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DESIGNING AND FOUNDATION WORKS OF THE SOLID-CAST REINFORCED CONCRETE SLABS UNDER COMPLEX GEOLOGICAL ENGINEERING CONDITIONS

ABSTRACT

Under complex geological engineering conditions, the foundations of buildings or structures are the most cost-intensive constructions (the costs for erection reach up to 15–20 % of the total reinforced-concrete expenses). At present, the matters of designing and calculation of solid-cast reinforced-concrete foundations for the purpose of reduction of the steel and concrete consumption as well as their cost are vital.

The article considers the peculiarities of the engineering-geological structure of the construction site, physical and mechanical characteristics of soils and matters of the engineering preparation of the base for casting-place reinforced-concrete foundation slabs under confined space conditions of the residential complex on the plots at the address: town of Khimki, Moscow Region (two 24-storeyed houses with the two-level underground parking and 17-storeyed residential house with underground parking). The efficient technology for compaction of weal soils is proposed, the actual soils characteristics obtained after the technology of performance of the works for the base compaction, the results of the foundation slab settlement calculation are provided and the results of comparison of the actual and design settlements of the foundations of the above residential houses are presented. Since it is practically difficult to take into account all the factors when calculating and designing the foundations, the geodetic observations of the foundation settlements were performed to check the expected deformations of the residential houses being designed under complex geological engineering conditions. The analysis of the actual and design settlements has shown that the actual settlements of the foundations are considerably less than those obtained according to the calculation during the designing that confirms in our opinion the correctly chosen technique of the base for the foundation slabs. At present, the settlements of all the constructed buildings have been stabilised and have not exceeded the maximum allowable values as follows from the results of the geodetic observations.

Keywords: foundation, cast-in-place reinforced-concrete slab, soil, characteristics of soils, settlement, base compaction technique, static probing, plate-bearing test.

INTRODUCTION

At designing and building of cast-in-place reinforced-concrete slabs under complex geological engineering conditions (at availability of inhomogeneous, highly compressible, collapsible, bulk and other soils in compressed base width) the main issues are: development of an effective method of works performance to increase the soil bearing capacity; determination of design characteristics of soils compacted in the process of foundation; calculation of the foundation base under deformations.

These issues were resolved when designing cast-in-place reinforced-concrete slabs at the construction sites of a residential complex in town of Khimki, Moscow Region (two 24-storeyed houses with the two-level underground parking and 17-storeyed residential house with underground parking).

The general view of the residential complex is shown in Figure 1.

Figure 1. View of residential development from the side of the bay

ANALYSIS OF GEOLOGICAL ENGINEERING CONDITIONS OF THE CONSTRUCTION SITE

Geological engineering surveys for the buildings of the residential complex were made by Stroyizyskatel LTD (RF) in 2011.
The analysis is made for the engineering geological element located below foundation base, the mark ± 0.000 is accepted – 175.200 m, the planned basement level is 166.300 m (-8.90 m).

Directly under the base of the foundations underlay:

Recent sediments (tOIV), represented by bulk soils, which are dominantly displaced soils formed during the construction of the Moscow Canal and the planning of the floodplain space, as well as the development of the territory and communications laying. Opened filled soil, mainly water glacial, lake and lacustrine-glacial genesis. They are represented mainly by silt loams, laminated clays (often with an admixture of organic substances) with clays interlayers and sandy loams, there are clays interlayers including small amount of turf (engineering geological element (EGE) 2-1, 2-2).

Below are underlayed:

Quaternary undivided fluvial-glacial and glaciolacustrine deposits of Dnepr and Moscow horizons (f, lgOIId-ms) comprise the major part of site geological section. These deposits are represented by clays, loams, sandy loams and sands.

Clays are developed within the whole site, underlay under filled soils and are opened almost with all the wells. Clays of glaciolacustrine genesis (EGE 3-1, 3-2, 3-3); they are often slit, laminated and thin-laminated, with ferruginization cavities, seldom with an admixture of organic substances; soft and hard plastic, rarely semi-solid consistency, in places with cavities and thin interlayers of sand, moist and water-saturated; there are gruss and gravel, less often small gravel of carbonate and crystalline can be found; in the roof there are heavy clay loams. Clays of fluvial-glacial genesis (EGE 4-1, 4-2) were found as separate wells. Clays are sandy, often deep arenaceous, with the gruss and gravel, with cavities and stratified sand.

Loams are less developed in geological section than clays. Loams by fluvial-glacial genesis (EGE 5-1, EGE 13, 14, 15) are sandy and often deep arenaceous with gruss and gravel of carbonate and crystalline rocks, with cavities and stratified sand, high- and hard-plastic, more seldom semi-solid. Glaciolacustrine genesis loams (EGE 6) are slit, laminated, high-plastic, often with an admixture of organic substances, with interlays of slit clay, high-plastic, often with slit loam layer, laminated and water-saturated sand; in some places in the section the loam is facially replaced by clays (EGE 6a).

Sands (EGE 9-1, 9-2) medium-grained (EGE 11-1, 11-2) and coarse (EGE 10-1, 10-2), including the gruss and gravel, seldom semi-gravel (EGE 12); damp and water-saturated. Under their bulk density the sands are of medium density and dense.

Quaternary deposits of Dnepr glacial clay (gOIId) are represented by glacial clay, sandy, semi-solid consistency, with inclusions of gruss and gravel of carbonate rocks (EGE -12 ÷ EGE -15).

Physical-mechanical, strength and deformation characteristics of soils are given in the table. A typical geological engineering section is shown at Figure 2.

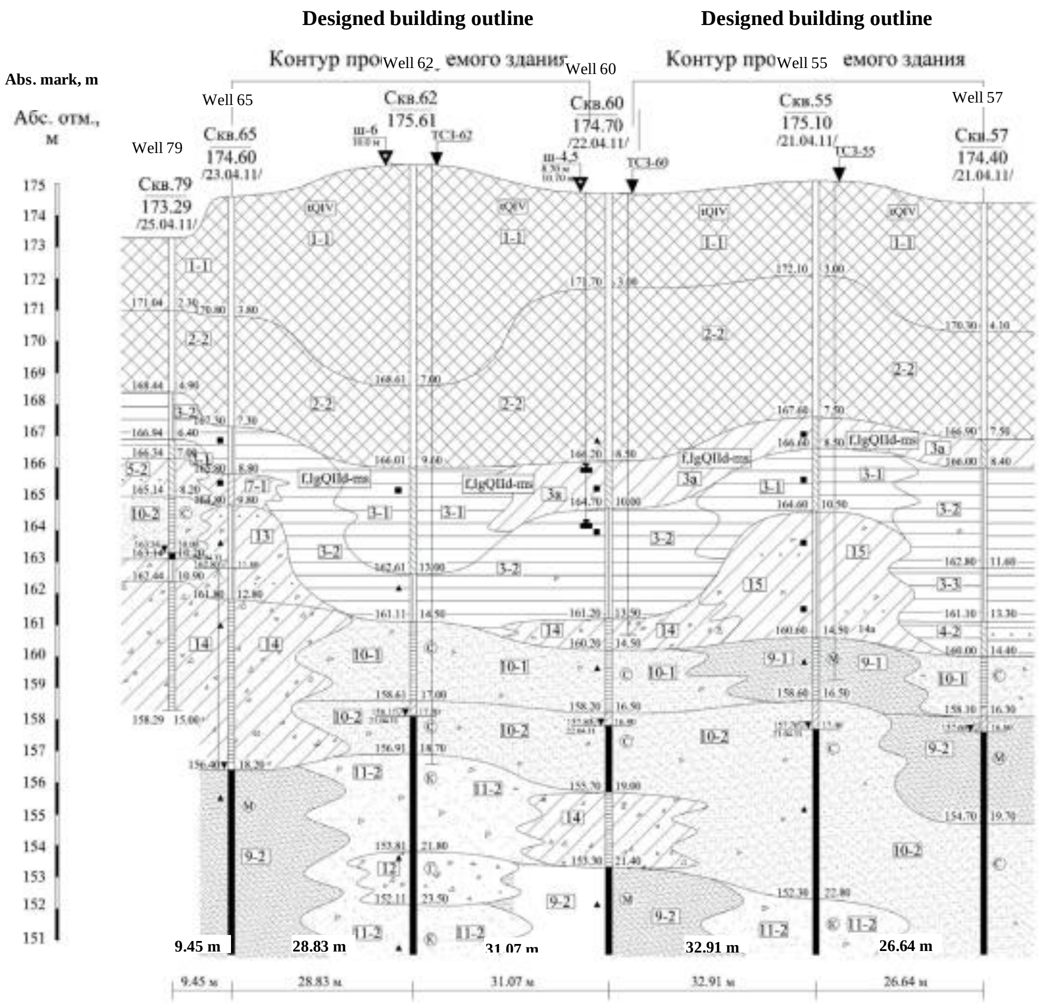


Figure 2. Typical geological engineering section

Physical and mechanical, strength and deformation characteristics of soils

EGE	Description	Specific gravity t/m³ (considering weighted water attack)	Specific cohesion t/m³	Internal friction angle, degr.	Stress-strain modulus, t/m³	Liquidity index, unit	Porosity index, unit	Soil particles specific gravity t/m³	Specific gravity, t/m3 (without consideration of weighted water attack)
		γ_{sb}^{*}	c_{II}	φ_{II}	E	I_L	e	γ_s	γ_{II}
1	2	3	4	5	6	7	8	9	10
2-1	Filled, clayey, packed	-	2.1	19	1300	0.53	0.84	2.68	1.88
2-2	Filled with high-plastic clay	-	1.9	17	900	0.59	0.54	2.68	1.85
3-1	High-plastic clays	-	3.3	16	1300	0.56	0.67	2.7	1.9
3-2	Hard-plastic clays	-	3.8	17	1600	0.37	0.84	2.7	1.89
3-3	Hard-plastic clays	-	4.2	18	1800	0.22	0.84	2.7	1.91
4-1	Hard-plastic clays	-	3.9	19	1700	0.33	0.84	2.7	1.91
4-2	High-plastic clays	-	3.6	18	1600	0.33	0.84	2.7	1.93
5-1	Hard-plastic loam	-	1.7	17	1600	0.29	0.84	2.68	1.9
6	Slit, high-plastic clay	-	1.5	16	1000	0.63	0.84	2.7	1.86
6a	High-plastic sand clay	-	1.7	16	850	0.63	0.58	2.68	1.8
9-1	Fine dense sands	1.044	0.2	35	3400		0.58	2.65	1.74
9-2	Coarse medium sands	1.044	0.1	32	2900		0.58	2.65	1.91
10-1	Coarse medium-grained sands	1.044	0.1	36	3400		0.58	2.65	1.78
10-2	Medium grained middle-density sands	1.044	0.0001	34	2900		0.58	2.65	1.92
11-2	Coarse, middle-density sands	1.044	0.0001	34	3000		0.58	2.65	1.96
12	semi-gravel middle-density sands	1.044	0.0001	38	3000		0.58	2.65	2
13	High-plastic loam	-	3.4	34	3200	0.28	0.49	2.68	1.79
14	Semi-solid sandy loam	-	3.4	23	2300	0.21	0.49	2.68	2.01
15	Light sandy clay	-	4.7	23	2500	0.21	0.49	2.7	2.02

PROJECT SOLUTION ON FOUNDATIONS BASE

Complicated factors in the design and construction of foundations at this construction site are:

- large capacity of filled soils;
- a complex (heterogeneous) geological engineering section of the site, caused by variegated bedding of various lithological differences in soils of different genesis;
- the presence of strongly hectic soils in the upper part of the section.

Analysis of structural schemes of buildings, loads and geological engineering conditions of the construction site allows recommending the cast-in-place reinforced-concrete slabs on a previously prepared basis as a foundation:

- for 24-storeyed house (with two sites) with the two-level underground parking on vibro-compacted sand and gravel cushion (*h*=2.50 *m*) (site 2) and compacted with driven piles C5-20 with 1.0 *m* stage (geomass) of soils at the separate site (site 1);
- for 24-storeyed house (with one site) with the two-level underground parking on vibro-compacted sand and gravel cushion (*h*=2.50 *m*) (site 2);
- for 17-storeyed house (with one site) with the underground parking on vibro-compacted sand and gravel cushion (*h*=3.00 *m*) and compacted with driven piles C3-20 with 1.0 *m* stage (geomass) of soils at the separate site.

This solution has allowed to avoid uneven settlements, caused by the presence of complicating factors, which can affect the reliability of operation of the above-foundation structures.

For 24-storey houses, for a relative mark of ± 0.000, the level of the clean floor of the 1st floor is taken, which corresponds to an absolute mark of 175,200 *m*. Planned basement level of slabs is 166,300 *m* (-8,90 *m*).

Preparation of the base for these foundation slabs is carried out in the following sequence:

- footing excavation is made up to mark 163.700 *m* (-11.50 *m*);
- a layer of gravel of fraction 10-40 mm (gravel fraction 10-70 mm) with a thickness of 0.4 *m* is produced to prevent the soaking or freezing of clay soils of the bottom of the footing, as well as to ensure normal passage and operation of machinery;
- works are carried out to strengthen the soils (EGE 3-2, EGE 3-3) in a separate section by means of a geomass from driven piles with a cross section of 200 × 200 *mm* in steps of 1.0 × 1.0 *m*, length of 5.0 *m* (C 5-20 series 1.011.1-10);
- a large or medium-grained sand layer without clay particles is made (the mass of particles less than 0.1 *mm* should not exceed 6 %) with a thickness of 0.85 *m* and a layer of broken stone (10-40 *mm* fraction) or gravel (10-70 *mm* fractions) with capacity 0.30 *m*;
- a dense of filled layers (sand and broken stone) is carried out by 15 passages of a vibrating roll with a mass of a sealing unit not less than 12-16 *tf*;
- the operational quality control of the sealed filled layers is made (K_y = 0.98);
- sanding with a large or medium-grained sand layer without admixture of clay particles (the mass of particles less than 0.1 *mm* should not exceed 6 %) with a thickness of 0.80 *m* and a layer of broken stone (10-40 *mm* fractions) or gravel (10-70 *mm* fractions) 0.20 *m*;
- sealing of filled layers (sand and broken stone) is carried out by 15 passages of a vibrating roll with a mass of a sealing unit not less than 12-16 *tf*;
- the entire construction site is planned by the mark of 166.200 *m* (-9.00 *m*);
- acceptance inspection of quality of sealing of a sand-gravel cushion is made;
- a concrete preparation device (concrete B7.5) with a thickness of 0.10 *m* is produced, which stands for the dimensions of the foundation slabs by 0.10 *m*;
- foundation cast-in-place reinforced-concrete slab is made in accordance with the project.

Surface sand compaction and broken stone preparation with a vibrating roller with a mass of a sealing unit 12-16 *tf* is performed in compliance with the following requirements:

a) the number of passes along one track 15 along the entire area with the last trace of not less than 20 cm with the grab of the previous track;
b) the speed of the vibro roll must be optimal and be about 4-6 *km/h*;

c) it is forbidden to stop the roller with the vibrating machine switched on for more than 30 seconds, this can lead to the destruction of the base (sudden immersion of the roller);
d) to avoid lateral soil displacement behind the sealing zone, a shoulder width equal to the width of the roller is arranged (approximately 1.5 *m*);
e) the oscillation frequency should be within 25-30 *Hz*, with an amplitude in the range of 1.5-2.0 *mm*;
f) after the end of the compaction, it is necessary to carry out control tests on the top of the compacted sand-gravel or broken stone (plate-bearing test, dynamic sounding);
g) if the required density cannot be reached, the compaction should be continued with a slightly increased or, on the contrary, reduced speed with selection of frequency and amplitude.

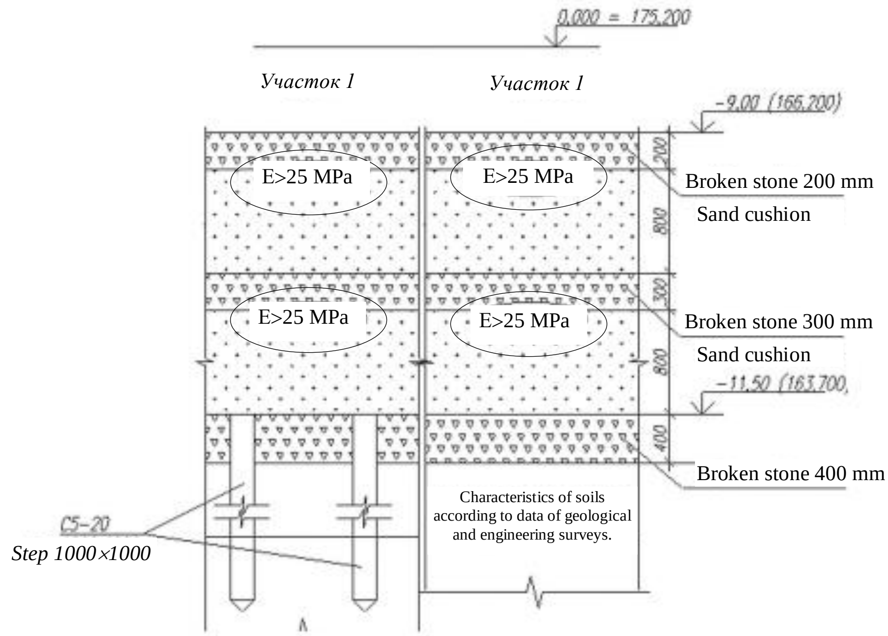


Figure 3. Diagram of prepared base for foundation slabs of 24- storey residential house

After the works on the engineering preparation, according to preliminary calculations the basis of soil characteristics should be as follows:

– for sand and gravel cushion when compacting of coarse sand and broken stone (gravel):
  c = 3.0 *kPa*, φ = 38 °, E = 35 *MPa*;
  when compacting of medium size sand and broken stone (gravel):
  c = 2.0 *kPa*, φ = 36 °, E = 35 *MPa*;

– for geomass from driven piles
  EGE 3-2 - E = 30 MPa, EGE 3-3 - E = 25 MPa;
  EGE 2-2 - E = 18 MPa, EGE 2-1 - E = 23 MPa;
  – for the remaining soils according to geological engineering surveys.

The diagram of the basement prepared for foundation slabs is shown in Figure 3.

Similarly, works are held to prepare the base for the foundation slab of a 17-story residential building.

BASE CALCULATION BY DEFORMATIONS

The purpose of calculating the base by deformations is to limit the absolute or relative displacements of foundations (in our case slab) and suprafundamental structures to such limits, under which the normal operation of the structure is guaranteed and its longevity is not reduced. This means that the strength and fracture toughness of foundations and suprafundamental structures are checked by calculation, taking into account the forces that arise when the structure interacts with the base.

According to Gomelproekt JSC:

- the depth of laying the foundation slab is 166.200 *m* (-9,00 *m*), taking into account the concrete preparation (δ = 100 *mm*);
- geometrical parameters of the foundation slab:
  A = 1516 m^2; B = 38.94 *m*; L = 38.94 *m*;
- average pressure on the base under the baseplate foot:
- p = 830 *kPa* (8.30 kg/cm^2).

In accordance with clause 1.23 of the "Guide for the design of slab foundation structures and tower structures" with a clay base, the own weight of the slab foundation can be taken with a coefficient of 0.5. In this case, the average pressure on the base under the foundation foot is p = 415 *kPa* (4.15 kg/cm^2).

Since the width of the base plate is b = 38.94 *m*> 10 *m*, and the thickness of the layer with the strain modulus E <10 *MPa* (EGE-6a) h = 1,4 *m* <0,2 H = 2,798 *m* in accordance with clause 2.10 (c) "Guide for the design of slab foundation structures and tower structures" [1], to calculate the settlement we shall use the design scheme of a linearly deformable layer.
The thickness of the linearly deformable layer and the base settlement are determined in accordance with Appendix G SP22.13330.2011 [2].

Analysis of the results of calculating the sediment of foundation slabs showed that the absolute precipitation is:

- 24-storey residential building (with two sites)
  $S = 7.25 \div 13.66$ *cm* <S_u = 15 *cm*
  (Appendix C SP22.13330.2011);
- 24-storey residential building (with one site)
  $S = 9.05 \div 12.15$ *cm* <S_u = 15 *cm*
  (Appendix G SP22.13330.2011);
- 17-storey residential building
  $S = 8.47 \div 9.69$ *cm* <S_u = 15 *cm*
  (Appendix G SP22.13330.2011).

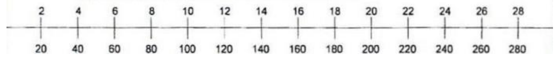
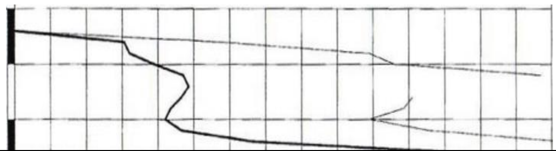
The roll caused by the heterogeneity of the base (relative difference in precipitation) (Δ S/L) is defined as the ratio of the difference between the sediment of the bore wells and the distance between them:

- 24-storey residential building (with two sites)
  $\Delta S/L = 0{,}00013 \div 0{,}00200 < (\Delta S/L)u = 0{,}003$
  (Appendix G SP22.13330.2011).
- 24-storey residential building (with one site)
  $\Delta S/L = 0{,}00003 \div 0{,}00038 < (\Delta S/L)u = 0{,}003$
  (Appendix G SP22.13330.2011);
- 17-storey residential building

$\Delta\ S/L = 0{,}00011 \div 0{,}00059 < (\Delta\ S/L)u = 0{,}003$
(Appendix G SP22.13330.2011).

BUILDINGS SETTLEMENTS MONITORING (BUILDINGS 5A AND 5B)

To determine the deformation properties of sand and gravel cushion with layer-by-layer filling and vibro-compaction by the technology proposed above, the experimental testing was carried out by static probing with LBU-50 machine with PIKA-17 equipment set (probe of type II), according to GOST 19912-2001 [3] (Figure 4) and vertical static load on the stamp, according to the procedure established by GOST 20276-99 [4] and GOST 30672-99 [5] (Figure 5), performed by Grand GEO LLC (Moscow).

EGE No.	Layer foot		Layer capacity	Soil description	Ground waters, depth/abs. mark	Sounding depth, m	Specific resistance of soil under the probe cone Q3, MPa / Specific resistance in the area of the lateral surface of the friction clutch of the probe F3, kPa
	Depth	Abs. mark					
	0.4	166.00		Soils are drilled			
1A	1.0	165.40	0.6	Medium-grained sands, dense, average degree of water saturation with inclusions		1	
2A	1.4	165.00	0.4	Broken stone			
1A	2.2	164.20	0.8	Medium-grained sands, dense, average degree of water saturation with inclusions		2	
2A	2.6	163.80	0.4	Broken stone		2.6	

Sounding location: 2C Sounding date: 16.04.2013 Well: 2 Drilling date: 17.04.2013 Surface absolute mark: 166.40 m. Sound type (by GOST 19912-01): 2, using SP 11-105-97 and GOST 19912-2001, GOST 20522-96	Ground waters			GrandGEO LTD			Drawing No. 4	
	Appear. Level, m	Established level, m	Measure date	Surveys Department Results of soil testing with static sounding (GOST 19912-01)			Site: Chimlk, 5A Yunnatov St., Right Bank building estate	
				Director for Production and Research	/Signature/	Kashirskiy V. I.	Site: Residential house	
				Leading specialist	/Signature/	Znamenskiy E. N.		
				Prepared	/Signature/	Kashirskaya V. V.	Page	Pages
				Checked	/Signature/	Kashirskiy V. I.		

Figure 4. Static testing of sand and broken-stone cushion

P	S1	S2	S3	S
0.00	0.00	0.00	0.00	0.00
0.05	0.02	0.09	0.14	0.08
0.10	0.65	0.72	0.80	0.72
0.15	0.91	1.02	1.29	1.07
0.20	1.56	1.75	1.82	1.71
0.25	2.02	2.29	2.34	2.22
0.20	2.02	2.29	2.34	2.22
0.15	2.02	2.28	2.31	2.20
0.10	2.01	2.28	2.31	2.20
0.05	2.00	2.28	2.29	2.19
0.00	1.75	2.03	2.16	1.98
0.05	1.77	2.11	2.21	2.03
0.10	2.29	2.42	2.56	2.42
0.15	2.72	2.94	3.12	2.93
0.20	3.12	3.35	3.66	3.38
0.25	3.69	3.92	4.11	3.91
0.30	4.24	4.68	5.02	4.65
0.35	4.79	4.92	5.21	5.31
0.40	6.21	6.33	7.45	6.66
0.35	6.21	6.32	7.45	6.66
0.30	6.20	6.20	7.45	6.66
0.25	6.18	6.18	7.44	6.64
0.20	6.16	6.16	7.42	6.63
0.15	6.13	6.13	7.43	6.61
0.10	6.11	6.11	7.41	6.59
0.05	6.08	6.08	7.38	6.56
0.00	5.68	5.68	6.86	6.07

Well No.	1
Test No.	1
Date	16.04.2013
Stamp type	flat
Stamp square, cm^2	2500
Test depth, m	0.40
Wellhead elevation, m	166.39
Ground waters level, m	-
EGE	1a
Soil type	sands

Estimated coefficients in accordance with GOST 20276:
Poisson ratio (v) = 0.3

Penetration ratio (Kp) = 1

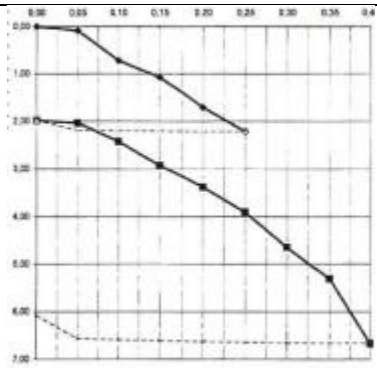
Stamp diameter (D), cm = 56.42

Stamp type ratio: $K=(1-v^2)$ 0.79 Kp D=40.56

Deformation module $E=K\Delta DP/\Delta S$ E2/E1 = 1.15

E_1 MPa = 39 in interval, MPa from 0.05 to 0.2

E_2 MPa = 45 in interval, MPa from 0.05 to 0.2



mm		
Layer foot	Soil specification	
IGZ-2a 0.40	broken stone	
IGZ-1a 1.20	Medium-grained sands, medium water saturation, dense	
IGZ-2a 1.50	broken stone	
IGZ-15 2.30	Medium-grained sands, medium water saturation, medium dense	

Figure 5. Tests of sand and gravel cushion with vertical static load on the stamp

During the construction of buildings, a geodesic monitoring of precipitation (Figure 6) is held. Average actual draft by the end of construction was:
24-storey residential building (with two sites) - S_{fact} = 7.7 cm;
24-storey residential building (with one site) - S_{fact} = 5.1 cm;
17-story residential building – S_{fact} = 12.5 cm.
Since the foundation plate is a rigid end structure, then the design load can be taken as an average,
The average sediment was:
24-storey residential building (with two sections) - S_{calc} = 10.3 cm;
24-storey residential building (with one plot) - S_{calc} = 10.2 cm;
17-storey residential building - S_{calc} = 9.3 cm.

Analysis of the actual and estimated settlements of 24-storey residential buildings showed that the actual precipitation is much lower than estimated, which is caused by additional compaction of the prepared base with a load increasing in the process of building construction. Precipitation of these buildings by the end of 2015 stabilized, which is confirmed by geodetic monitoring performed after the erection of buildings (0.5 years). Also, the precipitation stabilized after the 17-storey building was erected. Precipitation in this case is somewhat higher than the calculated ones (because of the large thickness of the layer of filled soils (up to 5 m) below the foundation slab), but do not exceed the permissible (Figure 6) ones.

CONCLUSION

Under specially selected technology for compacting low-strength soils a foot for monolithic reinforced concrete foundation slabs has been prepared during the construction of a residential complex in Khimki, Moscow Region (two 24-storey houses with a 2-level underground parking and a 17-storey residential building with an underground parking).

Analysis of the materials presented in the article suggests that practically any complex soils (heterogeneous, highly compressible, subsidence, bulk, etc.) can be the base for cast-in-place reinforced-concrete slabs after compaction by means of a specially selected technology for increasing the bearing capacity of soils.

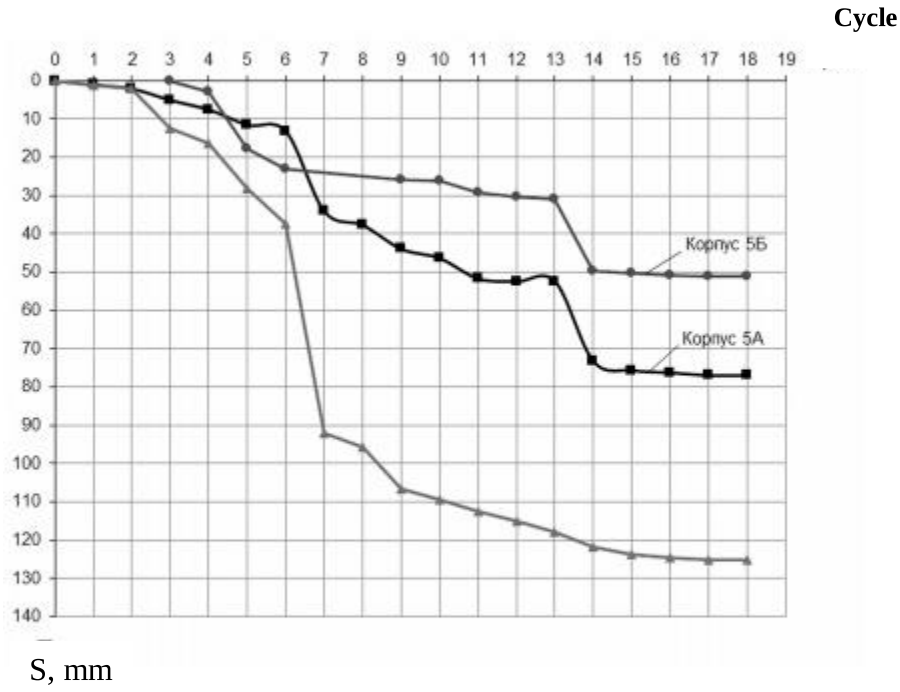


Figure 6. Geodetic monitoring of the settlements of buildings

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