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PECULIARITIES OF DESIGNING PILED-RAFT FOUNDATIONS FOR MULTI-STOREY AND HIGH-RISE BUILDINGS

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ABSTRACT: Currently in Multi-Storey and High-rise building to avoid intolerable relative settlement of separate constructions raft foundations are used. In connection with excessive loads base settlement often exceeds assumed value. In that case pile foundations are used. Often pile foundations are applied in comparative favorable ground conditions at the surface of the base. In such cases increase the bearing capacity of foundations and reduce construction cost are questions of first-rate importance for designers. One of the ways to increase the bearing capacity of a piled foundation is taking into account soil resistance in the base of the raft. Raft is similar to shallow foundation and can transfer significant part of the load into the base. It allows reducing number of pile in the foundation or shortening their length. As a result building terms and foundation costs reduce considerably. However, nowadays in Belarus there is no reliable and suitable in design practice methods of calculation of piled-raft foundations. In order to devise such methods we have analyzed the results of piled foundation tests fulfilled by various authors up to date and have carried out series of field and laboratory investigations in Minsk. The most important results of the investigations are provided in the article.

Introduction

Of late years pile foundations are used extensively in connection with increase number of storeys and load increment on the soil. Often pile foundations are applied in comparative favorable ground conditions at the surface of the base. In such cases increase the bearing capacity of foundations and reduce construction cost are questions of first-rate importance for designers. One of the ways to increase the bearing capacity of a piled foundation is taking into account soil resistance in the base of the raft. Piled raft is similar to shallow foundation and can transfer significant part of the load into the base. It allows reducing number of pile in the foundation or shortening their length. As a result building terms and foundation cost are reduced considerably. However nowadays there is no reliable and suitable in design practice methods of calculation pile foundations with bearing rafts. In order to devise such methods we have analyzed the results of piled foundation tests fulfilled by various authors up to date and have carried out series of laboratory and field investigations.

Long before the constitution of the first piled-raft foundations in the Soviet Union there were attempts to consider soil resistance in the basis of isolated and strip grillages. Such bases can be considered as separate fragments of the piled-raft foundation. Prof. A. A. Bartolomey had tested more than 70 pile foundation of natural size in different ground conditions. The length of piles was 3 … 12*m* [1]. The observed results show that the raft carries about 10 … 12% of the total load applied when length of piles was over 9*m* and space between piles *a*=3*d*. Bearing capacity of the raft is about 35 … 40% when lenth of piles is 5 … 8 *m* and *a*=6*d*. Prof. Golubkov has tested 2 prismatic piles (cross section: 0,35x0,35*m*, *L*=3,8*m*) and 2 pyramidal piles (cross section: head – 0,6x0,6*m*, foot – 0,1x0,1*m*, *L*=3*m*). One of the piles was tested with a raft and the other without a raft. Significant influence of the raft on total bearing capacity was determined, the more settlement the more influence of the raft. Bearing capacity of the raft was 27,5% in foundation with prismatic pile and 42% with pyramidal pile [2].

Laboratory researches of soil stress conditions in the base of piled-raft foundations were executed by Kozachok [3]. The researches show that distribution of vertical stress in the base of a raft is similar to a foundation plate on the natural basis. Stress diagram of different groups of piles with high and low rafts are given in fig. 1.

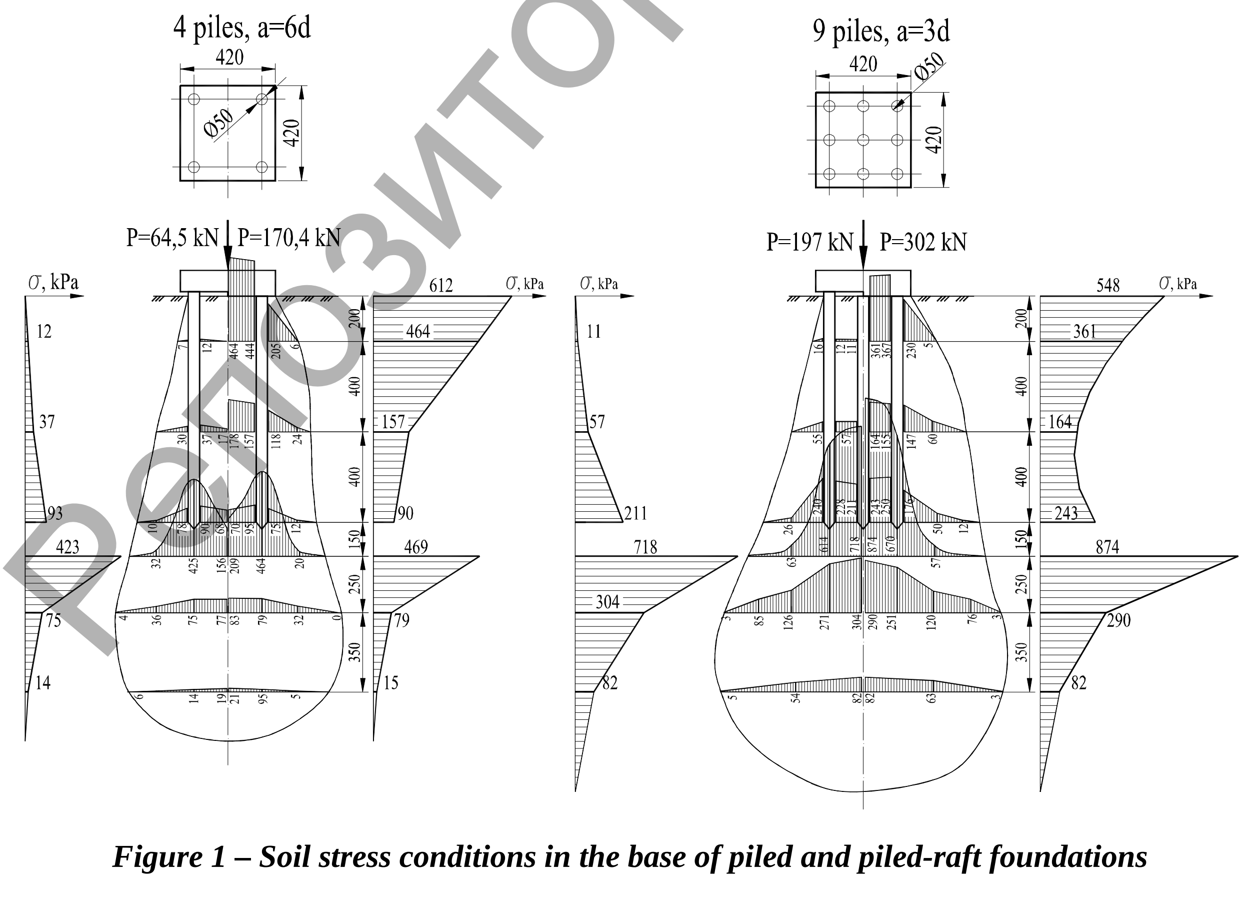


Figure 1 – Soil stress conditions in the base of piled and piled-raft foundations

The quantity of piles in group varied. At interaction of a raft with the base the part of loading is transferred to the top layers of the soil and the bearing capacity of the base is used more fully. Stress of the soil between piles is determined by friction forces along their side surfaces and the raft pressure upon soil. Friction forces increase with depth, stress from a raft, on the contrary, dissipates. As a result the saddle diagram with the minimum value in a point of equal tension from friction forces along side surfaces of piles and resistance of a raft.

Model and field tests

The part of the load that the raft carries grows up when the pile length is reduced and the space between piles is increased. Some test results carried out by different authors confirm it aim of the model tests was to determine the main factors of pile-raft-soil interaction. Model investigations were divided into small-scale and large-scale tests.

The object of the small-scale tests is to research the soil deformations under the raft in pile space. Models of driving piles (cross section 20x20*mm* and length 150*mm* and 300*mm*) were tested in the sand-filled test rig with transparent front wall. The soil was laid in the tray with layerwise compaction. Indicative strips were made of chalk through 50*mm*. The load was applied with leverage and weights.

Deformations of the soil in the base were fixed persistent by means of photofixation in the time of pile driving and loading of the groups. Significant surface warp of indicative strips was detected in process of pile driving.

After driving the pile tops were combined with the raft. Pile groups were subjected to static load. In the first place the high-raft pile foundation (without contact between the raft bed and the soil) were tested. Observational results show slipping of the lateral surface of the piles relative to surrounding ground. Additional minor displacements of the soil were found out only in the immediate vicinity of piles and away from the lateral surfaces were not occurred [4].

In the case of testing of the pile foundations with load-bearing raft the significant additional displacements of the soil in the pile space were observed. The settlement of the ground layers are diminished with depth similarly to shallow foundation (Fig. 2).

The results of research show that the soil under the raft in the pile space does not settle side by side with a high-raft pile group and can resist a considerable part of the external load.

The aim of the large-scale tests is to estimate efficiency of the raft consist of bored piles in sandy soil. Investigations have been performed on the Test Site of Geotechnics of Belorussian National Technical University. The single piles, raft, groups of piles and piled-raft foundations were tested with static load.

The raft was made as rigid square metal stamp (b=0,5m). Pile foundations consist of 1, 4, 6 and 9 bored piles with length of 1,0*m* and 2,0*m* and diameter of 0,06*m* were tested both with deep and high rafts. The results of pile foundation tests represented in figures 3 and 4.

The large-scale model test results confirm high efficiency of raft-soil interaction in full band of size-shape factors of pile foundation. In case of deep-raft pile foundation (or piled raft foundation) bearing capacity is significantly increased. The major bearing factors influencing the raft interaction are pile length, pile space and settlement on the foundation.

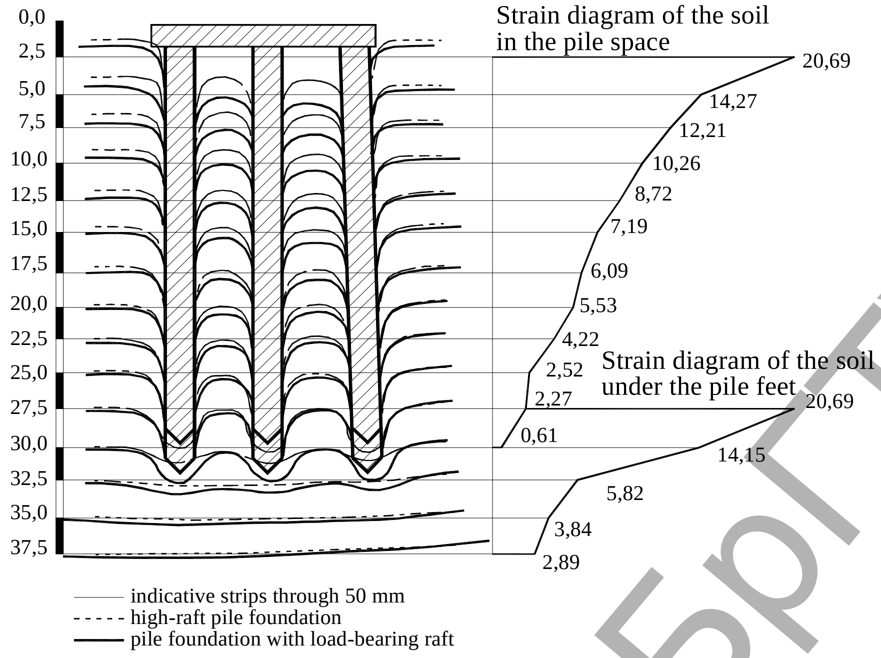


Figure 2 – Ground deformation in the base of pile foundation

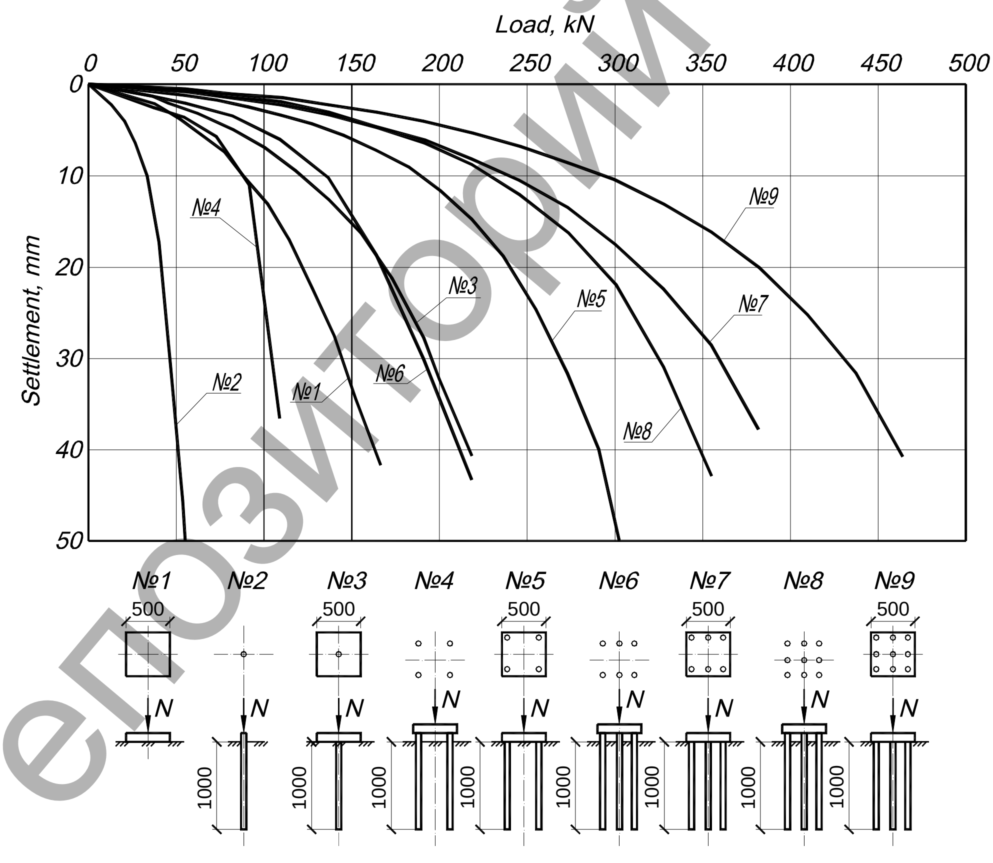


Figure 3 – The results of large-scale model tests of high-raft and deep-raft piled foundations consist of bored piles with length of 1000mm

The load-settlement diagrams presented in fig. 3 and 4 show that minimal increment of bearing capacity of the foundation take place in case of 9 piles with length of 2000*mm* (by 18%). In other cases bearing capacity increases with pile length shortening, pile space extension and settlement rising.

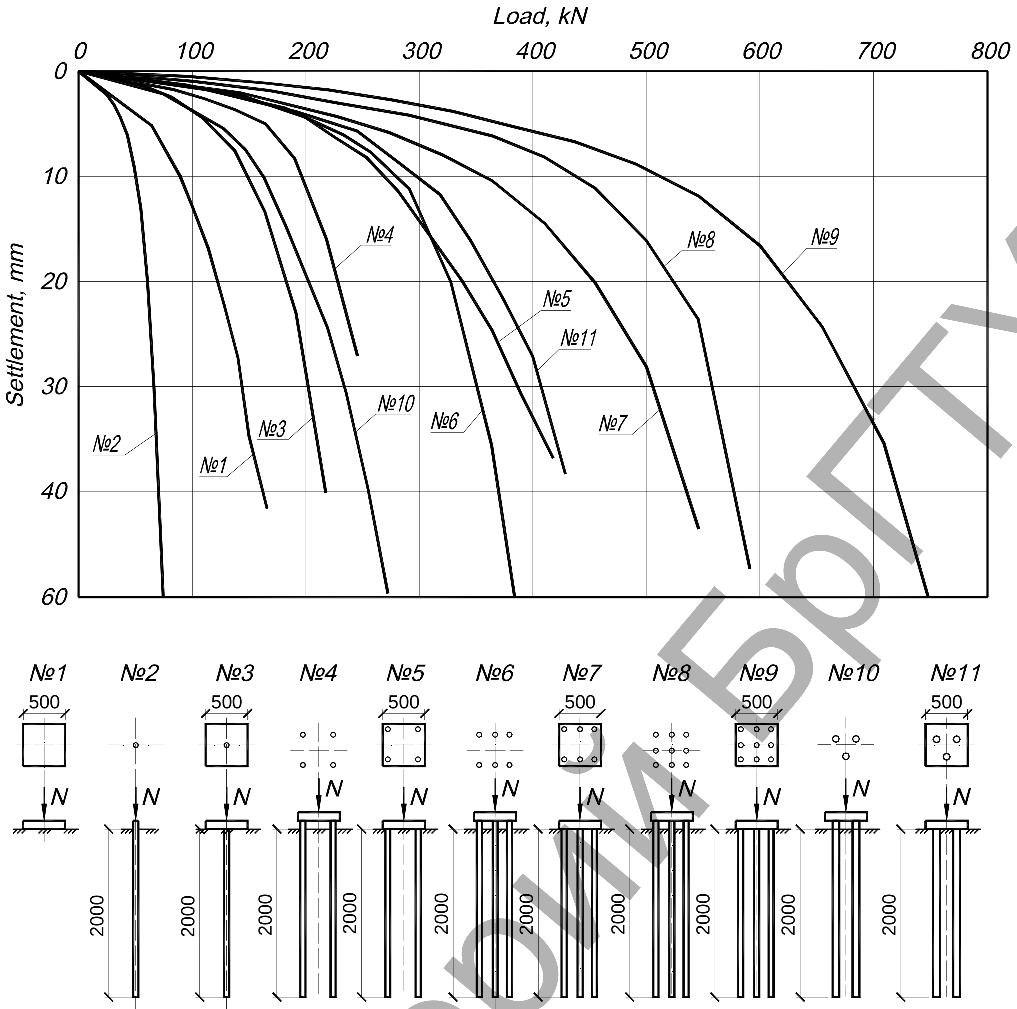


Figure 4 – The results of large-scale model tests of high-raft and deep-raft piled foundations consist of bored piles with length of 2000mm

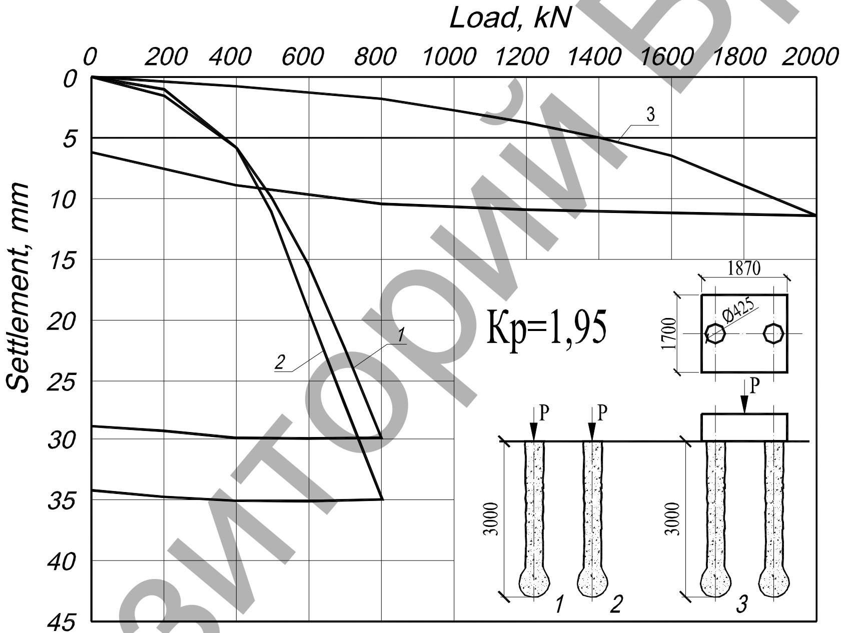
Building sites of Minsk are characterized by complicated geological conditions. Quite often the firm soils are located at the surface but at a depth of 5-10*m* a soft ground layers occur. Frequently filled-up ground is located at the surface. In these cases conventional long driven piles are used to transmit the load at deep-laid firm soil. The length of such piles could be 20*m* and more. The alternative foundation in such ground conditions consist of tapered piles with bearing raft. The sloping surfaces of tapered piles compact ground between piles and around the foundation. Bearing capacity of raft and lateral surface of piles considerably increase. Bearing capacity of raft with tapered piles much more than bearing capacity of raft with uniform cross-section piles. Stresses in the base of the foundation with tapered piles are dissipated in the top slices and do not reach soft ground layer at depth.

The results of tests prove efficiency of vibrostamped cast-in-situ tapered piles with bearing rafts when thick layer of filled-up ground is located at the surface. Strength characteristics of filled-up ground considerably improved due to consolidation. Sloping lateral pile faces eliminate negative friction. Compacted filled-up soil becomes the bearing layer both for piles and for rafts.

To estimate efficiency of piled foundations with bearing rafts static tests of single piles and couples of pile with the raft were carried out in different sites of Minsk in various ground conditions [5].

At the site in Belsky street 148 in Minsk firm loam soils were located at the surface but at a depth of 10*m* and more a soft loam soils with peat layers occurs. There were two alternate versions of foundation. The first was long driven prismatic piles with length of more than 12*m* to transmit the load at deep-laid firm soil. The second alternate was short vibrostamped cast-in-situ tapered piles (L=3-4*m*) with rammed dry concrete mix at the pile foot and bearing rafts to transmit the load at the surface layer of firm soil. Technical and economic assessment shows that the cost of the second alternate is far less. Bearing capacity of vibrostamped tapered piles was increased by 80% by means of ramming dry concrete mix at the pile foots and then by 30% by means of bearing raft. Raft ratio ($K_r=F_{pr}/F_p$= bearing capacity of piled-raft foundation/ bearing capacity of piled foundation) in such case K_r=1.30.

The subsoil in the site in Pritytzky Street consists of loessial loam, fine sand and peat layers. The first alternate versions of foundation was driven prismatic piles with length up to 20*m*. The second was vibrostamped cast-in-place tapered piles with widening at the pile feet (the length of the piles is 3 and 4*m*, diameter at the pile top 0.5*m*, diameter at the pile foot 0.3*m*).



1,2 – single piles; 3 – 2 piles with a raft (1.7x1.87 *m*)

Figure 5 – The results of tests of single piles and 2 piles with raft in residential quarter of Burdeinogo Street and Jakubovskogo Street

Single tapered piles and two fragments of foundation were tested with static load. Load-settlement diagram $S = f(N)$ shows that the raft interacting with subsoil increase bearing capacity of the foundation by 30-103% (K_r=1.30÷2.03). The magnitude of raft ratio K_r depends on raft area and ground conditions in the base of the piles and the raft [5].

The similar results were obtained in the site in residential quarter of Burdeinogo Street and Jakubovskogo Street. The two single bored piles and the same piles with a raft fragment were tested with static load (fig. 5).

Load-settlement diagram $S = f(N)$ shows that the bearing capacity of the foundation was increased by 95% (K_r=1.95).

Methods of analysis of piled-raft foundations

Analysis of model and field tests carried out in the Laboratory and Test Site of Geotechnics of Belorussian National Technical University as well as various building areas in Minsk and other cities allows to detect the basic factors which affecting the raft-soil interaction and to determine range of application of pile foundations with load-bearing rafts. Design methods of ultimate vertical load and settlement of piled-raft foundations were developed [6]. The results of theoretical and experimental researches performed by various authors were taken into consideration in development of the methods.

It has been found experimentally that the soil under the raft in the pile space does not settle with a pile group and in spite of traditional design approaches can resist a considerable part of the external load. Experimental total vertical stress diagrams in the base of various deep-raft pile foundations were carried out by Kazachok in the 1970s [3]. Contrastive analysis of experimental data and estimated stress diagrams received with linearly elastic semispace theory show that the experimental curves are similar to theoretical diagrams. Calculating error is not more than 5%. On basis of results of our investigations we can draw a conclusion that stress and depth of compressed layer of the soil in the base of a raft and shallow foundation are similar and can be described with similar methods.

The ultimate vertical load carried by pile foundations with bearing raft is calculated:

$$N=N_r+N_{pf} \qquad [1]$$

$$N=g_{cr}\, p_r\, A_r \qquad [2]$$

Were N_r = ultimate vertical load carried by pile group, N_{pf} = ultimate vertical load carried by the raft, pr = average contact pressure under the raft bed depends on ground conditions and the assumed settlement of pile group, A_r = raft area without total cross-sectional area of the underlying piles, g_{cr} = factor depends on ground surface preparation under the raft bed:

g_{cr} =1.0 for compacted stone bed,

g_{cr} =0.9 for compacted sandy soil,

g_{cr} =0.8 for compacted clay soil,

The settlement of pile foundations with bearing raft is calculated:

$$S_{pf}=S_p+S_{add} \qquad [3]$$

S_p = settlement of pile group under the load N_r, S_{add} = additional settlement of pile group arise from additional vertical stress under the pile feet in case of $H_c>L$ (H_c = compressed layer of the soil, L – pile length).

Detailed description of computing methods of pile foundations with bearing rafts, range of application, test and control methods are given in the article [6].

The experience of use vibrostamped tapered piles was adopted in the site of Orthodox Church in Sukharevo district in Minsk.

Ground conditions under the raft:

1) - dust clay sand (E=18*MPa*, h=4m);

2) - soft sandy clay (E=6*MPa*, h=2*m*);

3) - sandy clay with organic residues (E=10*MPa*, h=1,5*m*);

4) - peat (E=3*MPa*, h=2,5*m*);

5) - firm sand (E=25*MPa*).

The first alternate was foundation consist of 480 driven prismatic piles with length of 14*m* and cross sections 0.3*m* x0.3*m* and 0.35*m* x0.35*m*.

The most reasonable decision in such ground conditions is load transfer onto relatively firm upper layers of base. Calculation of the foundation according to [3] has shown that the raft transmits 40% of the load onto the base and the rest part of the load is transmitted by vibrostamped tapered piles with length of 3m, top diameter 0.5*m* and foot diameter 0.3*m*. The foundation consists of 285 tapered piles and 32 driven prismatic piles made before.

The cost foundation was reduced almost in two times by means of use short vibrostamped tapered piles with bearing raft.

Conclusions

1. The pile-pile interaction in sand significantly increases bearing capacity of the pile in a group.

2. The raft has significant influence on mode of deformation of the base. The large volume of the soil take part in the work and increase bearing capacity of the base about 10 – 100% depending on size and shape of foundation and ground conditions of the site. The large reserve of bearing capacity of the base has not investigated sufficiently.

3. When load is increased the settlement of piled-raft foundation take place more uniformly than piled foundation. On the graphical char $K_p=f(N)$ there is no pronounced critical point and sudden loss of bearing capacity.

4. The basic factors which affect the work of the raft in foundation are ground conditions, quality and consolidation of soil under the raft, size and shape of the foundation (type of piles, pile length and space, width of the raft); load on the foundation.

5. Application of short vibrostamped tapered piles with widening at the pile foots and bearing rafts is more effective than conventional foundations consist of driven prismatic piles. Compressing stress transmits into ground along the whole length of lateral pile faces without negative friction and by the raft. Upper layers of filled-up soil are compacted by means of sloping lateral pile faces and bearing capacity of this soil increasing considerably.

6. Application of our investigation results in construction practice shows that taking into account soil-raft interaction can reduce the cost of pile foundation in certain cases in 30-50%.

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