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Foundations of unique buildings and structures of St. Petersburg in difficult soil conditions

Fondations de bâtiments et de structures uniques de Saint-Pétersbourg dans des sols difficiles

R. A. Mangushev
Saint Petersburg State University of Architecture and Civil Engineering, Russia

A.I. Osokin
Saint Petersburg State University of Architecture and Civil Engineering, Russia

Abstract. Engineering-geological conditions of St. Petersburg, which are characterized by a large thickness of weak water-saturated lake-glacial deposits, are presented. The main characteristics of the base soils and examples of static sensing results are presented. The main technical characteristics of the foundations of the complex "Lakhta-Center", including a skyscraper with a height of 462 – the tallest building in Europe and a multifunctional center with a height of 85 to 15 m are considered.

1. INTRODUCTION

Saint Petersburg is the northernmost city in the world that has the population size over one million people. Founded in 1703 in the delta of the Neva River as the capital of Russia, the metropolitan city was developing broadways for almost 300 years - most of the buildings had 2 to 12 floors. Only in the early 21th century, high-rise construction began on the periphery of the city, and now a number of floors reaches 25 floors and more in the buildings erected on piles. The construction of the Lakhta Center Multifunctional Complex on the coast of the Gulf of Finland was a unique event for the metropolis, and the high-rise part of the Lakhta Center was completed in 2018. Unique building structures and technologies were used to construct its substructure.

2. ENGINEERING AND GEOLOGICAL CONDITIONS WITHIN SAINT PETERSBURG AREA.

The central historical part of Saint Petersburg is formed by deltaic deposits of fine-grained and silty sands with a thickness of 2 to 5 m underlain by the thick layer of soft lake-glacial and marine deposits. These soils have comparatively high and non-uniform compressibility.
The lake-glacial deposits – clays, loams and sandy loams – are practically pervasive and have the stratified or ribbon structure. These soils are characterized by high natural moisture content and porosity, anisotropic mechanical properties, high compressibility, heaving properties and thixotropy.

In this part of the city, the relatively firm moraine deposits occur at a depth of 15 to 30 m from the ground surface.
Within the city area, primary deposits are represented by Proterozoic, Paleozoic and Ordovician deposits covered by Quaternary sediments. It is in these deposits that the main subway tunnels and sewage headers are located. Fig.1 shows an example of the engineering and geological conditions of the northern part of Saint Petersburg.

3. LAKHTA CENTER MULTIFUNCTIONAL PUBLIC AND BUSINESS COMPLEX

3.1. *General*

The Lakhta Center is a public and business complex located on the coast of the Gulf of Finland in the Primorsky District of Saint Petersburg. The Complex includes a skyscraper 462 m high and a multifunctional building divided by the atrium into the South and North blocks[1] (Fig. 1).
The total area of the buildings is 400 thousand m². The skyscraper is considered as the northernmost in the world and the tallest in Russia and in Europe. Its height with a spire is 462 m, the total weight is 670 thousand tonnes, a number of floors is 87. The top floor of the skyscraper is located at an elevation of 372 m.

[1] The architectural design of the Complex was developed under the guidance of Architect F. Nikandrov. The General Designer was ZAO Gorproekt, the General Contractor was Arabtech (UAE)

Figure 1. General view of Lakhta Center Multifunctional Complex

3.2. *Principal design features of skyscraper substructure*

During the construction of the Public and Business Complex, a pile field of 2080 drilled cast-in-situ piles was used. In this case, 264 piles with a diameter of 2 m were constructed under the tower, 848 piles with a diameter of 1.2 m under the multifunctional building and arch, and 968 piles with a diameter of 0.6 m under the stylobate (Fig. 2).

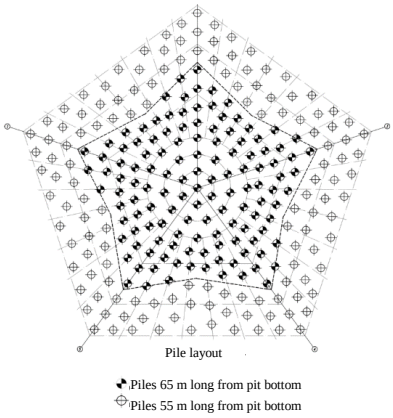


Figure 2. Plan of pile field under skyscraper building

The box-shaped foundation of the skyscraper consists of three tightly reinforced slabs that are enclosed by a diaphragm wall in the form of a regular pentagon, which penetrates down to undisturbed firm Cambrian clays (Fig. 3a).

A space between the three slabs of the box-shaped foundation is formed by underground floors, in the center of which a reinforced concrete core of the skyscraper is located with 10 radial walls going from it to the external perimeter. The walls have a thickness of 2.5 m and the total height of 11 m (Fig. 3b).

a)

b)

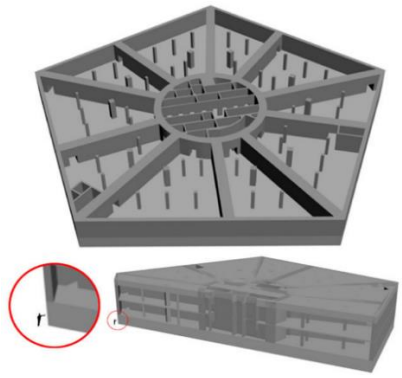
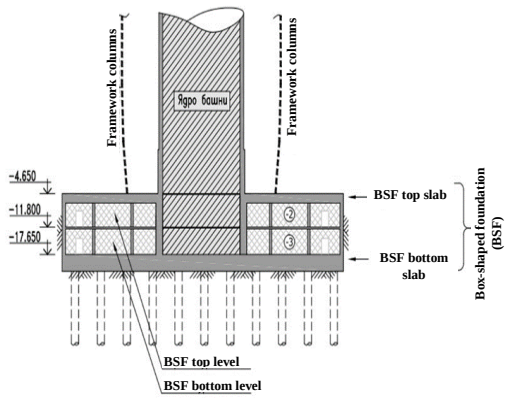


Figure 3. Box-shaped foundation and core of tower (a); model of box-shaped foundation and human scale (b)

The total height of the box-shaped foundation is 20 m, the inside diameter of the core is 24.5 m. The bottom reinforced concrete slab of the box-shaped foundation is 3.6 m thick, a diameter of its reinforcement bars is 32 mm with the reinforcement bars spaced at 16.5 cm. A total of 15 reinforcement mesh levels are installed in the bottom slab. The top slab is 2 m thick, the middle slab is 0.4 m thick[2]. The reinforced concrete core, which is the main stability structure of the skyscraper, is made hollow: inside it, there are located utilities, vertical transport, service rooms and safety areas. The core is rigidly connected to the box-shaped foundation, which transfers the load from the tower to the piles.

The diaphragm wall is a retaining structure of the excavation pit that protects the excavation pit against underground water and pressure of soil. The disk spacer system holds the walls of the excavation pit during the construction of the box-shaped foundation (Fig.4).

a)



[2] The construction of the diaphragm wall and the box-shaped foundation was carried out by ZAO Geostroy

b)

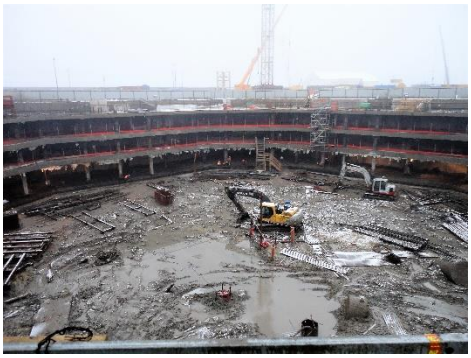


Figure 4. Sectional diagram and axonometric view of diaphragm wall with spacer disks and pile field (a) and general view of construction works (b).

The total length of the diaphragm wall is 300 m around the five sides with a height of 31.5 m and a width of 1.2 m. When the excavation pit is being cut, the stability of the diaphragm wall is provided by 4 spacer disks. In construction of this retaining structure, there were used 105 reinforcing cages with a weight of 20 tonnes. The bottom slab of the skyscraper box-shaped foundation is supported by the drilled cast-in-situ piles that are constructed according to the Bauer technology using a protective pipe 2 m in diameter of two types: in the center of the building, there are piles 65 m long, while along the perimeter, there are piles 55 m long[3]. (Fig.2). This was done in order to compensate for a greater settlement produced in the center of the building as compared to the edges. The total number of piles is 264 each.

The load-bearing capacity of one pile is approximately 5 thousand tonnes, which is 2.5 times higher than the design load. In general, the total load-bearing capacity of the pile field is over 1,300 thousand tonnes, and at that, it supports the total load of 670,000 tonnes.

3.3. *Specific features of substructure construction for multifunctional buildings*

Two buildings located on the sides of the high-rise landmark are built with the height difference of 22 to 85 meters and have a two-level underground space (Fig. 5 and 6).

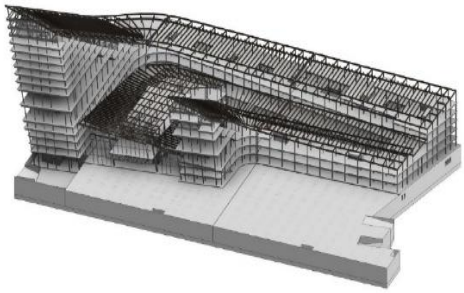


Figure 5. General layout of load-carrying structure of multifunctional building

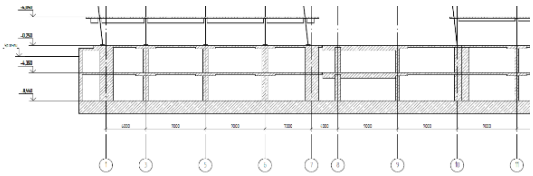


Figure 6. Fragment of substructure (no piles are shown) of designed multifunctional building across one of sections

Based on the load summary results, the pressure was calculated underneath the mat with a thickness greater than 1 m. In order to provide the uniform settlement of the building, it was decided to specify the same diameter of the piles for the entire pile foundation. The piles were taken with D = 1.2 m and a length of 34 m with different spacing between them. The piles were installed at an interval of 3 m under the high-rise part of the building and at an interval of 9 m under the foundation that carries a smaller load. The actual load-bearing capacity of the pile was taken as equal to 1,400 tonnes. Thus, the optimum rigidity of each section with a characteristic load has been achieved.

Taking into account that the construction site is adjacent to the water area, as well as the high groundwater level, a retaining wall of the excavation pit (diaphragm wall) 27.5 m deep and 0.8 m thick is constructed and buried into disturbed clays, whose roof is located at a depth of 25 m from the surface.

The second purpose of the retaining structure was to secure the walls of the pit during the excavation of the latter and the construction of the zero-level part of the building. Fig. 7 shows a fragment of the stage-by-stage excavation of the pit using berms and braces.

Section 1-1

[3] The design and monitoring of the pile field was developed and conducted by Gersevanov Research Institute of Bases and Underground Structures (Gersevanov Institute), the piles were constructed by Bauer (Germany)

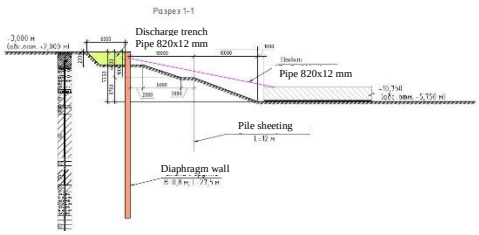


Figure 7. Layout of diaphragm wall in soil conditions of construction site

4. PRINCIPAL STRUCTURAL SOLUTIONS FOR SUBSTRUCTURE OF GAZPROM-ARENA FOOTBALL STADIUM

The construction works on the Gazprom-Arena Stadium were completed in 2016. The Stadium successfully hosted the 2017 Confederations Cup matches, the 2018 World Cup matches and many other competitions.

A new stadium was designed as an arena of oval shape in plan, with the 9-storey volume that is located on the cone-shaped volume of a man-made hill.

The main functional purpose of the building is a multifunctional football stadium of the highest category, closed-type, year-round use with a retractable field, a sliding roof and viewing stands that accommodate 68,000 seats.

The following was used as foundations of the facility:

a) Drilled piles 24 m long, 520 mm in diameter: 9000 ea. Soil load-bearing capacity of piles is 2600 kN. Concrete grades B30, B40, W8 and reinforcement A-500C were used for their construction.

b) Drilled cast-in-situ piles 28 m long, 500 mm in diameter: 1440 ea. Soil load-bearing capacity of piles is 8000 kN. Concrete grade B40, W8 and reinforcement A-500C were taken for their construction. The pile heads are combined using reinforced concrete cast-in-situ rafts of variable thickness, H = 900 to 1500 mm.

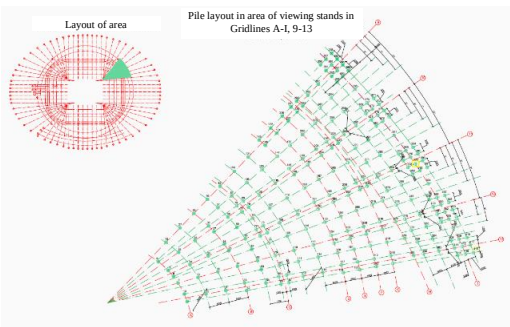


Figure 8. Principle of pile arrangement under viewing stands for one of segments

The sliding roof is supported by 8 inclined pylons that rest on the structure. Taking into account the high horizontal and moment loads that are transferred to the edge of the foundations of the pylons, the pile foundation structures for the roof supports are taken as space systems made of contiguous drilled cast-in-situ piles 1500 cm in diameter and 28 m long (Fig. 9).

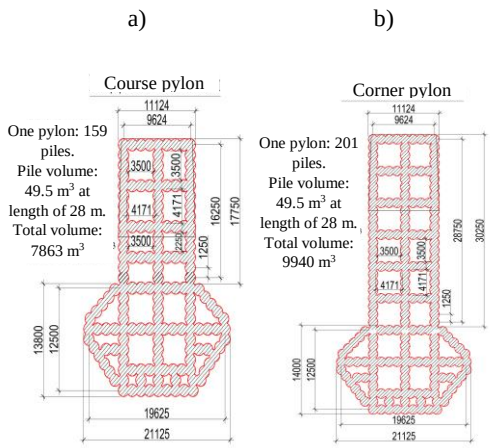


Figure 9. Construction of pile foundations for roof supports
a - course pylon; b - corner pylon

The retractable field with a weight of 8,400 tonnes including the grass turf, heating and blow-off system, engines and the metal frame is moved outside the stadium bowl. To meet the above requirements, a pile field is constructed under the slab of the retractable field. The pile field is made of drilled cast-in-situ piles 520 mm in diameter and 24 m long spaced at 3.0 x 3.0 m; then, additional piles were constructed in the bridge area above the retractable field (fig. 8.30). A thickness of the raft slab is taken as equal to 400 mm.

The construction works on the Gazprom-Arena Stadium were completed in 2016. The Stadium successfully hosted the 2017 Confederations Cup matches, the 2018 World Cup matches and many other competitions.

4. CONCLUSIONS

The foundations of the unique buildings and structures that were recently constructed on the thick layer of weak soils in Saint Petersburg are made of drilled cast-in-situ piles that are driven to low-compressible primary soils - Cambrian clays - showed the high load-bearing capacity and provided the acceptable absolute and non-uniform settlements.

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