Piled raft foundation assessment based on geotechnical monitoring results

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Abstract. Article discusses data analysis of geodetic and strain gauge monitoring of stress-strain state of high-rise building foundation. Recommendations are given to improve monitoring system by expanding its analytical component through use of computer modeling, accounting for the work of foundation structure and soil base under gradual increase in number of stories of the building. Monitoring data is compared with results of calculations and design studies. Their qualitative and quantitative convergence is notable. Recommendations are given for further foundations design of high-rise buildings.

In recent years there has been intensive construction of high-rise buildings, both in our country and around the world. Over the past decade the world has witnessed strong growth in the construction of skyscrapers with height over 150 m [1]. Construction of tall buildings has its own characteristics that must be considered both in pre-design and design stages [2, 3]. In particular this applies to geotechnical monitoring, which needs to be done according to the normative documents [4]. This article presents experience of Moscow State University of Civil Engineering on organization and conducting monitoring of the high-rise building foundation in the complex of buildings of MIBC "Moscow International Business Center "Mercury city tower". Unique to the monitoring of high-rise buildings, is consideration of the construction sequence of the building, which allows us to accept controlled parameters in accordance with the sequence of increasing load on the foundation of the building [5].

Seventy story building of multi-functional complex "Mercury city tower", with a 5-storey underground part and 5-level top floor, with height of 338,0 m is considered a unique structure [6]. Foundation design of a multifunctional complex designed by NIIOSP named after. N.M. Gersevanov had piled raft foundation made from uncased bored piles [7]. Design proposed installation of 379 uncased bored piles of various diameter and length, of which 153 piles of 1500-20, 108 uncased bored piles of 1200-20 and 118 uncased piles of 800-17. Uncased bored piles of 1500-20 were placed under the central core, and uncased bored piles of 1200-20 were placed under the framework of high-rise part. Outside high-rise part mostly had, uncased bored piles of 120-20 and 800-17. Heads of the piles were joined by the plate with height of 4.35 m and an area of 6450m2 (area of the raft slab under central core accounted for 635m2). Under the central core and columns of the high-rise part piles are arranged as continuous pile field with spacing of 2.2÷5m. Outside of high-rise part spacing of piles is 4,4÷8,2m. In total, 381 piles were installed. Length of the piles from bottom of the foundation pit was 16,35÷of 19.35 m., depending on the diameter of the piles, calculated load value varies in the range of 1000÷2400tnf.
Soil base under the building consisted of fractured limestones of different strength. Strength of the limestone varied from low to average. In this regard, to strengthen the limestone, cementation to a depth of about 6 m under all piles was made. Hydrostatic pressure under the slab was caused by artesian suvorov aquifer, the value of which varied in the range of 3.1-10t/m2. To calculate piled raft foundation SCAD Office system was used, allowing us to carry out strength calculations and to design building structures of various types and purposes. General view of the design model of "Mercury City Tower" foundation structures, designed by MGSU, is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** General view of the design model of the foundation structures of the building “Mercury City Tower”

Diagram of piled foundation, which consists of different types of uncased bored piles of 1500–20, 1200–20, 800–17 in geological structure of the soil base of the building is shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Diagram of the geological structure of the soil base of "Mercury City Tower" building and location of the piles.
Due to the fact that the "Mercury City Tower" building considered a unique construction, a comprehensive geodetic and strain gauge monitoring of foundation structures under was organized and conducted during construction. Aim of the monitoring was to ensure future operational safety and reliability of the building constructions.

Design of stress-strain state monitoring of foundation structures was developed by JSC "Institute Hydroproject". According to the design, piles and foundation slab were installed with 186 sensors (98 sensors in the piles, 72 sensors in the foundation slab, 16 sensors at the base of the foundation slab).

However, conducted culling the sensors showed that only 68.8% of the original number of sensors remained in operational condition. In this regard, to assess changes of forces in the foundation slab and in the piles related to increasing height of the building, MGSU have developed a 3-D model and made calculations of the piled raft foundation together with above-foundation structures. Developed model (Figure 3), allowed to account for a phased construction of the building.

![Figure 3. Design model of the building.](image)

Characteristic to the conducted calculations was ability to compare effective forces in foundation structures at a certain stage of construction of the building with the monitoring information on the date corresponding to the relevant stage of construction.
Designed values of monitored parameters were established for each considered stage of construction of the building. Those values were required to conduct geodetic monitoring of deformations of the foundation slab and strain gauge monitoring of the foundation slab and piles. During this monitoring, pressure at the base of piles and slab was controlled, alongside with stresses in the piles and the slab, and displacements of the slab. Designed values were set based on analysis of materials by NIIOSP named after N.M. Gersevanov. In the future they were compared with data obtained during monitoring. This allowed to assess stress-strain state of the foundation structures and their actual operation in central core area as well as to determine the changes in stress-strain state and actual operation of foundation of structures in areas not covered by the monitoring.

Analysis of the results showed that the calculated deformations obtained with consideration of phased loading are comparable with the observed deformations. And this, in turn, testifies to the correctness of the chosen design diagram and correctly calculated stiffness parameters of the soil base. At the 1st stage of loading development of vertical settlements over time of various areas of the foundation slab, show both qualitative and quantitative difference. Area of the slab beneath the central core undergoes gradually developing settlement; deformations of peripheral areas are alternating in nature and in some cases show deformations values with opposite sign.

Described process of development of vertical deformations of the foundation slab surface in time contributed to the formation of "subsidence bowl" under the central core, with maximum deformations of around -2.9 mm (Figure 4). However, this "subsidence bowl" on first and second stages of construction of the building is located outside of the central core and the contour of the high-rise part, due to lower stiffness of the foundation compared to the central core, with symmetric loading. Formation of "subsidence bowl" under the central core led to the emergence of a deflection of the central core relative to the peripheral areas, which was predicted at the stage of project development.

But, starting from the third stage, the "cup" started to gradually shift under the high-rise part, due to the increase in loads from above-foundation structures and displacement of the center of gravity of the building (Figure 5).
Fig. 5. Isofields of settlements of foundation slab starting from third stage of loading (construction of high-rise part).

Comparison of recorded values of slab deflection, with their calculated values indicates that at the end of the reporting period, actual values of deflections were comparable with the calculated values.

Analysis of the calculation results of internal forces in piles and strain gauge monitoring data showed that the axial force varies along the length of the piles. It reaches a maximum value near the bottom of the foundation slab and decreases toward the tip of the pile. It was found that on average 71% of the load to the ground is transmitted through the friction at the lateral surface of pile, other 29% is transmitted using the tip of the pile. Operation of piles on friction of the side surface with the ground is confirmed by the monitoring data that were comparable to the results of the calculation, almost at all stages of loading.

Analysis of the results of calculation of internal stresses in foundation slab, made in the framework of the present work and strain gauge monitoring data showed that in general, distribution of internal stresses in the foundation slab according to the results of spatial reference computation of MGSU computer model in general coincides with the data calculation performed during the design stage. However, there are still some differences in the distribution of stresses and this difference lies in the values of active forces.

In reality, area of effect of maximum stresses have somewhat different contours of distribution, and peak values are offset in plan, as a result number of the points on the slab, equipped with control and measurement equipment, are located outside the area of maximum stresses.

Calculated internal stresses in the slab are comparable with the stresses calculated with data form the monitoring system, existing select differences between the calculated stresses and monitoring data are not related to the inaccuracy in the calculation, but caused by an error in the stress calculations done with sensor data in cross-section due to their small quantity.

During calculations with consideration to the sequence of construction of the building, accuracy of the sensor data with fully built framework was confirmed. It was found that at the initial stage of construction sensor readings had a significant influence form internal stresses, due to shrinkage and creep of concrete.

Experimental and analytical approach used in the work allowed us to estimate stress-strain state formation characteristics in areas of the slab and piles, including areas, not covered by monitoring.
The study of load transfer by piles to the ground, showed that the originally designed as end-bearing piles, transfer 71% of the load to the ground through friction on the lateral surface of pile, and the other 29% through the tip of the pile. Analysis of the obtained results showed that in real-life conditions piles work as friction-bearing piles. Conducted calculation and analytical studies once again prove the importance of consideration for sequence of construction of high-rise buildings when setting monitored parameters.

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