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Practical restoration-related experience with creation of basement level and underground parking into and near architectural monuments in down-town of Saint-Petersburg

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Abstract. Geotechnical construction in Saint-Petersburg is governed by the specific features of geological conditions. There is large thickness of soft water saturated soil underlays at the basement monuments and historical buildings. This soft water saturated soil become thixotropic under insignificant dynamic effect (construction action, transport, seasonal freezing and etc). The experience of the renovation, reconstruction old buildings with construction of the deep basements, underground parking in the inner yards or near the architectural monuments in the central part of Saint- Petersburg are given in this article. This paper provides the description of geotechnical solutions, which were realized on the various cultural heritage buildings, such as Catholic Church of St.Catherine on the Nevsky prospect, Taurid Palace, Christmas Church on the Sands, shopping mall «Galeria» on the Ligovsky prospect. The authors analyzed some failures of buildings and facilities as the result of incorrect methods and technologies of the deep excavation.

1. Introduction

The architectural beauty and expressiveness of Saint Petersburg was created by the distinguished Russian an European architects Many of buildings in the historical part of the city are architectural masterpieces unrivaled anywhere in Europe and in the world, which requires that they should be preserved and delicately and safely adapted to the nowadays conditions of use.

The development of urban areas began in the XVIII century with district that define the nowadays historical center. By decree of Peter I, the city buildings started to be constructed primarily in stone from 1715. The city was built up on a regular basis in accordance with the Master Plan prepared by Domenico Trezzini and Jean-Baptiste Le Blond.

After having existed for more than 100 years, a large number of old buildings are at such a stage of operation when failures accumulated over the long period of operation of the building take place actively. Thus, for example, the destruction of the load-bearing structures of buildings (walls, roofs, foundations), decorative elements of the facade and interior finishing may take place and the deformation of the structural elements and the entire building may occur with cracks being formed.

In addition, over a long period of operation of residential buildings, the requirements for living conditions have changed, which led to the obsolescence of old residential development. The factors of dilapidation and obsolescence of the old buildings are eliminated during the capital repair and reconstruction of buildings, and in the case of heritage buildings, it is an adaptation for modern use.

Since the end of the 19th and the beginning of the 20th century, the development of the underground space in residential buildings and courtyard areas was carried out by construction of basements intended for functioning as warehouses and service indoor spaces, while the so-called "suspended yards" were arranged and served as storage areas for coal and fireplace wood for heating of buildings. The suspended yards are an underground space of different height (from 2,0 m to 2,4 m) located under the courtyard surface. As a rule, the walls and columns of the suspended courtyard are made of rubble stone or brick, and the floor structures are made in the form of metal beams, on which brick or concrete vaults are constructed. As the results of engineering survey in a number of suspended yards show, all load-bearing structures of the floors in the suspended yards are in the state of failure and require failure-prevention repair and overhaul repair.

Today, a popular and justified action to increase the investment potential of the historical buildings and the life quality of the city people, who live in the central historical districts, is the development of the underground space with the operational basements being provided and the construction of underground parking lots, which, in essence, have to replace the existing suspended courtyards creating comfortable conditions by means of preventing vehicles from crowding in the courtyards.

2. Features of engineering and geological conditions in historical part of the city

Geologically, the considered reconstruction sites with construction of underground parking are formed by the strata that are characteristic of the central part of the city. According to the data of drilling and cone penetration test, the site is geologically formed to a depth of 45,00 m as follows: recent technogenic formations (t_{IV}) represented by filled soil (EGE-1); biogenic deposits (b_{IV}) represented by peaty soil (EGE-2); lacustrine-and-marine deposits (lm_{IV}) represented by silty sands, compact with interlayers of sandy loams (EGE-3), plastic sandy loams with interlayers of very soft clayey loams (EGE-4); Upper Quarternary deposits (Q_{III}) of lacustrine-and-glacial (lg_{III}) genesis represented by flowing clayey loams with interlayers of very soft clayey loams, banded and stratified (EGE-5), plastic sandy loams (EGE-6); Upper Quarternary deposits (Q_{III}) of glacial (g_{III}) genesis represented by plastic sandy loams (EGE-7, 8), semi-hard clayey loams with interlayers of low-plastic clayey loams (EGE-9); Middle Quaternary deposits (Q_{II}) of lacustrine-and-glacial (lg_{II}) genesis represented by plastic sandy loams (EGE-10), Vendian deposits of Kotlin horizon (V_{2kt}) represented by hard clays (EGE-11).

Based on the composition and physical and mechanical properties, eleven engineering-and-geological elements (EGE) are distinguished in the area under survey. From the surface, packed filled soils (EGE-1) (t_{IV}) occur that include: sand of different fractions mixed with construction debris, with fragments of wood, rubble and brick, wet and water-saturated. The life of filling is 15 years. Filled soils are pervasive on the site and have a thickness of 1,80 to 3,80 m. Under filled soil, biogenic deposits (*bIV)* occur that are represented by peaty soils (ИГЭ-2) grayish-black, water-saturated with the layer thickness of 0,40-1,40 m. Lower in depth, lacustrine-and-marine deposits (*lmIV)* occur that are represented bysilty sands, compact and plastic sandy loams with interlayers of clayey loams that are of very soft consistency. Lacustrine-and-marine deposits include: heterogeneous silty sands, compact, gray, with interlayers of sandy loams, water-saturated, with organic impurity (EGE-3), which occur at a depth of 1,80-4,80 m and are distributed over the layer thickness from1,60 to 3,70 m; plasticity sandy loam, silty, with interlayers of very soft clayey loams, light, silty, thixotropic, gray, with interlayers of silty sands, water-saturated (EGE-4) that are occurred at a depth of 5,70-8,00 m and have a thickness of 3,10 to 3,80 m.

Upper Quaternary deposits (*QIII*) are represented by lacustrine-and-glacial deposits (*lgIII)* in the form of flowing and very soft clayey loams, banded and stratified, plasticity sandy loams. They occur throughout the surveyed site under lacustrine-and-marine deposits (lm_{IV}). Flowing and very soft clayey loams, banded and stratified, thixotropic, brownish-gray, with interlayers of silty sands, water-saturated (EGE-5) occur at a depth of 9,20 to 11,20 m and have a thickness of 2,00 to 5,90 m.

Lower along the section, plastic sandy loams, silty, thixotropic, gray, with interlayers of silty sands, water-saturated, with individual inclusions of gravel and pebbles (EGE-6) occur. They are encountered at a depth of 11,50 to 17,10 m, the layer thickness of the above soils is 1,90 to 3,90 m.

Upper Quaternary glacial deposits (Q_{III}) occur in the surveyed area under Upper Quaternary lacustrine-and-glacial deposits (lg_{III}) and represented by plastic sandy loams and semi-hard clayey loams with interlayers of low-plastic clayey loams.

According to the grain size, physical and mechanical properties: and results of cone penetration test, plasticity sandy loams are divided into the following engineering-and-geological elements: plasticity sandy loams, gritty, gray, with interlayers of sands of different fractions, water-saturated, with gravel and pebble up to 10-15 % (EGE-7), they occur at a depth of 15,30 to19,00 m and have the layer thickness of 3,00 to 5,20 m; and plasticity sandy loams, silty, gray, with interlayers of sands of different fractions, water-saturated, with rare gravel and pebble (EGE-8), which occur at a depth of 18,50 to 22,00 m and, accordingly, have a thickness of 2,20 to 2,50 m.

Lower along the depth of occurrence, there are semi-hard clayey loams with interlayers of low-plastic clayey loams, light, silty, gray, with interlayers of silty sands, water-saturated, with gravel and pebble up to 5-10% (EGE-9). The roof of the above clayey loams is encountered at a depth of 21,00 to 24,30 m. This layer has a thickness of 5,70 to 12,70 m.

Middle Quaternary deposits (Q_{II}) in the form of lacustrine-and-glacial deposits (lg_{II}) are represented by plastic sandy loams and well-developed under Upper Quaternary glacial (g_{III}) deposits and represented by plastic sandy loams, gray, with interlayers of silty sands, water-saturated, with individual inclusions of gravel and pebble (EGE-10), they are encountered at a depth of 32,50 to 34,00 m, the penetrated thickness is 0,70 to 2,50 m.

Upper Proterozoic deposits of Vendian system (V) of Kotlin horizon (Vkt) are represented by hard clays and encountered, according to the data of the engineering and geological survey, under Middle Quaternary lacustrine-and-glacial deposits. They are represented by hard clay, heavy, silty, greenish-gray, with interlayers of silty wet sands (EGE-11) and encountered at a depth of 35,10 m, the penetrated thickness was 9,90 m.

The hydrogeological conditions are characterized by the presence of underground water confined to the Quaternary deposit system: recent filled (t_{IV}) soils, peaty soils (b_{IV}), recent lacustrine-and-marine (lm_{IV}) sands and interlayers of sands in sandy loams and clayey loams of lacustrine-and-glacial (lg_{III}) and glacial (g_{III}) genesis.

On the site, non-artesian underground water is encountered at a depth of 1,80 to 3,80 m, which can be correlated to the annual average underground water level. The groundwater recharge occurs due to precipitation seepage and backwater effect from the rivers and channels, which are located in the proximity of the area under survey, during the period of storm surge phenomena. The maximum long-term amplitude of the underground water table fluctuation is 1,50 to 1,80 m (based on the data from the "Materials of reports on underground water regime of Leningrad artesian basin for 1987 - 1990" published in 1991). In the unfavorable seasons (periods of rains and snow melting, as well as backwater effect), the maximum underground water levels can be expected at a depth of 1,0 m.

3. Types of foundations of the old buildings

At the base of the buildings of the Petrine era, we can see the foundations of limestone, sandstone or granite boulders or diabase that are bonded, as a rule, on lime mortar. In some cases, when the construction took place on sandy soils with the bed being buried above the underground water level, there are individual buildings where the joints were not filled with masonry mortar and fine sand was used to level the surface when laying masonry. We encountered a foundation of this type at the time of the survey of the Bobrinskys' mansion in Galernaya Street.

Taking into account that the buildings had to be built on weak water-saturated soils, the regulatory documents of the Petrine period recommended that logs of wood - sleepers as we call them today - should be placed along the foundation structure when constructing rubble-stone foundations with the bed located below the groundwater level. Trunks of larch or softwood (spruce or pine) were used as sleepers. Wooden foundation structures in the form of sleepers served to distribute pressure on weak water-saturated soils from a building under construction, and had a utilitarian purpose to save stone -

difficult-to-obtain building material. Stone quarries were located far from the city and the delivery of stone was a costly exercise.

On the construction sites where there was peat at the base of buildings and along the banks of rivers and canals, pile foundations were used with wooden piles driven to a depth of 8,0 m.

Numerous results of engineering surveys in the old buildings of the historical center show that, in the case where the wooden foundation structures (sleepers, piles) are located below the groundwater level, they are in satisfactory conditions even today, after more than three centuries.

During the development of the historical center, there were used various designs of foundations and their materials. We can note a number of patterns that are characteristic of the foundations of buildings built in the XVIII - XX centuries.

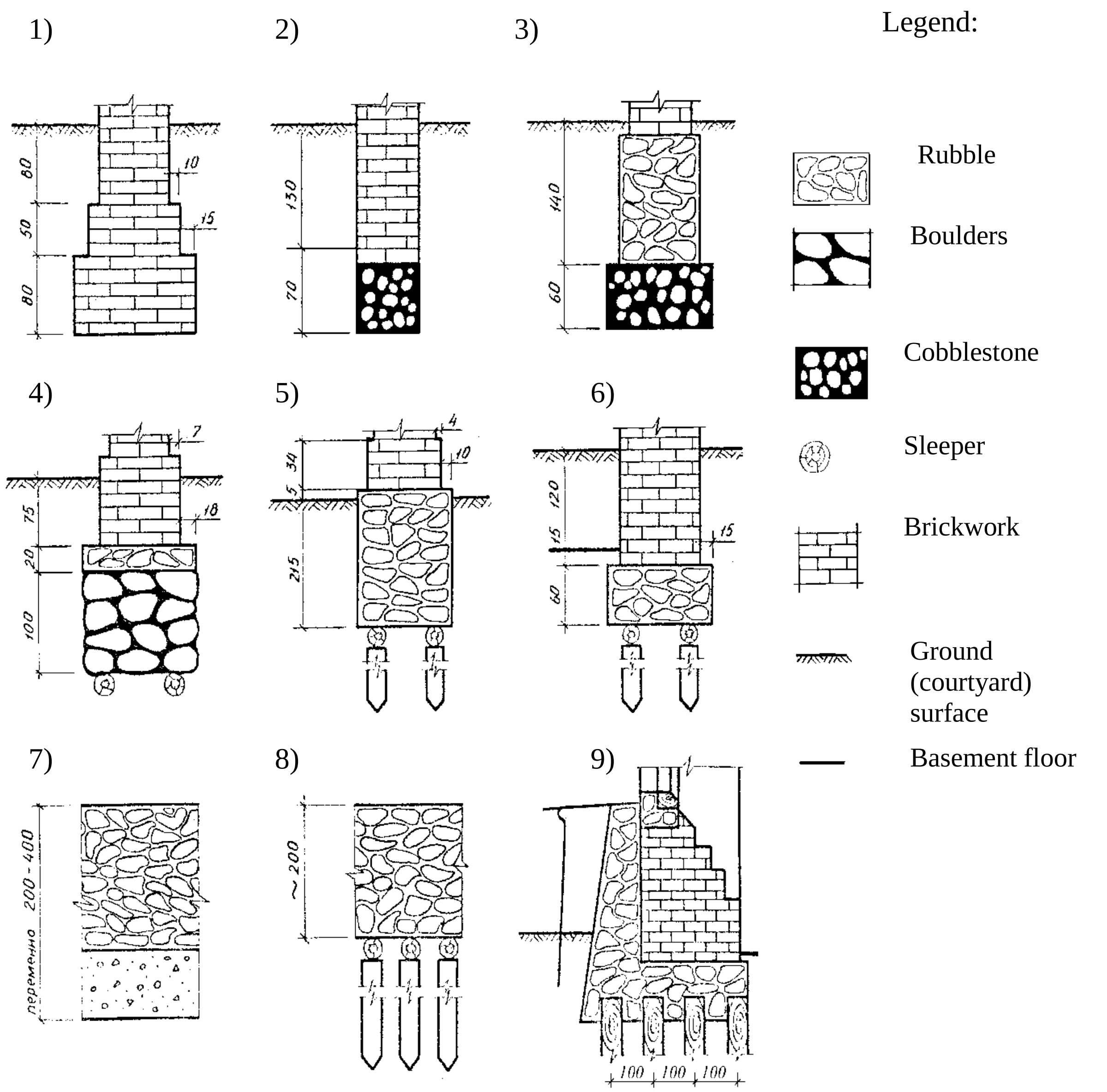

Figure 1. Principal types of foundations of historical buildings in Saint Petersburg (according to S. N. Sotnikov)

Figure 1 shows the cross sections of typical foundations of civil and residential buildings based on a summary of the engineering survey results for 64 historical buildings and architectural monuments. The major part of the stone buildings under consideration is situated in the Central, Petrogradsky, Admiralteisky and Vasileostrovsky Districts of the city and has 2 to 6 stores.

Out of the sampling in question, 44% of the buildings have silty clay soil as bearing stratum under the foundation bed. In 56% of the buildings, there are sands of varying grain size (as a rule, litorina deposits from silty to medium-grained).

The foundations of 82% of the buildings are made of rubble, granite or lime stones, and only 18% are made of burnt brick. Sleepers were found under the foundations of 22 buildings (34%), and timber piles (14%) were found under 9 buildings.

The analysis made allowed assessing the basic parameters of the surveyed foundations including those that depend on a number of stores in the buildings.

A depth of the surveyed foundations to the ground surface was 1,5 to 5 m. In this context, it should be noted that a size of the cultural layer reaches 3 m in some districts of Saint Petersburg.

For the sampling in question, bed width *b* varied from 0,5 m to 2,8 m for the sand-base foundations and from 0,8 to 2,3 m for the silty clay bases (Figure 2). As it can be seen from the percentage distribution of the width values for the foundation bed, the most common size is b = 1 to 1,5 m. The next position in terms of popularity are foundations with width b = 1,5 to 2,0 m, a ratio of which to the total number of the buildings surveyed is, respectively, 20 and 25%. In some cases, the bed width of rubble-stone foundations may be significantly greater than the average specified values. For example, at the base of the Lobanov-Rostov’s House, the foundation bed width was 4,0 m, and wooden sleepers were found at its base.

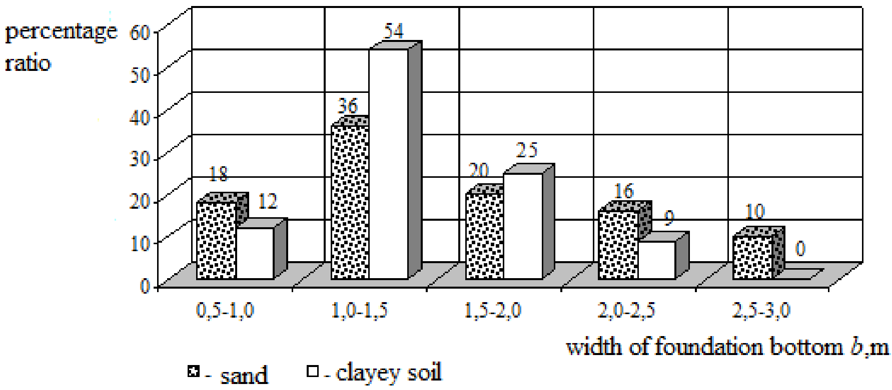

Figure 2. Percentage distribution of the foundation bed width in surveyed buildings

In the sampling under consideration, the foundation depth of the buildings *d* varied from *d* = 0,3 m to *d* = 3,0 m for the sand bases and from 0,7 m to 2,5 m for the silty-clayed soils. Sleepers were mostly found at the foundation depth of 1,2 to 1,8 m.

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From the graph of the percentage distribution of the depths of the surveyed buildings (Figure 3), it follows that the most common depths are values *d* of 1,5 to 2,0 m. These values are explained by the seasonal depth of soil freezing in this region, which is 1,2-1,4 m.

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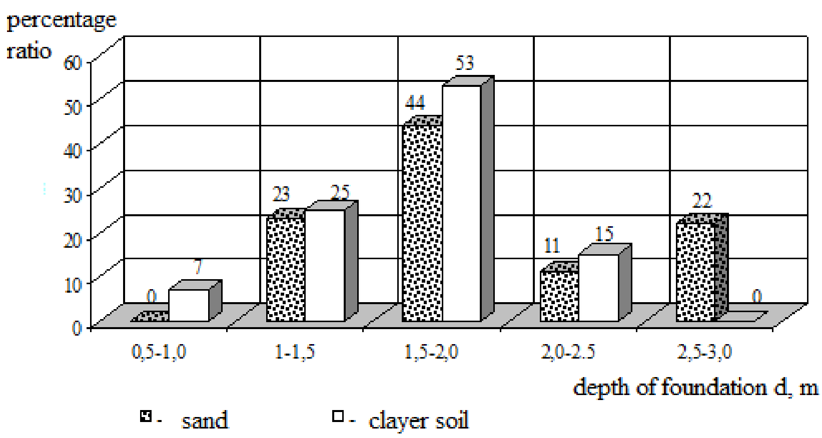

Figure 3. Percentage distribution of foundation bed width in surveyed buildings

The comparison of the actual averaged pressure *p* acting on the foundation bed of the surveyed buildings to the permissible pressure on the foundation soil indicated in the current regulations, in particular, value *R* according to the formula given in SP allowed determining the following regular patterns (Figure 4).

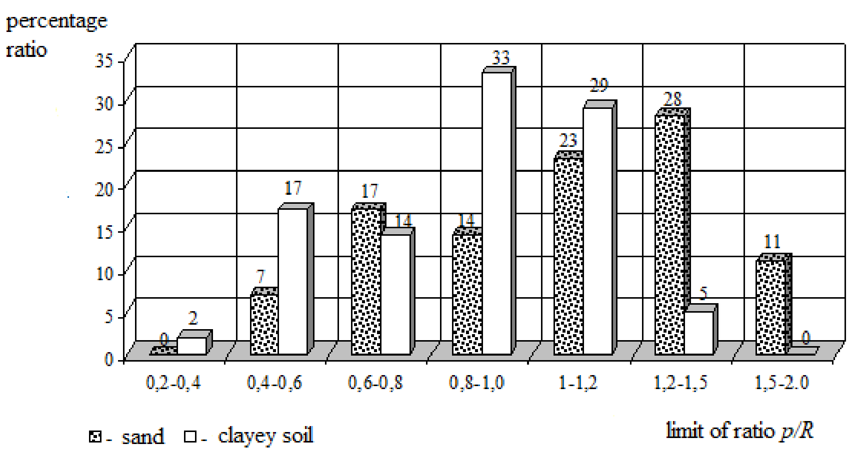

Figure 4. Percentage distribution of ratio *p*/*R* for examined buildings

The comparison of the actual averaged pressure *p* acting on the foundation bed of the surveyed buildings to the permissible pressure on the foundation soil indicated in the current regulations, in particular, value *R* allowed identifying the following specific features for the foundations of the buildings built in the central part of Saint Petersburg: in 62% of cases, the pressure on foundation bed exceeds the permissible standard pressure *R* if there are sandy soils at the foundation bed, and in 34% of cases, the excess in pressure on foundation bed occurs if there are silty-clayed foundation beds.

Thus, for the old buildings of Saint Petersburg, a ratio of the actual pressure to the calculated soil resistance obtained by formula SP 22.13330.2016 (SNiP 2.02.01-83) has a margin of the load-bearing capacity of the foundation soil only in 24% of cases for sandy foundation beds, and in 33%, for silty-clayed soils, which indicates the presence of an overloaded foundation bed in accordance with modern standards.

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4. Engineering solutions for adaptation of architectural monuments with construction of basements and underground parking

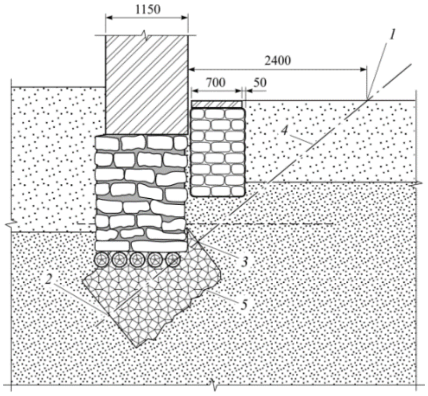
Let us analyze the basic engineering solutions used in restoration practice for the adaptation of historical buildings and architectural monuments with the development of underground space. In this case, we consider the conditions to make a basement deeper and to construct an underground floor in the internal courtyard space to accommodate a parking.

The history of the underground space development of the residential and civil buildings of Saint Petersburg goes back to the Petrine era. The most remarkable example of systematic development of underground space in the restrained urban conditions is the construction of the so-called "suspended yards" under the areas of residential and public buildings in the late XIX and early XX centuries. They were of service purpose: to store of fireplace wood for stove heating. At the present time, there are more than 71 of such yards in the city. Most of them are in the state of failure and pre-failure and require overhaul repairs.

The construction of basements and their deepening is one of the most demanded tasks of the engineering restoration of historical buildings and buildings-monuments. As a rule, the basements of the XVIII and the first half of the XIX century had floor structures in the form of brick vaults supported by walls and internal columns. Basement floors were made over the ground or by masonry where the brick was placed on edge in the floor structure. At the base of the floor, it was arranged a clay trap or bed drainage from where groundwater was discharged to the nearest canals and rivers using wooden drainage gutters. Later, for the construction of floor structures above the basement, metal beams were used, a span between which was filled with brick, brick-concrete or concrete vaults, and the floor structure was made of concrete over brick fill material, of concrete over crushed rock floating a surface with cement. In the floor structure of the basements of the buildings constructed in the beginning of the XIX century, the engineering survey revealed waterproofing made of rolled bituminous materials.

To make basements deeper, the construction practice uses several methods to consolidate the soil during excavation below the foundation bed (Figure 5):

- construction of pile sheeting of drilled injected piles up to 250 mm in diameter around the perimeter of the indoor space when it is deepened;
- jacking of metal pile sheeting around the perimeter of indoor space to prevent scouring of soils from under the foundations;
- injection consolidation of soils at the foundation bed to a depth of at least 1 meter from the elevation of planned excavation; injection consolidation of soils can be done using cup-type injection pipe strings or using Jet Grouting technology;
- relocation of foundations of building on drilled injected piles or on jacked piles made of metal pipes.



a)

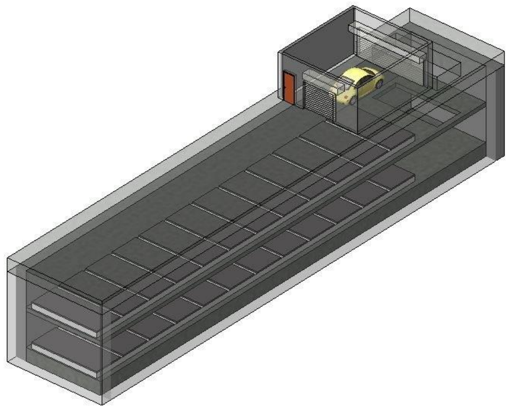

b)

Figure 5. a) Schematic view of operations to underpin the foundations of old building by Jet Grouting: *1* – starting drilling point; *2* – bottom drilling point, beginning of jet grouting; *3* – end point of jet grouting; *4* – center line of grout borehole; *5* – stabilized soil body; b) the view of as-built Jet Grouting column

It should be noted that engineering solutions for the construction of underground structures are useful to consider as integrated ones. In this case, the design includes technologies for shoring of pit, excavating of soil and constructing the very structures of underground facility. Given this approach, a design section will also include engineering measures to protect the excavation pit and the underground facility against underground water. As conditions for safe construction, preventive measures are considered to provide preservation of the existing buildings located in the vicinity. When developing an integrated design, all proposed engineering solutions shall ensure that the environmental protection requirements are met.

When designing underground structures in the conditions of historical development, one of the mandatory requirements is the geotechnical forecast (geotechnical justification) of the impact of construction work on a change in the stress-strain state of soil mass and the deformation of existing buildings and facilities. In this context, the modeling of the situation takes into account the strict regulatory restrictions on additional deformations for monument-buildings.

As an example of an analysis of the possibility to construct an underground parking in the internal courtyard space, let us consider Building 24 in Kirotchnaya Street. The building has a courtyard of irregular shape with a suspended yard throughout its area. The building was constructed in 1844, and is known as the revenue house of Yu.B. Bak.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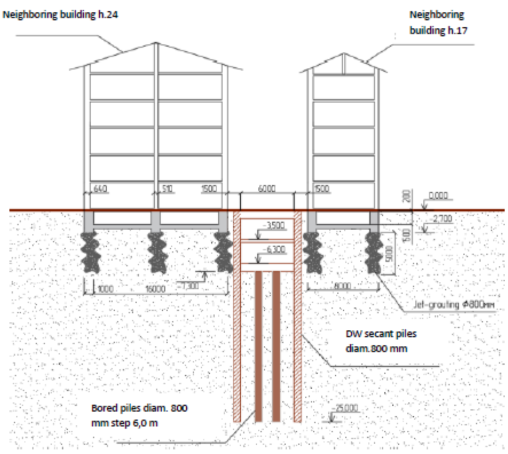


b)

Figure 6. View of parking model (a) and computational model (b) in courtyard No.1, Building 24, Kirotchnaya Street.

We considered the possibility to construct, in the backyard (No.1), a two-level underground parking with dimensions of 6x36 m (pit depth is 7.50 m) designed for 20 cars (Figure 6). The pit shoring for the parking is supposed to be constructed of drilled cast-in-situ piles 620 mm in diameter and 25 m long lowered into compact Proterozoic clays.

In case of excavation of pit using the Top-Down method and preventively underpinning the foundations of neighboring buildings using drilled injected piles or the Jet Grouting method, the geotechnical justification performed using PLAXIS PC showed that additional settlement of neighboring buildings will not exceed 10 mm, i.e., will not exceed the permissible values in accordance with existing standards, both in terms of the amount of permissible settlement and its relative unevenness(Figure 7).

In this regard, the designs and technologies for enclosing structures during the construction of an underground structure in historical buildings must satisfy the following basic requirements:

- to provide the stability of the pit walls during and after the full development of soil;
- to take up a load from the structure, if the fence is part of the structure of the underground structure;
- to provide waterproofing;
- the shoring shall be constructable, possibly reusable (during its temporary use), it shall not obstruct the pit, interfere with the excavation and backfilling of soil and the installation of main structures;
- to provide the preservation of operated ground and underground historical facilities that falling into the zone of impact of the underground structure under construction.
- to provide compliance with environmental requirements (compliance with acceptable standards for noise, vibration, environmental protection).

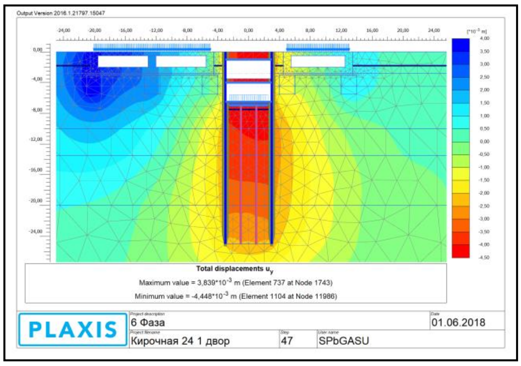


Figure 7. Example of numerical calculation of additional settlements of building structures near the parking lot in courtyard No. 1, Building 24 in Kirotchnaya Street.

When designing of shoring in water-saturated soils, a depth of the pit shoring structures should be specified taking into account their embedding into the confining bed (in order to provide excavation operations without dewatering).

A design of the excavation pit shoring, as well as of the foundation bed of underground structures is calculated according to two groups of limit states.

The first group of the limit states provides for the following calculations:

- stability of the wall location against shear, tipping and turning;
- stability, load-bearing capacity and local strength of the bed;

- strength of structural elements and joints;
- load-bearing capacity and strength, stability of spacer or anchor elements;
- filtration stability of the bed.

The second group of the limit states provides for making such calculations as:
- beds, retaining walls and their structural elements for deformations including the determination of horizontal displacements;
- reinforced concrete elements of wall structures for crack opening.

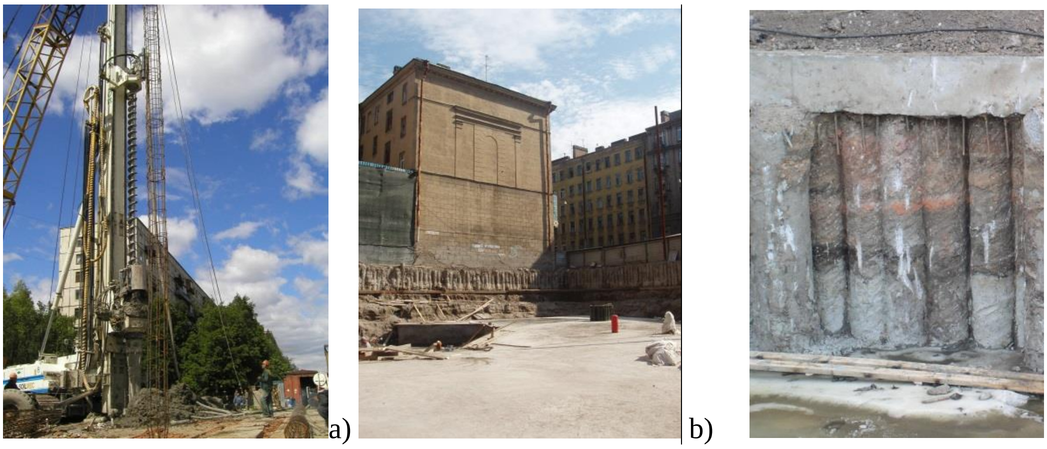
Given the construction of the excavation pit shoring based on the diaphragm wall technology using a flat hydraulic grab, the stability of the walls of the trench filled with bentonite slurry should be calculated for stability.

When determining the contact stresses and lateral soil pressure on the structures of excavation pit shoring, the following shall be taken into account:
- external loads and impacts on soil mass such as surcharge from stored materials, load from building mechanisms, transport load on the roadway, load transmitted through the foundations of neighboring buildings and structures, etc.;
- engineering-and-geological and hydrogeological conditions of the site;
- slope of soil surface, topographic roughness and deviation of the boundaries of the engineering-geological elements from the horizontal;
- the ability to install berms and slopes in the excavation pit during the operations performance;
- strength properties at the wall - soil mass contact;
- deformation characteristics of retaining wall, anchor and spacer elements;
- sequence and technology of operations;
- capability to overdig during the excavation process;
- additional pressure on retaining walls caused by heaving, swelling of soils, as well as operations to inject grouting into the soil, cementing, etc.;
- temperature and dynamic (vibration) effects.

Shoring of excavation pits can be fixed by one or several tiers of braces or anchors. A number of tiers of the bracing structures, the technical parameters of soil anchors are determined by calculation depending on a height of pile sheeting to be fixed and soil conditions. A type of anchor shall be specified based on the design pulling load, the type of soil and the conditions of operations.

Depending on the features of the engineering and geological conditions on the site, the following methods to drill boreholes are used to install drilled cast-in-place piles in soft soils:
- rotary drilling using three-cone bits or drill bucket with a borehole being formed under bentonite slurry (drilling mud);
- rotary drilling with the stability of the borehole walls being provided using casing pipes in clayey soils of soft to hard consistency, medium-and coarse-grained sands;
- sometimes, in the presence of artesian horizons of underground water, a combination is used in the form of consolidating the borehole walls with casing pipes and filling the borehole with bentonite slurry to create backpressure and prevent water-saturated soils from being carried over into the borehole.

In recent years, the Double Rotary technology has been introduced into the construction practice construct pit shoring of drilled piles where a casing pipe and a continuous hollow auger are used at the same time, through the holes in which the borehole is filled with concrete during the drilling process, and the reinforcement cage is lowered into cast concrete using vibration preloading (Figure 8).



a) b) c)

Figure 8. Construction of piles using the double rotary technology (a), view of excavation pit (b), whose pile sheeting is made using double rotary technology and view of construction of pile sheeting of piles (c) made using this technology

Construction of pile sheeting of drilled secant and tangent piles has several advantages:

- Capability to construct piles in different lengths resting and the required elevation where the roof topography of strong soils taken as foot of piles is highly rugged. In this case, vertical loads on the piles 250 – 550 mm in diameter and 18,0 – 32,0 m can take up a wide range of loads of 300 to 1500 kN. This allows rationally using the pile sheeting as a load-bearing structure to transfer the loads from the walls of the structure to the dense soil of the base;
- improving the reliability of structures by means of reducing the total and non-uniform settlements;
- prevention of process-oriented movement and deformation of soil mass and neighboring buildings due to drilling operations in the particular area;
- low technological impact on the surrounding buildings in the presence of dedicated diamond tools to construct the secant piles.

In the past 25 years, the jet grouting or jet technology has been used to consolidate the excavation pit walls in special conditions. The principle of this method to consolidate the walls of the excavation pit is to mix the soil using consolidating grout with partial or complete replacement of the soil with grout by means of high-pressure injection.

When sequentially forming adjacent soil-cement elements, the jet technology is used to install vertical sheets made of soil-cement piles, which, working as a part of pile sheeting of excavation pits, can be reinforced with metal elements of pipes or I-beams. The pile sheeting of excavation pit can be made of one row of secant soil-cement piles (for example, 800 mm in diameter spaced at 650 mm) or by staggered arrangement of piles of smaller diameter in two rows. Soil-cement piles inclined at an angle of 30 – 45° to the vertical can also be used to consolidate such pile sheeting. The sheeting piles and consolidated piles are combined at the top by a cast-in-situ reinforced concrete cap beam. To increase the stability of the walls made by jet grouting, they are reinforced with steel pipes 500 – 600 mm in diameter or rolled beams ($\boldsymbol{h}$ = 50 – 60 mm), spaced at 1,5 – 2 m along the wall (Figure 9).

Figure 9. Construction of shoring of excavation pit using soil-cement mass when building pedestrian underpass in Avtovo

Pile sheeting of excavation pits in the restrained urban conditions can be constructed of metal, reinforced concrete, plastic and wooden elements of flat and irregular shapes and of various profiles, which are lowered into soil by vibratory penetration or by jacking including in pilot boreholes (Figure 10).

For deep excavation pits that are large in plan, steel sheet piles of various profiles are widely used the engineering practice. Steel profiles of the U-, Z-, H-shaped cross section are most widely used. In some cases, there are used sheet piles of irregular shape, pipe sheet piles in the form of half-pipe, as well as flat sheet pile elements.

In the practice of constructing underground structures, there is a practice, in European countries and in Saint Petersburg, to use metal sheet piles that are subsequently undergo special-purpose processing as sheet piling for underground parking. However, it should be taken into account that the sheet-pile wall belongs to flexible types of fastening, therefore it is advisable to use it in the absence of significant loads near the edge of the pit.

Figure 10. Indentation of the Arcelor sheet pile during construction of the basement of the business center at Nevsky Prospect, 55

Recently, we have been actively using the diaphragm wall method for shoring of excavation pits, which is one of the most advanced and universal to construct underground facilities in open pits (Figure 11).

The technology for the construction of diaphragm walls as shoring of excavation pits makes it possible to construct:

- in the immediate vicinity from existing buildings and structures;
- given the significant depth of structure (down to 50 m);
- given large sizes in plan and irregular shape of structure;
- at high underground water level.

According to the soil conditions, the diaphragm wall can be used in any dispersed soil except for flowing clayey soils, silts and quicksand, as well as in the presence of water-absorbing soils with high filtration flow rates.

Figure 11. Construction of diaphragm wall during adaptation and restoration of Mikhailovskaya Dacha Building Complex to accommodate the Higher Police School Saint Petersburg State University campus

In our opinion, the diaphragm wall is the most universal and flexible in the current restrained conditions of urban development to solve the problems of adapting the heritage monument areas when constructing excavation pits and providing the preservation of cultural heritage sites. The equipment used in Saint Petersburg is capable of constructing trench walls to 70 m deep and 400 to 1200 mm wide.

 a)  b)

Figure 12. View of bracing structure in the form of struts (a) used in construction of Pravda-the Renaissance Office Center and reinforced concrete beams (b) on construction site of Business Center at Suvorovsky Pr. 2 (Semi-Top-Down construction technology)

To provide the stability of the diaphragm wall, various retaining systems are used, principal of which are struts, bracing structures, soil anchors, and the Top-Down technology for excavating the pits.

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The struts are used to consolidate the shoring of wide excavation pits. In height, struts can be installed in one or two rows (Figure 12a). The main disadvantage is the difficulty of excavation work near the strut-framed shoring. Currently, the most common method of consolidating the shoring of excavation pits during open-pit construction is the installation of a temporary bracing system of metal elements.

In restrained urban conditions, underground and buried structures are often built using the closed or semi-closed method (Figure 12 b) of constructing an excavation pit using the top-down technology, which minimizes the impact of the construction on the natural stress-strain state of the soil mass that surrounds the construction site. This method involves the construction, from the ground surface or from intermediate elevations in the pit, of temporary or permanent supports inside the outline of the facility that support the flooring of the building substructure, that are concreted over soil and take up outward pressure from the shoring of excavation pit. Soil is excavated in the pit from under the flooring through service openings (Figure 13 a). The underlying flooring is concreted in succession as the soil is removed. In case of using the temporary supports, on which the flooring rests, they are dismantled upon completion of construction of foundation slab and permanent columns or load-bearing walls that are concreted from bottom up (Figure 13 b). .


a)

b)

Figure 13. Construction of deep excavation pit using Top-Down method in construction of administrative building: a) the view of the Top-Down construction site; b) inside Top-Down system.

The construction methods using semi-closed or closed technologies for pit excavation are considered today as the most low-impact technology relative to the existing neighboring buildings providing the minimum settlements, in comparison with the other methods of pit consolidation, of existing buildings and structures.

5. Conclusion

The analysis of engineering-and-soil conditions in the historical part of Saint Petersburg, the technological methods to construct basements and the construction of underground parking in the vicinity of historic buildings allow concluding that such construction is possible with the integrated engineering approach being provided to select the structural and process-oriented solutions taking into account the minimum possible deformations of existing buildings.

Calculations using the PLAXIS software package showed the possibility of the construction and the efficiency of the diaphragm wall as shoring of excavation pit together with the use of the Top-Down technology to excavate the foundation pit. A prerequisite for the safety of such construction is the implementation of preventive underpinning of foundations, and, if necessary, strengthening of structures of neighboring buildings.

In addition, the key to the successful construction of basement floors and underground parking is a well-targeted and complete program of geotechnical monitoring and scientific-and-engineering support throughout the entire cycle of engineering restoration and construction that allow the timely adjustment of the construction processes preventing unacceptable non-uniform deformations of surrounding buildings.

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