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CONSIDERATION OF RAFT AND SOIL INTERACTION IN PILED-RAFTS DESIGN

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ABSTRACT

Based on the analysis of the piled-raft foundations, as well as experimental investigations of the geotechnical engineers, it is stated that the load of a piled-raft foundation is transferred both to a raft and a pile. When a piled-raft foundation design, the account of this factor allows the significant decrease of the foundation cost. To work out the method of a piled-raft foundation design, the experimental and numerical investigations have been carried out.The paper gives some results of the experimental and numerical investigations of piled-raft foundations. A method of the evaluation of a load part transferred to a raft and the piles is suggested. The conditions of the load transfer to a raft when a foundation loading are determined.

INTRODUCTION

In practical calculation of a piled-raft foundation, the most important is the consideration of the raft-soil interaction, as the excluding of the raft out of the piled-raft foundation leads to an increase of the specific consumption of materials and a foundation cost. To develop a method of the evaluation of the load transferred to a pile and a raft when a piled-raft foundation calculation investigations have been carried out to solve the following problems:

- determination of the rules of the load redistribution and working out the method of the part of the transferred load evaluation;
- determination of the conditions of the load transfer to a raft when a foundation loading.

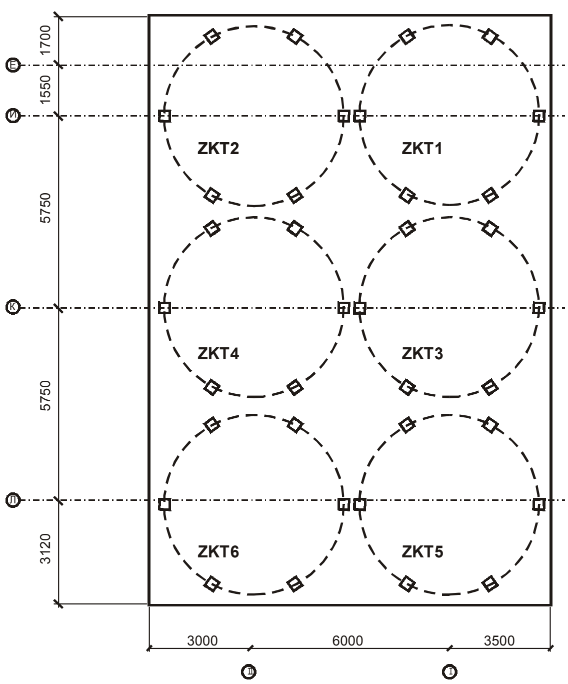

Fig. 1. The plan of the tanks ZKT

EXPERIMENTAL INVESTIGATIONS

Procedure of carrying out the experimental investigations

The experimental pile field of piled-raft foundation for containers (ZKT) to store the components used in the process of beer production is designed of 30 x 30 driven piles with 8 m penetration depth and 1.5 m pile spacing (fig.1,2). The thickness of a solid raft is 600 mm.

The experimental investigations are complex and include:

- soil research for the evaluation of its physical and mechanical characteristics;
- pile test both as single and in a pile field;
- evaluation of a load share transmitted to a pile and a raft;
- numerical investigations for a “load-settlement” diagram plotting.

The complex of soil researches in a test site includes holes boring with soil sampling and the subsequent laboratory sample processing, CPT before- and after pile penetration.

To estimate the actual loads transferred to the piles, the heads of two central and one edge pile are instrumented with the strain gauge dynamometers with a circular measuring element (fig. 3). Settlements of each of three piles are measured while

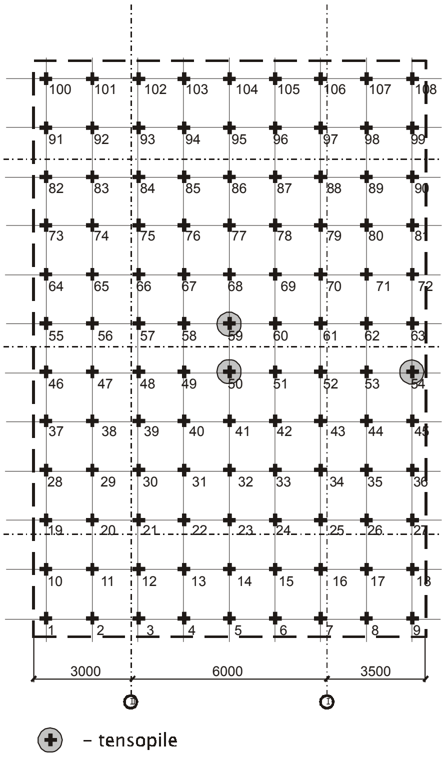

Fig. 2. The plan of the piles desplacement

their loading in a pile field as containers filling. Loads transferred to a foundation in a process of its construction, containers asembly and their filling are given in table 1. As pile load increases, each load-cell strain gauge load is measured and design elevation of the raft surface above each load-cell strain gauge is recorded with the following steps of loading: a solid raft without loading, a solid raft + ZKT construction, a solid raft + ZKT construction + product.

Table 1. Loads transferred to a foundation

No. of loading	Stage of construction	Pressure under the raft bottom, MPa
1	A solid raft is constructed	0.0015
2	The construction ZKT is mounted	0.0018
3	Tanks are filled with a product	0.12

By results of loads and settlements measurement, by load-cell strain gauges readings and by means of levelling, diagrams “load-pile settlement” are plotted for 3 test piles in a pile field and loads transmitted to a pile and a raft are evaluated.
The numerical investigations are carried out using the program of the elasto-plastic calculation of the geotechnical constructions (Gotman et al. 2001). By results of the above numerical investigations, a diagram “load-settlement” is plotted for 30 x 30 cm, 8 m length piles with 1.5 m spacing with the initial soil characteristics of the natural soil and compacted one in the process of penetration and loading.

Fig. 3. A strain –gauge dynamometer with a circular measuring element

<u>Analysis of results of the experimental investigations</u>

By results of soil investigation, the test site is a clayey soil up to 16 m depth which overlies semigravel and medium-grained sand. The geological structure of the test site consists of the following deposits (from top to bottom) to 14.5 m depth.
1.Fill-up soil (tQ) consists of loam, black earth, constructional refuse, asphalt, crushed aggregate, etc., the thickness of the layer is 0.8-1.3 m.;
2.Loam (abQ_{111}) brown, light, low-moist, of soft and stiff consistency, the thickness of the layer is 6.4-8.5 m.
3.Clay (aQ_{111}) grey-brown, of stiff consistency with sand nests, the thickness of the layer is 6.4 m.
4.Sand (AQ_{11}) grey, gravel and medium grained, thickness laid bare is to 2.0 m.
Physical and mechanical properties are given in table 2. Results of soil CPT before- and after a pile penetration are given in table 3.

Table 2. Indices of physical and mechanical properties of soils on a test site

No.of holes	Sampling depth, m	I_L	Soil density,ρ kN/m^3	φ, grad.	E, MPa	C, MPa
C-1	3	0.25	19.5	18	20	0.037
	7	0.5	19.5	15	9	0.02

Analysis of CPT results shows the compaction of soil both between the piles and in a pile field base. The resistance under the probe tip increases on the average by 20%, and the specific resistance along the pile lateral surface doesn’t practically change.
A complex of the method prescribed measurements is carried out for 3 trial piles penetrated in a pile field. Results of pile loads measurements and the corresponding settlements are given in table 4.Analysis of table 4 data shows the maximum pile load in a foundation not to exceed 10 kN with a raft

Table 3. Soil resistance under the tip (q) and along the probe lateral surface(f)

Depth,m	Before a pile penetration		After a pile penetration	
	q,MPa	f,MPa	q,MPa	f,MPa
1	-	-	-	-
2	1.50	0.06	1.8	0.058
3	1.80	0.055	2.0	0.050
4	1.45	0.05	1.8	0.045
5	1.55	0.045	2.1	0.040
6	1.20	0.045	1.4	0.045
7	1.15	0.075	1.55	0.076
8	1.45	0.075	1.75	0.07
9	1.30	0.069	1.65	0.072
10	1.15	0.09	1.30	0.08
11	1.20	0.078	1.3	0.075
12	1.30	0.075	1.45	0.075
13	1.40	0.080	1.67	0.08
14	1.30	0.09	1.50	0.10

settlement of 2.5 cm. Results of loads and settlements measurements of test piles being combined with a raft and a single pile are shown in figure 4 . Analysis of the diagram 2 in figure 4 shows the dependence "load-settlement" for piles, combined with a raft to be near to linear. The diagram "load-settlement" of a single pile (1) have the characteristic points of inflection showing the non-linear character of the diagram, the limit load capacity of a single pile is reached at a 200 kN load. Different performance of piles tested as single and combined with a raft, doesn't allow a pile field design based on results of single piles test without considering their interrelation in a piled raft foundation.

Table 4 Results of measurements of test pile loads and a foundation settlement

Stage of construction	No.of a test pile	Actual load, kN	Settlement, m
A solid raft is constructed	1	27	0.0078
	2	32	0.0040
	3	30	0.0075
The ZKT construction is mounted	1	37.6	0.0118
	2	38.4	0.008
	3	40.7	0.0115
Tanks are filled with a product	1	211.2	0.024
	2	203.1	0.0221
	3	204.1	0.0253

For the 8 m test piles penetrated with a pile spacing 1.5 m, a mathematical modelling of a process of a pile axial load is carried out based on solution of an elasto-plastic problem (Gotman et al.2001). The modulus of a base deformation ranged from 9 to 40 MPa. As a result, diagrams "load-settlements" are plotted with the modulus of deformation in a pile field base equal to 9; 1.2; 1.5; 2.0; 2.4 MPa (fig.5). To make an analysis, results of a pile in a pile field calculation are shown in figure 3 with the natural modulus of deformation (E_0 = 9 MPa) and with the increased one (E_0 =20 MPa) respectively. In figure 4 they are marked as 3 and 4 respectively. The comparison of the curves 2, 3 and 4 in figure 4 shows the pile settlements obtained with the natural modulus of deformation (curve 3) to be several times more than that with the actual one. This confirms the necessity of considering the soil compaction in a pile field base when driven pile fields design. The comparison of the test and design results shows the coincidence of the design and actual settlements with the modulus of deformation 20.0 MPa (curve 4). Thus, the modulus of deformation of the pile field soil base is significantly more than that of the natural soil.

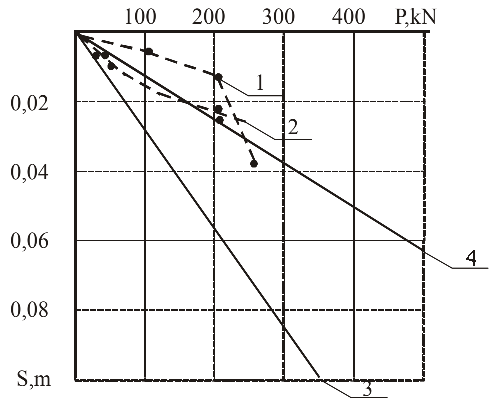

Fig.4 . Diagram "load-settlement" of the test pile and the piles in a pile field by design: 1,2-a test single pile and a pile field,respectively;3,4-by design with the modulus of deformation E=9MPa and 20MPa, respectively

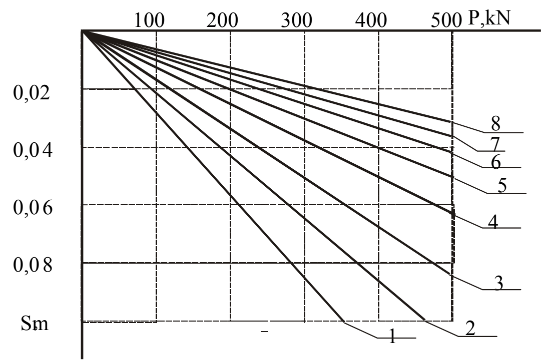

Fig.5 . Diagram "load-settlement" of the piles in a pile field by design (1-8) with the modulus of deformation E= 9MPa, 12MPa, 15MPa, 20MPa, 25MPa, 30MPa, 35MPa, 40MPa respectively

By data in table 4, the pile load derived with the 100% filling of the tanks is 270 kN. According to load measurements results (see table 1), the maximum pile load is 211 kN. Thus, it is obvious that with 100% filling of the tanks the pile accept only part of the load (about 70%), and 30% of the load is transmitted to a solid raft.

THE EVALUATION OF THE LOAD PART TRANSMITTED TO THE PILES AND A RAFT OF A PILED-RAFT FOUNDATION

One of the simplest engineering methods of the evaluation of a load part transmitted to the piles and a raft is the method based on solutions of the contact problems of a raft on an elastic base (Randolf, 1994). The necessary condition of a contact problem solution is an ensuring of a contact between a soil and a raft bottom. However, it cannot be done always. In case of transmission the soil between piles together with the piles when a foundation loading, all the load is transferred to the piles, thus, the evaluation of the part of the load transferred to the piles, has no sense.
So, the most important point of the investigation is the evaluation of the sphere of such problems solution application to estimate the load part accepted by the piles and a raft.

The evaluation of the sphere of the contact problem solution application to estimate the load part accepted by the piles and a raft

It is stated experimentally that the load is transferred to a raft irrespectively of the reaching by the pile its limit state, but provided the soil movement is not bound with the piles displacement. It takes place when at the level of the pile tips, zones of normal stress distribution in the soil σ_z are not closed.
Thus, the criterion of the possibility of loads redistribution in a piled-raft foundation is the relative soil and pile movement at the level of the pile tips. To obtain the optimum relationships of a field parameters (a pile length and spacing) satisfying this criterion, a numerical investigation is carried out with the use of the solution of a plane problem of the elasticity theory.
In the investigation carried out, the piles and the surrounding soil are modelled to be a set of finite elements in a plane stressed state $\sigma_y = 0$. The calculation is carried out in the plane XOZ. When specifying the initial data, the following assumptions are taken:

- fracturing in a soil mass is not allowed that is realized by combining the corresponding nodes displacement in the direction of X,.Z. U_y;
- the horizontal displacements along the vertical bound of the design region are taken equal to 0, the vertical displacements along the horizontal bottom bound of the design region are taken equal to 0;
- the stresses due to the natural soil pressure are not taken into consideration.

The basic equations of the plane problem of the elasticity theory are the equations of the generalized Hooke's law. In accordance with these equations the stressed-deformed state is evaluated depending upon the generalized modulus of deformation E and Poisson's ratio v. So, when the initial data selection, the deformational soil characteristic E varied and that is of a pile and a raft concrete was constant.

For two modifications of the deformational soil characteristics (E = 10 MPa and 15 MPa, v = 0.35), 12 types of a pile field of 30 x 30 driven piles are considered, provided the variation of a pile length (from 4 to 10 m) and their spacing (from 1.3 to 1.8 m) in a pile field.
As a result of the calculations carried out, the stress and displacement fields are obtained. The stress fields represent a set of normal stresses σ_z isolines, the displacement fields represent the displacements Z in the plane XOZ. The results of the numerical investigation allow to conclude that for 30 x 30 (d) driven pile fields the transmission of the load to a raft is possible with the spacing 1.5 m (5 d) and more.

The evaluation of the load part transmitted to the piles and a raft of the piled-raft foundation

The results of the experimental and theoretical investigations show that a load transmitted to the piles of the piled-raft foundation is evaluated by a set of factors: physical and mechanical properties of soil under the raft and under the pile tip, pile length and pile spacing. These factors can be specified by two parameters: coefficient of subgrade reaction of a raft base (K_r)and pile stiffness ratio(K_p). Thus, the relation of these coefficients determines the part of the general load transmitted to both the piles and a raft.

To obtain the analytical solution for the estimation of a raft role in a piled-raft foundation performance, an investigation of the rules of loads redistribution between a raft and the piles for a skeleton structure is carried out (Gotman et al. 2001). While carrying out the investigation, a contact problem of a raft on an elastic foundation was solved. As a result of the above investigation, the interrelation of the dimensionless parameters is obtained: K_r/K_p (the ratio of coefficients of a raft base and a pile stiffness); $R_z n/\sum N$ (a load part accepted by the piles); $EBH^3/K_p a^2 l$ (the ratio of a raft and a pile base stiffness); $N \cdot a^2 / b^2 K_p S_u$ (the ratio of an actual pressure and the pressure accepted by the piles). N - a column load; n – a number of piles, R_z – piles reaction, H – a raft thickness; b – columns spacing, E – elasticity modulus of a raft concrete; S_u – the ultimate assumed settlement of the structure; B – a raft width; l – a pile length.Based on the analysis of the diagrams of the dimensionless parameters dependence, the following formula is obtained to estimate the load N_p transmitted to the piles

$$N_p = \sum N(\alpha - \beta \frac{K_r}{K_p}) \quad . \qquad (1)$$

Parameters α and β are evaluated by graphs plotted based on the analysis of a function $(R_z n)/\sum N$ with different values of N, H, K_r, K_p (Gotman et al 2001) . For the piled-raft foundation with the following parameters : H= 0.6 –0.9 m, L/B=1-1.5, l = 6-12 m, a = 4-6d, the coefficients α and β can be taken equal to 1 and 0.8 respectively.

THE PRACTICAL APPLICATION OF THE INVESTIGATIONS RESULTS

As a result of the experimental and theoretical investigations carried out, the design procedure is suggested. Based on this procedure, the regional Code on a piled-raft foundation design is worked out. The procedure of a piled-raft foundation design allows the determination of the parameters of a pile field (pile spacing and a pile length) based on a single pile calculation by static tests and CPT data, as well as by theoretical calculations of piles and a foundation, considering a pile behaviour in a foundation. The procedure includes the following calculation steps: the calculation of piles resistance in a pile field (P); the determination of the pile-soil interaction factor (ξ) (Gotman et al 2001) and the pile spacing (a) by condition $\xi > 1$; the calculation of the elastic base characteristics and a pile load N determination considering the load transmission to a raft; control of the condition 1.1 $N_p \geq P \geq N_p$ and a pile length determination.

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