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Design of 462 meters high Lakhta Center Tower and monitoring results during construction process

Conception de la tour centrale de Lakhta de 462 mètres de haut et suivi des résultats pendant le processus de construction

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ABSTRACT: The results of monitoring performed during the construction of the Lakhta-Center Tower in St. Petersburg r evealed that the actual settlement of the foundation installed in stiff clayey soils was less than designed one. Moreover, the load distribution in piles differed from the modern concept of the piles group behavior: the load resistance in central piles was larger than in edge piles, and they showed a single pile performance. A series of calculations was made to understand the reason for such discrepancies showed that only enhanced stiffness of founding stratum and smaller thickn ess of compressible soil mass might produce such effect. Overconsolidation and anisotropy of soils, interaction of piles a nd increase in their capacity when loading, as well as the relationship between strain state and varying deformation mod ulus during the construction might have a significant influence on the stiffness of the founding stratum. Installation of th e piles performed prior to excavation significantly enlarged the foundation rigidity and led to prestressing of the soil ma ssive, thus excluding soil softening and increasing horizontal stress.

RÉSUMÉ : Les résultats de la surveillance effectuée lors de la construction de la tour Lakhta-Center à Saint-Pétersbourg ont révélé que le tassement réel des fondations installées dans des sols argileux rigides était inférieur à celui prévu. De plus, la répartition de la charge dans les pieux différait du concept moderne du comportement du groupe de pieux : la résistance à la charge des pieux centraux était plus grande que celle des pieux de bord, et ils ont montré une performa nce de pieu unique. Une série de calculs a été effectuée pour comprendre la raison de ces écarts a montré que seule u ne rigidité accrue de la couche de fondation et une plus petite épaisseur de masse de sol compressible pourraient produi re un tel effet. La surconsolidation et l'anisotropie des sols, l'interaction des pieux et l'augmentation de leur capacité lors du chargement, ainsi que la relation entre l'état de déformation et le module de déformation variable pendant la constru ction pourraient avoir une influence significative sur la rigidité de la strate de fondation. La mise en place des pieux ré alisée avant le creusement a considérablement augmenté la rigidité des fondations et conduit à une précontrainte du sol massif, excluant ainsi l'adoucissement du sol et l'augmentation des contraintes horizontales.

KEYWORDS: high-scrapper, piles, calculations, monitoring.

1 INTRODUCTION

The Petropavlovsk Cathedral was considered the tallest building in St. Petersburg until 2012. The height of its spire is 122 meters. For a long period the construction of the buildings taller than the spire of the Cathedral has been restricted in St. Petersburg. However, the current tendency to construct tall buildings in large cities has not passed St. Petersburg by. For instance, a 126 meters high building was erected in 2012. Construction of another highrise building with the height of 145,5 meters was completed in 2013. At the same time, the soil investigation for the construction site of the tallest building in Europe was conducted in the Okhta district of St.Petersburg in 2008…2010 (Petrukhin V.P., et al 2010, Trufanov A.N., Shulyatyev O.A, 2010). However, due to the pressure of the public, who protected the historical view of the city center, the engineering survey and the design works were terminated.

Later, the project was revived and a new construction site was planned to be arranged at a greater distance from the city center in the Lakhta vicinity. The name of the structure – Lakhta-Center originated from the name of the vicinity. Herewith, the designed height of the structure became 465 meters by then.

The height of the spire is 462 m. The tower's structural system is core/outrigger. The area of the first above ground floor is approximately 2000 square meters. The unfactored load from the superstructure is 4913 MN; the factored load is 6590 MN. Thus unfactored uniform distributed pressure on the ground is 2,45 MPa.

2 GROUND CONDITIONS

The results of the engineering survey have shown that the construction site comprises interstratified layers of soft varved clay, silty clay and sand (SU 1-4) overlying Moraine deposit (SU 5,6). These are underlain by Vendian clay (SU 7-9), which in turn overlies Sandstone imbedded with siltstone and mudstone (SU 10) (Figure 1) (Shulyatyev O.A., 2016).

There had been insufficient experience in construction of skyscrapers in St Petersburg by the time the development of the Lakhta-Center project was under consideration. The above mentioned high-rise buildings were founded on piles extended into rather stiff moraine bearing stratum. It was evident that this stratum was unable to bear the pressure produced by heavy Lakhta Tower. The lithological stiff rock units occurred at a depth of more than 200 meters. In this case, the Vendian clay was considered the most appropriate founding stratum. The depth of the Vendian clay occurrence ranges from 25 to 105 meters.

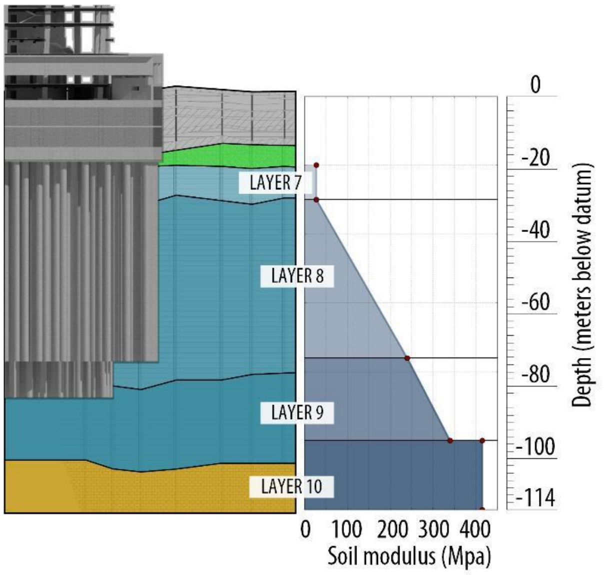

Figure 1. Geological cross-section and distribution of the deformation modulus versus depth. Boreholes: 1 – with tell-tales for assessing sequential deformation of the soil layers; 2 – equipped with strain gauges for measuring deformation of 65 meters long piles; 3 – equipped with pore pressure gauges; 4 - equipped with strain gauges for measuring deformation of 55 meters long piles

The Vendian clay can be classified as either very stiff clay or very weak rock. This soil had never been utilized as a bearing stratum for comparable pressure level. In the engineering practice, the Vendian clay has been occasionally interacted during metro tunneling, and it has been considered as a container medium for the toxic waste storage.

Engineering investigation of the site included standard laboratory tests, such as oedometer and triaxial compression tests. Field investigations comprised plate-bearing tests performed inside a casing at a 30m depth meters, pressuremeter tests up to 120 m depth, O-Cell static load pile tests and geophysical tests.

Soil investigation revealed specific properties of the Vendian clay. The stratum was over consolidated (OCR = 2…3) and exhibited mechanical anisotropy (stiffness in the vertical direction is 2..3 times less than in horizontal direction). The clay also showed rheological behavior, which, according to predictions, could result in increase in settlement by 30% over 100 years of the structure life cycle. Besides, the soil stiffness linearly in- creased with depth (Figure 1).

3 FOUNDATION STRUCTURES

The investigation of the Vendian clay has shown that overall stability and safety of the foundation structure can be ensured either by utilizing super-long piles or by expanding the area of foundation thus reducing the pressure on the soil. The latter approach also enhances structural resistance to the lateral loads and reduces possibility of tilting. For the purpose, a new concept of a box type raft has been developed. The bottom of the box has a shape of pentagon inscribed in a circle of 100 m in diameter (figure 2). The 5542 square meters area of the bottom reduces the unfactored pressure to 886 kPa (Shulyatyev O.A. 2016).

Pile length and spacing parameters were governed by the results of serviceability limit state (SLS) calculations. The pile spacing is minimal below core wall area and gradually increases towards the edges (figure 3).

4 GEOTECHNICAL MONITORING SYSTEM

The comprehensive system of the geotechnical monitoring included 2800 sensors of different type and provided the following measurements: pile load, pressure under the bottom of the piled raft, layer-by-layer soil displacement, foundation settlement, soil pore pressure, and the box-shape foundation capacity (Figures 4,5) (Travush V.I. et al, 2018).

Mean design pile load was calculated at 2545 tons. Pile loading tests performed (conducted, carried out, fulfilled etc.) using submersible jack technique (O-Cell) showed that piles car- ried the design load with a sufficient safety margin (Travush V.I. et al 2018). Numerical back analysis assessed the top-down pile capacity. The average pile resistance at the required settlement of 40 mm was more than 65 MN.

Pile internal forces were measured in the 12 selected piles equipped with groups of 4 vibrating wire (VW) strain gauges in seven different levels along the pile length, 336 in total. Each group contained four strain gauges. Totally, there were 336 measuring devices installed in the pile field.

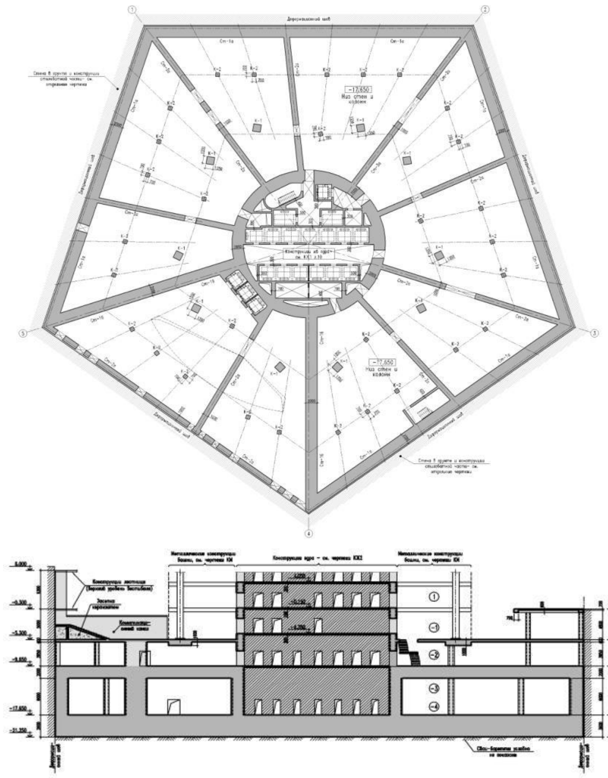

Figure 2. Layout and cross-section of the box-shape pile raft. The tower foundation was designed with respect to the state of the art concept of utilizing piles of varying length (Figures 1, 3). This ensures the stiffness of the pile foundation enough to sustain excessive loads transmitted by a rigid central core of the superstructure.

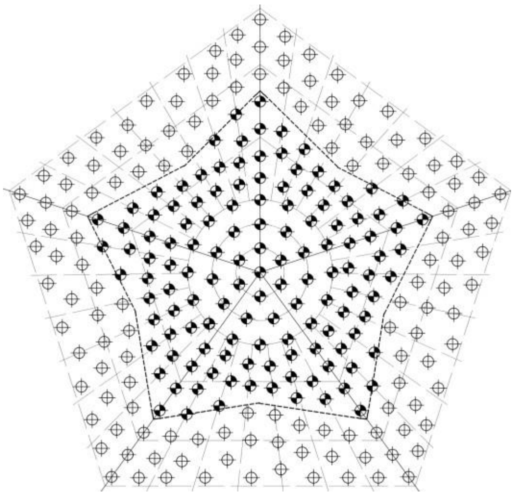

Figure 3. Piles layout. Piles are 65 m and 55 m long, 2 m diameter.

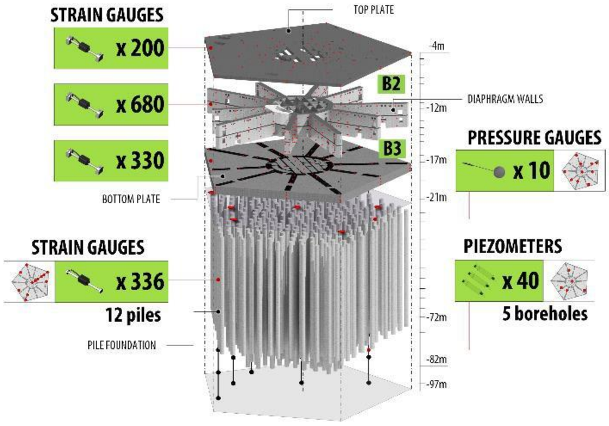

Figure 4. Scheme for the geotechnical monitoring of the underground structure with loads (MN) applied to the tower foundation

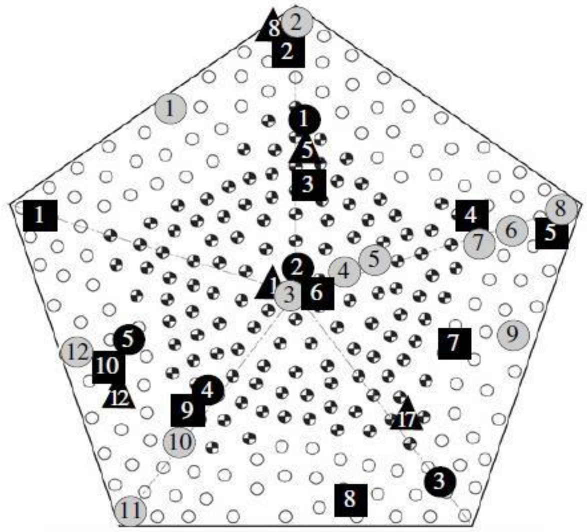

Figure 5. Schematic diagram of the sensors layout: bore- holes instrumented with pore pressure gauges (PP); - bore- holes instrumented with extensometers (EX); - pressure sensors for measuring contact pressure under the bottom of the foundation (PS) - for 65 meters long piles and for 55 meters long piles; piles equipped with strain gauges.

The pressure under the foundation box was measured with 10 VW pressure sensors. Layer-by-layer soil deformation was observed by 5 borehole extensometers, each one was instrumented with 19 benchmark points. The lower benchmark was installed at a depth of 95 meters, the upper one - at the 28 meters depth. That was 13 and 11 meters below piles and foundation box bottom respectively. Layer-by layer soil deformation was measured manually with a set period. The lower benchmark was taken as a conventionally fixed one.

The vertical displacement of the foundation was monitored by the geodetic leveling. Therefore, benchmarks were installed into the both lower and upper foundation slabs.

5 ANALYSIS OF THE GEOTECHNICAL MONITORING RESULTS

5.1 *Contract pressure under the foundation slab*

The contact pressure measured under foundation slab showed the following (Figure 6). The maximum measured average pressure under the bottom of the box foundation reached 72.4 kPa by November 2020, which is about 16% of the total weight of the erected structure (41.18 MN) and was in good agreement with the calculation results and general ideas about the pile foundation operation.

Considering the change in the contact pressure over time showed two sudden drops in pressure. The first one occurred at the beginning of the construction, when the semi top-down bracing system was dismantled and foundation slab was set into operation. The second pressure drop took place after the complete erection of the superstructure and was caused by the pressure re- laxation under the foundation slab and, consequently, by the partial transmission of the load to the piles. Initially, before the foundation was installed and “flexible” load produced by concrete foundation mattress was applied, the supporting soil sustained the total load. This increased the lateral loads and led to the additional squeezing of the piles with the soil. By November 2020, the average contact pressure became 47 kPa, which corresponded to the load of 267.35MN or 10% of the total weight of the erected structures. Due to the performed finishing, the weight of the structure increased and another pressure surge took place with an average of 20 kPa or 30% of the total changed contact pressure under the piles cap.

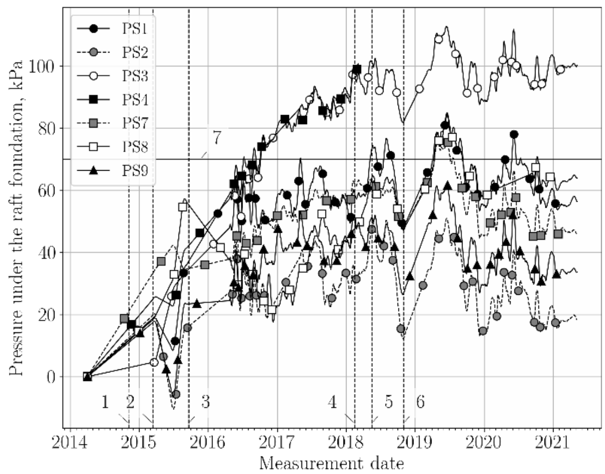

Figure 6. Changes in the contact pressure based on readings from PS1…PS9 sensors taken during the construction (the date of the last changes – March 2019): 1 – installation of the concrete foundation mattress, 2 – the beginning of the cross-brace system dismantling, 3 – completion of the underground structure construction, 4 – completion of the reinforced concrete structures, 5 – mounting of the spire, 6 – finishing, 7 – the designed contact pressure under the pile cap.

5.2 *Pile forces*

The monitoring results provided data on the load distribution along the pile shaft over time after execution of the foundation slab. Table 1 presents the loads carried by each pile head. The analyzed results showed that central piles sustained larger loads than those on the corners. Taking into account that pile spacing is 1…4d, where d – is a diameter of the pile, such load distribution contradicts with a pile group effect theory, according to which, the edge piles bear the majority of the loads (Poulos, H.G., 1968; Katzenbach R., 2017; Fedorovsky V.G. et al, 2008; Shulyatyev O.A. et al, 2009; Kharichkin A. et al, 2009).

The numerical back-analysis of the test results revealed that the closer agreement with calculated load distribution could have been achieved if the soil base had been more rigid, and if soil stiffness had exceeded the ones obtained from investigation re- sults by two times, as well as if the thickness of the compressible stratum had been significantly smaller (Table 1).

Table 1 Load distribution in the piles' heads

No of P ile	Pile head capacity (MN) with regard to:		
	Monito ring re sults	Calculation wit h investigated soil properties	Calculation with enlarged soil s tiffness
Central piles			
PL 3	32.5	11.9	18.1
PL 4	35.3	12.9	18.6
PL 5	-	12.3	19.4
Row piles			
PL 6	20.4	15	15.5
PL 7	8.1	11.9	12.6
PL 8	12.9	23.3	12.9
Edge piles			
PL 1	9.4	15	12.9
PL 9	10.2	15.7	15.7
PL 12	11	15.1	12.6
Corner piles			
PL 2	9.5	23.7	13.5
PL 8	12.9	23.3	12.9
PL 11	10.6	23.3	13

In order to increase the rigidity of the soil base the follow- ing factors were taken into account: overconsolidation and anisotropy of soils, interaction of piles and an increase in pile capacity while loading, correlation between strain state and deformation modulus variation during construction process. Installation of the piles performed prior to excavation significantly enhanced the soil base rigidity and led to prestressing of the soil massive, thus excluding soil softening.

Loads on piles depend on distance between piles (pile group effect), thickness and stiffness of layer between pile and soil (for piles with toe on rock socket this influence is minimum), elastoplastic deformations of piles (Pouls. H.D. and Devis E.H., 1980; Pouls. H.D., 2017), soil-structure interaction and sequence of construction (Fedorovsky V.G. et al, 2013 a, b; Shulyatyev S. 2013 e.t.c).

Bokov I.A. et al, 2019 show that with decrease thickness and increase stiffness of the underlying soil group effect and redius of influence decreases significantly.

The monitoring results showed that the distribution of stress evenly occurred along the entire length, regardless of the pile position in the field (Figure 7). The distribution of stress along pile length was close to a linear one, which indicated a constant skin resistance of 93 kPa (maximum 201 kPa) for central piles and 41 kPa (maximum 91 kPa) for corner piles. The above- mentioned axial force distribution was unable to reach even with modeling piles as 3D elements and soil properties overhaul.

When the building's frame was erected, stress continued to increase in the heads of corner and edge piles (figure 5,8; piles PL2, PL8, PL1). On the contrary, stress sustained by the heads of central piles was reducing. End bearing capacity of piles in- creased independently of their position (fig. 8). Such load distri- bution could be associated with the creeping phenomena.

The tensile stress of almost 1.42 MPa, which corresponds to the load of 4.46 MN, in the lower part of almost all the piles except for PL4, PL6, PL8 and PL9 was increasing from the be- ginning of observations till the last measurement (March 2019). Firstly, this indicated that the stress did not reach the pile toe, and the pile skin carried most of the load, and secondly, that softening of the soil in the lowest part of the foundation went on together with compressing phenomenon.

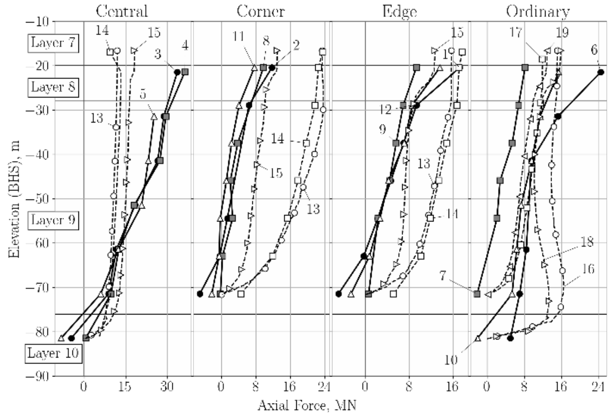

Figure 7. Stress distribution in the piles by March 2019: 1…12 – according to the monitoring results PL1…PL12 respectively; 13…19 – calculated (13, 16, 17 without changing the foundation properties, 14 – with 3D modeling, 15, 18, 19 – with regard to enhanced rigidity and stiffness of the foundation and increasing thickness of the compressed massive)

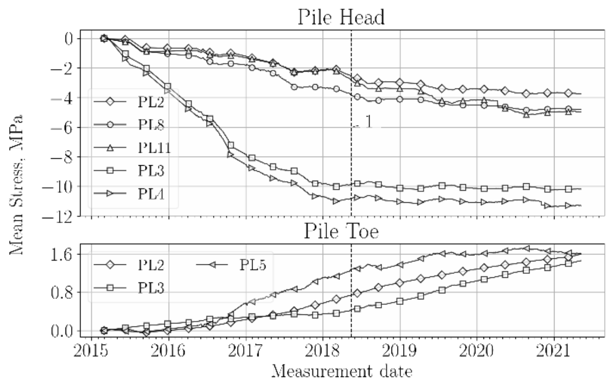

Figure 8. Changes in the pile tension measured during the construction (the date of the last measurement –March 2019): 1 – the completion of the building frame erection.

5.3 *Layer-by-layer soil deformation*

When analyzing layer-by-layer soil deformations under the foundation, the lower benchmark was taken as a relatively fixed point, since in most cases the stresses did not reach the lowest part of the pile shaft. In general, the measured layer-by-layer deformations indirectly confirmed the load distribution in piles, indicating that at a depth of 65-75 meters, a softening phenomenon took place and the foundation settlement evenly occurred over the entire depth. This pointed at the independent pile behavior (Figure 9). At the beginning of 2017, the soil softening in the lowest part of the foundation was recorded in three observational boreholes. The last measurements taken in February 2018 recorded the softening phenomenon only in one of them (see borehole EX8 in figure 9). Maximum foundation settlement of

30 mm was observed in the central area, minimum settlement of 12 mm was recorded in the edges. This confirmed the measured horizontal load distribution between the piles

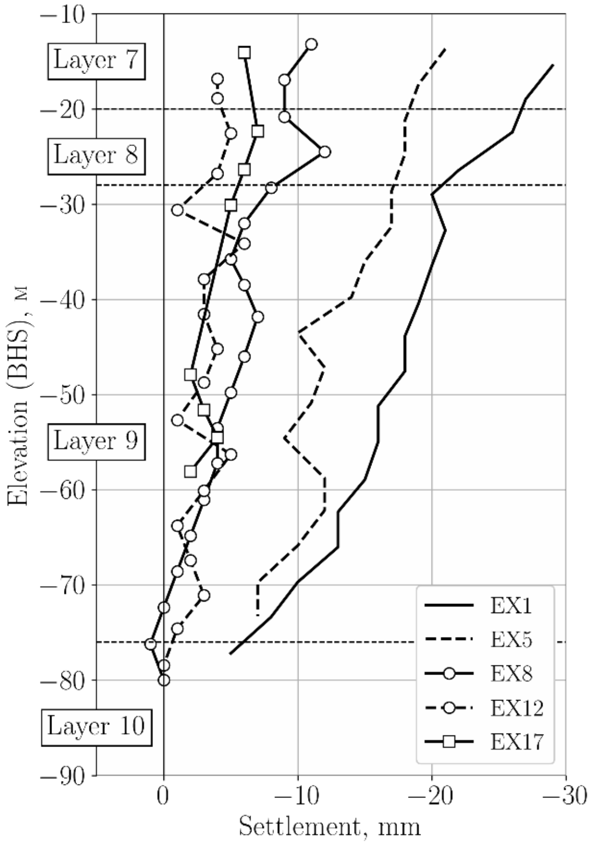

Figure 9. Changes in foundation deformation with depth based on the layer-by-layer deformation measurements conducted in observational boreholes.

5.4 *Foundation settlement*

According to observations carried out in March 2018, maximum settlement was 32 mm by the time. The same settlement had been calculated for the foundation with a greater rigidity and stiffness, and for the smaller thickness of the compressible soil massive (Fig. 10). At the same time, the calculation performed using the initial soil parameters results in the increase in the settlement by nearly two times

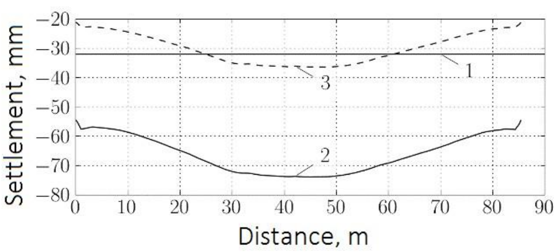

Figure 10. Diagram of the calculated and measured foundation settlement along the axis 2: 1 – observed maximum settlement, 2,3 – settlement calculated regardless changes in foundation properties, and for the cases with a foundation with higher rigidity and stiffness and with smaller thickness of compressible soil massive.

6 CONCLUSIONS

1. According to the results of geotechnical monitoring following conclusions can be drawn:
   - The measured settlement of the foundation (both absolute and relative values) and pile loads are lower than the calculated ones. On the one hand, this confirms the reliability of the foundation, on the other – indicates the factors significantly increasing the soil base rigidity: overconsolidation and anisotropy of soils, interaction of piles and an increase in their capacity while loading, relationship between strain state and deformation modulus variation developed during the construction process. Installation of the piles performed prior to excavation significantly increased the soil base rigidity and led to prestressing of the soil massive, thus excluding soil softening.
   - The load produced by the reinforced concrete structure (pile cap or concrete foundation mattress) transfers directly to the soil when poured, after that 90 % of the subsequent load transmits to the piles.
   - Clayey soils, which lay directly under the foundation slab, may suffer strain relaxation resulting in redistribution of loads between piles and pile cap as well as between piles themselves.
2. The pile-pile interaction in a pile group (group effect) requires additional research, since even with the distance between the piles equal to 2-3 diameter, they can work as separate ones.
3. The analysis shows the need to improve methods for calculating pile foundations, especially for unique heavily loaded high-rise structures on stiff clayey soils, for which the use of standard models and approaches can lead to results that differ significantly from their actual work.
4. Since the loading of the foundation and its deformation continue, the shown monitoring results are intermediate but they can already become the basis for a detailed analysis of the influence of the factors specified in clause 1 on the stiffness of the foundation. They also should be taken into account when performing geotechnical calculations.

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