opinion of the most of scientists ( Randolph, 1994). Taking into account that when pile foundation design, the main base information includes results of boring, CPT and pile static tests, investigations are necessary for working out a method of pile group parameters evaluation. The method is based on a single pile computation, but at the same time it should consider the peculiarities of pile behaviour in group.

By results of piled raft foundations and pile groups investigations (Randolf, 1994; Bartholomey et.al., 1994), the distinctive peculiarities of their behaviour compared to a single pile are:

- soil consolidation in a pile group base;
- principle differences in the manner of loads transfer at the contact "pile-soil";
- redistribution of a load between a raft and piles.

As a result of authors' investigation, a method of computation and design of a piled raft foundation is suggested based on results of computation and a single pile test, corrected in dependence on foundation parameters. Correction is done by results of numerical simulation of a pile-soil-raft interaction.

## 2 NUMERICAL INVESTIGATION OF PILE-SOIL INTERACTION IN A PILE GROUP

To study the regularities of pile-soil interaction in a pile group, the numerical-investigation is done by a mathematical simulation of a process of pile penetration by an axial force. The mathematical simulation is done using an axisymmetrical version of a program of geotechnical constructions elastoplastic calculation (Shapiro, 1996). Mathematical simulation (by means of finite element method) of loading with a press-in force is one of the modern methods of computational prediction of pile axial capacity and analysis of pile interaction with soil medium. It is confirmed by a high appreciation in review (Review, 1986; Randolph, 1994) and by an increasing number of examples of pile test numerical simulation by solution of mixed problems of elasticity and plasticity theory (Shapiro et.al., 1996; Zaretsky & Karabaev, 1985; Shapiro, 1985; Fedorovsky & Bezvolev, 1994).

In given section of the report, a comparison of test results of 30x30 cm, 12m length driven reinforced concrete pile is presented:

- computations (numerical experiments), simulating pressing-in of both single pile and a pile in group;
- in situ tests of a single driven pile and one driven pile in group (with unloaded adjacent piles).

The procedural base of calculations, simulating pile jacking by an axial force, is a combination of initial stresses method (ISM) with an axisymmetrical version of finite element method (FEM). The theoretical base is a mathematical description of soil as a solid isotropic medium, simulated according to plasticity flow theory. An adopted engineering diagram allows development of places of soil pre-limited

stressed state with calculation of fixed boundaries. Based on calculation results, a curve of pile "load-settlement" dependence is plotted.

In formulation of an elastoplastic problem, the following hypotheses are presented:

- the development of non-linearity being taken into account, includes plastic deformation of forming with complicated stressed state, free deformation with tension, shear along the given surface;
- with complicated stressed state (compression with shear), general deformations include both linear (elastic) and plastic parts, the plastic component of deformations occurs when the stressed state reaches the ultimate strength by condition of Mises-Schleicher-Botkin (Drucker.&Prager, 1952) as follows:

$$\alpha J_1 + J_2 - K = 0 \quad (1)$$

where  $J_1$  ( $J_2$ ) = the first and the second invariants of stresses tensor;  $\alpha$ ,  $k$  = soil strength characteristics with three-dimensional stressed state;

- vectors of main plastic deformations (and their velocities) and main stresses with complicated stressed state are taken coaxial;

- at a stage of plastic deformation, a dilatancy with a relation between volume change and forming is taken into account which is expressed by an arbitrary constant (non-associated flow law).

Natural (initial) stressed state is taken hydrostatically distributed.

Procedural computation parameters are fixed in the following dimensions: coefficient of convergence acceleration of an iterative process of ISM – 1.5, admissible standard of force error  $E_F = [\sum(F_i^2)]^{1/2} = 0.005P$  where  $(\{E_i\})$  = vector of force error, being evaluated according to procedure ISM;  $s$  = number of a node;  $i$  = current stage of iteration. At the last load stages, a number of iteration steps necessary for convergence reached 50 – 80.

The calculation was done for a cylindrical pile equal by an area of its lateral surface to a prismatic pile placed in a center of a calculation area. The calculation area is adopted to be cylindrical with the radius  $r_m$  equal to  $10d$  for a single pile with the diameter "d", and with the radius  $r_m$  equal to  $a/2$  for a pile in group (with pile spacing equal to "a") (Fig. 1).

The boundary condition on an outer surface of a calculation area is a restriction of horizontal displacements over the vertical surface and vertical displacements over the horizontal surface. The condition inside the calculation area is a restriction of tangential stresses over the vertical surface of a soil-pile contact  $\tau < f_s$  where  $\tau$  = tangential stress along the pile shaft,  $f_s$  = soil limit specific resistance along the pile shaft which should be determined by CPT data. Figure 1 shows the division of the calculation area into finite elements and boundary conditions for calculation of a single pile ( $r_m = 10d$ ) and a pile in group ( $r_m = a/2$ ).

The initial data of computation includes mechanical characteristics of soil in each finite element: density ( $\gamma$ ), modulus of deformation ( $E$ ), Poisson's ratio ( $\nu$ ), angle of inner friction ( $\varphi$ ), specific cohesion ( $c$ ), strength characteristics  $\alpha$  and  $k$ , connected with an inner friction angle ( $\varphi$ ) and specific cohesion ( $c$ ) as  $\alpha = (\sin \varphi)/3$ ,  $k = c \cos \varphi$ , dilatancy parameter ( $\lambda$ ), taken equal to  $0.5\alpha$ . When preparation an input information, the natural values of the above parameters are corrected considering base consolidation due to pile penetration. The characteristics of consolidated soil are evaluated by recommendations of Bartholomey A.A given in his monograph (Bartholomey et al., 1994) in dependence on the natural soil characteristics. An engineering-geological profile of experimental site for which computations were performed is shown in Figure 3. Soil investigations included boring with monoliths sampling and laboratory treatment of samples. Mechanical characteristics of base soil used in computations, are shown in Table 1.

Computations results were compared with test results of a 30x30 cm, 12 m length single pile and a 12 m length pile in a 10x30 pile group.

Results of calculation the tangential stresses along a single pile shaft and a pile in group are shown in Figure 2. Comparison of curves 1,2,3,4 in Figure 2 shows that in contrast to a single pile the tangential stresses of piles in group occur at the first steps of loading near the pile base and extend upwards with the pile loading increase.

Figure 3 shows curves "load-settlement" obtained by a single pile calculation (1) and by CPT results of a separately penetrated

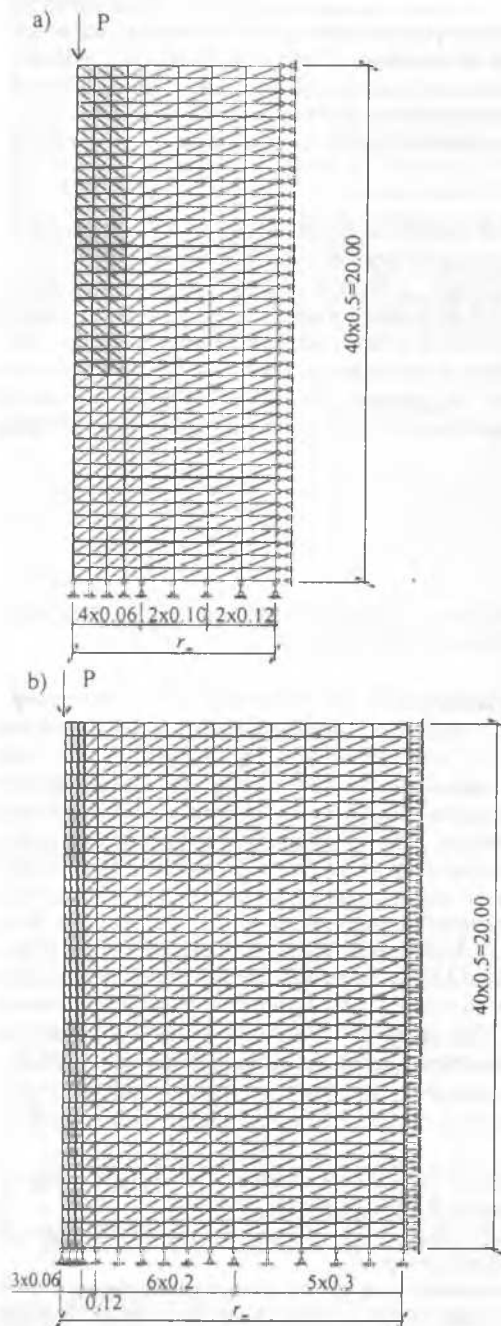


Figure 1. Division of design area: (a) for a single pile; (b) for a pile in group



### 3 EVALUATION OF A PILE IN GROUP AXIAL CAPACITY

By results of pile in group computation (curve 4 in Fig.3), a linear dependence "load-settlement" is obtained. It allows considering a pile as a "rigid punch" through the whole range of loads and evaluation of part of pile settlement due to load transferred to its base ( $P_b$ ) using a Boussinesq solution for evaluation the settlement of a point on a surface of half-space being at a distance ( $r$ ) from the place of force ( $P$ ) application.

The results of experimental investigations with tensopiles use (Gotman, 1998) show that in clayey soils part of settlement of a single pile, transferred to a pile base, corresponding to an area of elastic deformations on diagram "load -settlement", can be also evaluated by Boussinesq solution.

Now, based on the above solution, evaluate settlements of a single pile ( $S_1$ ) and a pile in group ( $S_2$ ) due to force  $P_{b1}$  and  $P_{b2}$  respectively

$$S_1 = \frac{P_{b1}(1-\nu_1^2)}{\pi E_1 r_1}, S_2 = \frac{P_{b2}(1-\nu_2^2)}{\pi E_2 r_2} \quad (2)$$

where  $E_1, E_2$  = moduli of deformation and  $\nu_1, \nu_2$  = Poisson's ratios,  $r_1 = r_2 = d/2$ ,  $d$  = pile dimension.

In formulas (2) as well as in the subsequent ones, all parameters with index 1 refer to a single pile, parameters with index 2 - to a pile in group. Having taken  $\nu_1 = \nu_2$  and  $r_1 = r_2$ , find the relation of settlements  $S_1$  and  $S_2$

$$\frac{S_1}{S_2} = \frac{P_{b1}}{P_{b2}} \cdot \frac{E_2}{E_1} \quad (3)$$

Load transferred to a pile base, is

$$P_b = \xi P \quad (4)$$

where:  $\xi$  = a part of load transferred to a pile base;  $P$  = overall pile load.

Substituting (4) in (3), solve the equation (3) relative to  $P_2$ :

$$P_2 = P_1 \frac{\xi_1}{\xi_2} \frac{E_2}{E_1} \frac{S_2}{S_1} \quad (5)$$

Taking into account that use of Boussinesque solution is limited with an area of elastic deformations, values  $P_1$  and  $S_1$  of single piles correspond to a linear part in the diagram "load-settlement" and  $S_2$  - to a limit permissible structure settlement. In formula (6) let's change product  $(\xi_1/\xi_2)(E_2/E_1)(S_2/S_1)$  to  $K$

$$P_2 = KP_1 \quad (6)$$

Thus, dependence is obtained for transfer from a single pile axial capacity to a pile in group axial capacity. A single pile axial capacity  $P_1$  is evaluated by results of a single pile test and CPT data with the settlement  $S_1$  corresponding to a linear part in diagram "load-settlement".

Coefficient  $K$  is evaluated by two methods:

-as parameters product  $(\xi_1/\xi_2)(S_2/S_1)$ , for practical computations of piles with pile spacing more than  $4d$  in homogenous clayey soils admitted to take a product  $(\xi_1/\xi_2)(S_2/S_1)$  equal to 1, and relation  $E_2/E_1$  equal to

$[1+(2/\pi) \sum_{i=2}^n (r/S_i)]$ , where  $S_i$  is the spacing of the  $i^{\text{th}}$  pile from pile 1 (Randolf, 1994);

- theoretically, by means of analysis of curves "load-settlement" for a single pile and a pile in group depending on parameters of a pile group (pile spacing, pile length), as load relations  $P_1$  and  $P_2$  with settlements  $S_1$  and  $S_2$ , corresponding to an area of elastic deformations for a single pile ( $S_1$ ) and a limit admissible structure settlement for a pile in group ( $S_2$ ).

Figure 4 shows dependence of coefficients  $K$  on pile spacing. Diagrams in Figure 4 are plotted by test results of  $30 \times 30$  cm, 6-12 m length single piles and  $30 \times 30$  cm, 6-12 m length piles in group with pile spacing 0.9 m, 1.2 m, 1.5 m, 1.8 m in clayey soils. An engineering-geological profile of a base is shown in Figure 3. The computation is performed with use of an axisymmetrical version of a program of geotechnical structures elasto-plastic computation (Shapiro et al., 1996).

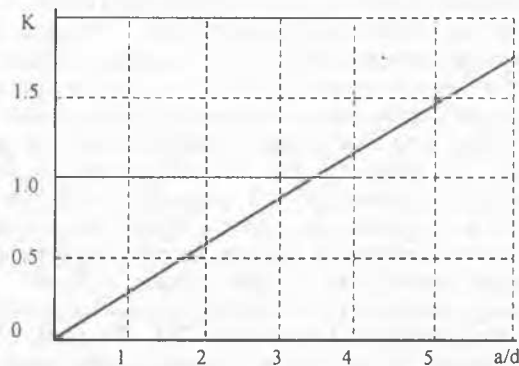


Figure4. Dependence of ratio  $K$  on pile spacing ( $a/d$ )

It follows from the diagrams in Figure 4 that with pile spacing increase, coefficient  $K$  increases. Indeed, with pile spacing increase, pile interaction reduces and axial capacity increases. The value of coefficient  $K$  changes from 0.62 to 1.7. With pile spacing  $a = 3d$ , it is minimum and practically always is less than 1, with  $a = 4d \div 6d$ , the value of  $K$  is more than 1. It shows that pile spacing for a given site should be taken in the range of  $4d \div 6d$ .

Thus, the axial capacity of piles in group depending on parameters of a pile group (pile length and pile spacing) and limit admissible structure settlement, is suggested to be evaluated by test results and design by CPT data of single piles in conjunction with the theoretical comparative design of single piles and piles in group. Design of a piled raft is done by the following condition

$$P_2 > N_p \quad (7)$$

where  $P_2$  = axial capacity of a pile in group, evaluated by formula (6);  $N_p$  = pile load, evaluated by recommendations of section 4.

### 4 REDISTRIBUTION OF LOADS IN A PILED RAFT FOUNDATION

By results of experimental investigations of pile groups, it is stated that a load transmitted to a foundation is taken up both with a raft and a piled foundation. For practical calculations, the most important is an evaluation of a share of load transmitted to piles. A share of load transmitted to piles of a raft piled

foundation is evaluated by a totality of factors: physical-mechanical characteristics of soil under a pile base, pile length and pile spacing. Generally, these factors can be evaluated with two parameters: stiffness coefficient of a raft base  $K_r$  and stiffness coefficient of piles  $K_p$ . To evaluate a share of load transmitted to piles of a raft piled foundation, a numerical investigation of regularities of load redistribution between raft and piles is carried out.

As a result of above investigation, the connection of dimensionless parameters is evaluated:  $K_r/K_p$  (relation of stiffness coefficient of raft base and piles),  $R_z n/\Sigma N$  (a share of load taken up by piles),  $E \cdot B \cdot H^3/K_p a^2 l$  (relation of raft and piled foundation stiffness),  $Na^2/b^2 K_p S_u$  (ratio of real pressure to that taken up by piled base), where  $N$  = a column load;  $n$  = number of piles;  $R_z$  = pile reaction;  $H$  = raft thickness;  $l$  = pile length;  $b$  = column spacing;  $E$  = modulus of raft concrete elasticity;  $S_u$  = limited permissible settlement.

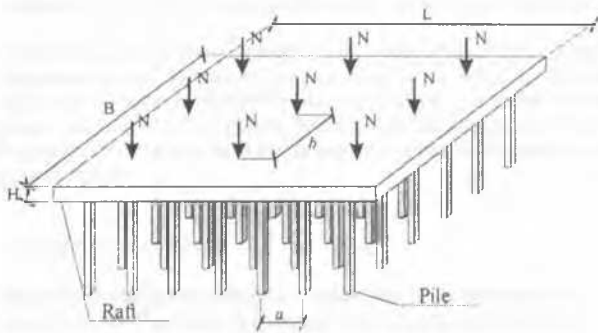


Figure 5. Design scheme of a piled-raft foundation

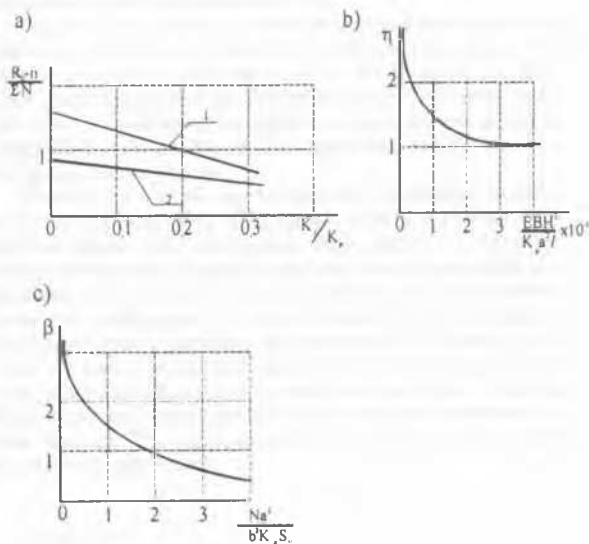


Figure 6 Diagrams of parameters dependence:

$$(a) \frac{R_z n}{\Sigma N} = f\left(\frac{K_r}{K_p}\right), (b) \eta = f\left(\frac{E B H^3}{K_p a^2 l}\right); (c) \beta = f\left(\frac{N a^2}{b^2 K_p S_u}\right)$$

In numerical investigation, a solution of a contact problem is used for a raft on an elastic base, realized by a program complex "LIRA" (Gorodetsky et al., 1981). The procedural base of a solution is a finite element method, the theoretical one is a method of local elastic deformations.

The investigation is carried out for a foundation slab with the following initial data (Fig.5):  $L = 24$  m;  $B = 24$  m;  $b = 6$  m;  $a = 1.2$  m;  $H = 1.3, 1.0, 0.8$  m,  $N = 10000, 5000, 3000$  kN;  $K_r = 0$  and  $1500$  kN/m<sup>3</sup>;  $K_p = 15000, 10000, 5000$  kN/m.

To obtain an analytical dependence of a share of load taken up by a pile, maximum values of pile reaction ( $R_z$ ) are evaluated with the different values of parameter  $K_r/K_p$  and diagrams of parameter  $R_z n/\Sigma N$  dependence on parameter  $K_r/K_p$  are plotted when  $K_p = 15000$  kN/m (1);  $K_p = 5000$  kN/m (2) and  $H = 1.3$  m;  $N = 5000$  kN (Fig. 6a). Graphs in Figure 6(a) are approximated with the linear function

$$\frac{R_z n}{\Sigma N} = \eta - \beta \frac{K_r}{K_p} \quad (8)$$

Having changed  $R_z n$  to  $\Sigma N_p$  in formula (8), determine the overall load transmitted to piles

$$\Sigma N_p = (\eta - \beta \frac{K_r}{K_p}) \Sigma N \quad (9)$$

Parameters  $\alpha$  and  $\beta$  are evaluated by graphs in Figure 6 (b, c) plotted based on analysis of a function  $(R_z n)/\Sigma N$  with different values of  $N, H, K_r, K_p$ .

## 5 CONCLUSIONS

Based on results of numerical simulation and experimental investigations of raft foundations, a design method is suggested, which includes a parametric optimization of pile group by results of CPT, pile tests and numerical simulation. The above method takes redistribution of loads between a raft and piles into account. The parametric optimization is carried out by modifying two parameters: pile spacing and pile length. The criterion of optimization is the difference between a load transferred to a pile ( $N_p$ ) and pile axial capacity ( $P_2$ ). At each calculation step the following condition is checked:

$$P_2 - N_p < 0.1 N_p \quad (10)$$

where  $N_p = \Sigma N_p / n$ ,  $N_p$  is evaluated by formula (9);  $n$  = the overall number of piles;  $P_2$  is evaluated by formula (6). A program "PRF" is worked out by the method suggested.

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